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OPTOELECTRONIC DEVICES

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EDITORIAL

The advances which have led to the maturity of optical fiber communications result from major improvements of past decades in semiconductor lasers, light emitting diodes, detectors and fibers. The present revolutionary progress in optical communication is a consequence of the lucky concurrence of the increasing economical need for high capacity, high data rate transmission technologies and the abilities of optoelectronic solutions. Inversely, the development process requires the rapid evolution of optoelectronic devices.

The new components and technical solutions utilized in optical communications proved widely applicable in the sensing and measuring technology as well. These new fields of application inspired further efforts in device engineering to meet user's requirements. A result of these endeavours established the rapidly progressing technology of photonics which now penetrates all areas of optical communications.

Hungarian scientists and engineers sensed the above depicted evolutionary trends in time. In the Research Institute for Technical physics of the Hungarian Academy of Sciences, research, development and manufacturing of semiconductor lasers, LEDs and detectors working in several wavelength windows has started. Measuring equipments were designed and fabricated for qualification of fibers and optical links. In the Research institute for Telecommunication, the Research Institute of the Hungrian PTT and the Telephone Factory "TERTA", a wide-range program was carried out for development and application of varions optical communication links. Research has been started for discovering basic physical phenomena of photonics in the Central Research Institute for Physics of the Hungarian Academy of Sciences and at several departments of the Technical University of Budapest. The teaching of subjects relating to these topics has been also introduced at the Technical University of Budapest.

This activity is illustrated by some high level products and numerous international and Hungarian papers, scientific reports and books. The whys and wherefores of the poor economical success of these efforts are well known. However, the main profit of pioneer's work is embedded in the brain of the engineering society. This manifests itself in the sensitivity to photonic problems, the treasury of ideas, and the world-wide work of the well educated new generation of optoelectronic engineers. My firm conviction is that these values will be fruitful among the challenges and new possibilities of the future.

The initiator of this special issue of the Journal on Communications was one of the most talented pioneer of Hungarian optoelectronics, my friend, the late Edmund Lendvay. His tragic death hindered him to continue his extensive scientific work and to complete the editing of this issue. His memory obliged me to follow his initiatives according to the best of my knowledge.

Two survey papers intend to keep the reader informed in the wide variety of optoelectronic devices. The first is based on an URSI Review and looks over the components of optical communications, the second original survey sums up the fiber optic sensors. The selected problems of optical electromagnetic waves discussed in other two contributions are related to the topic of integrated optical systems.

The guest editor hopes these papers will be found interesting and useful by the readers.

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István Habermajer was born in Budapest. He graduated in electrical engineering from the Technical University of Budapest in 1959. He received the "dr. techn." degree in 1964, and the Candidate of Technical Sciences degree in 1989. From 1959 to 1963, he worked at the Hungarian Television Company. Since then he has been at the Technical University of Budapest, and became an Associate Professor at the Department of Electron Devices. He is a technical advisor at the Research Institute for Technical Physics, and directed several R&D projects in the field of semiconductor device measurements. His current education activities are related to electron devices, semiconductor physics and optoelectronics. His main interests are analysis and design of semiconductor lasers and photodetectors. He is a member of several technical committees.

ADVANCED OPTOELECTRONIC DEVICES — A SURVEY

The paper provides a survey of recent results in the field of optoelectronic devices. The selected topics are in the forefront of optical communication, optoelectronic sensing and measuring technics. The survey is based on a recent URSI review.

1. INTRODUCTION

The first optical links have been installed nearly two decades ago. On the base of their economical and technical success, optical links are now widely used both in long-haul and local communications. These two branches of telecommunications impose different requirements upon optoelectronic devices. The long-haul links require devices for handling the high information speed and the high span-length. For the optical data path of local area networks, complex mass produced devices and optoelectronic IC-s are needed. The optoelectronic sensing and measuring systems open up a wide field of applications but expect some new features of devices. To reach these targets, the results of physics, material sciences and more effective design methods are required.

The selected topics of this deal with the latest trends, based on an URSI Review *[Ref A., 1990]*.

2. DEVICES AND APPLICATIONS

2.1. Semiconductor Lasers and Light Emitting Diodes

Extensive research and development efforts in semiconductor lasers have been devoted to improving reliability, reducing threshold current and increasing bandwidth. In the past two decades, lasers have become highly reliable devices with projected lifetimes of over 100 years. Threshold currents as low as submilliampere have been reported *[Marclay et al., 1989]* and thresholds below 10 mA are now common. Bandwidths have increased from tens of MHz to greater than 20 GHz *[Bowers and Pollack, 1988]*. The energy distribution between different longitudinal modes of laser diodes has been explained by *Joindat and Boisrobert* [1987]. In recent years, the continued evolution of fiber optic systems toward higher and higher bit rates, and the emergence of coherent transmission techniques have placed stringent performance demands on semiconductor lasers *[Bowers and Pollack, 1988, O'Mahony, 1988]* as well as requirements for single frequency operation with narrow linewidth and wavelength tunability *[Kobayashi and Mito, 1988]*. These demands have required more sophisticated and complex device structures such as multiple-quantum-well active layers and/or integrated grating feedback.

Several of the performance characteristics of semiconductor lasers have been enhanced by the use of quantum-well laser structures *[Arakawa and Yariv, 1986]*. These include low threshold current density, high-power capability, low chirp width, narrow spectral linewidth, and higher resonance frequency. The high differential gain due to a restricted density-of-states function is responsible for improvements in resonance frequency *[Arakawa and Yariv, 1986]*, linewidth *[Koch et al., 1988; Sasaki et al., 1989]* and chirp *[Spano et al., 1988]*.

For fiber optic transmission, a major research thrust has been the development of lasers capable of dynamic single frequency operation, i.e., lasers that exhibit single longitudinal mode oscillation during high-speed modulation. Lasers that incorporate an integrated distributed Bragg grating, the distributed feedback (DFB) laser *[Nishimoto et al., 1987; Baryshev et al., 1988; Kakimoto et al., 1989]*, and the distributed Bragg reflector (DBR) laser *[Koch et al., 1988]* are rapidly being developed for single-frequency applications. Several structures designed to increase mode discrimination and achieve narrow linewidth have been reported, including coupled cavity resonators, external feedback elements, surface emitters, and distributed resonators *[Bowers and Pollack, 1988; Amann et al., 1989]*. Surface-emitting laser diodes and light-emitting diodes have been fabricated and operated, including new types based on a coaxial transverse junction structure *[Yamada et al., 1988]* for various future applications, such as monolithic two-dimensional arrays for optical image processing as well as optical interconnections for integrated optics.

MO—CVD (metal organic-chemical vapor deposition) technology has been successfully established for the growth of the InGaP/InGaAlP double heterostructure on GaAs substrates. New visible lasers have been realized emitting at 660—680 nm with output powers of 3 to 5 mW. Long-term reliability has been confirmed by accelerated aging *[Okuda et al., 1989]*. These lasers will find wide applications in point of sales (POS) scanners, laser beam printers, and optical disk systems.

Recently a wide range of high-power semiconductor lasers has emerged. One of the most rapidly developing applications is pump sources for solid-state lasers. Others include optical recording, high-speed printing, database distribution systems, free-space communication, local area networks, doppler optical radar, and optical microwave sources. Higher output power has been achieved from phase-locked laser arrays *[Reinhoudt and Van der Poel, 1989]* using quantum-well structures grown by using the MO—CVD technique. One-dimensional arrays of 100 lasers have exhibited peak pulse powers as high as 134 W and CW power levels of 8 W, and even higher powers may be achieved with two-dimensional arrays.

2.2. Photodetectors

Research and development of photodetectors have been primarily directed toward fiber optic transmission systems and various sensor applications. Fiber optic applications have concentrated on p-i-n photodiodes and avalanche photodiodes (APDs) for transmission at 1.3 and 1.55 μm. Recently, metal-semiconductor-metal (MSM) Schottky barrier photodiodes have received considerable attention because of their potential for integration into integrated receivers. The most widely used photodetector for lightwave communication has become the InGaAs/InP p-i-n photodiode, and efforts have focused on reducing the dark current, optimizing the responsivity, reducing the capacitance, and maximizing the bandwidth *[Forrest et al., 1988]*. Some of the techniques used to achieve low capacitance are small area junctions *[Tucker et al., 1986]*, air bridges, thick insulators, semi-insulating substrates, and detector-waveguide coupling *[Bowers et al., 1986; Bornhold et al., 1987]*. Tunable superlattice p-i-n photodetectors in waveguide configurations for dual-wavelength demultiplexing at a data rate of 1 Gbit/s have been fabricated and analyzed *[Larsson et al., 1988]*.

Planar p-i-n photodiodes have also been realized with InGaAs/InP crystals grown on semi-insulating InP substrates. By reducing the capacitance, a maximum cut-off frequency of 14 GHz has been achieved *[Miura et al., 1987]*. High-speed InGaAs and GaAs photodetectors have been fabricated, and response times of 2 ps were measured *[Loepfe et al., 1988]*. An array of balanced mixer circuits for coherent detection, consisting of an InGaAsP waveguide 3-dB directional coupler integrated with InGaAs p-i-n photodiodes, has been demonstrated *[Chandrasekhar et al., 1988]*.

The internal gain of APDs provides higher sensitivity than p-i-in photodiodes but APDs cost more and require more complex bias circuitry. Since the sensitivity margin increases with bit rate, a major thrust in APD research has been to increase the bandwidth and the gain-bandwidth product. High-speed APDs have been fabricated using InGaAs/InGaAsP epitaxial wafers, and a Be-implanted guardring has been found to achieve a reproducible and uniform avalanche gain. Thus a gain-bandwidth product of 75 GHz has been obtained *[Torikai et al., 1988]*. By optimizing the structure of APDs with separate multiplication and absorption regions, maximum bandwidths of 8 GHz have been reported with a gain-bandwidth product of 70 GHz *[Campbell et al., 1989]*. Morevoer, a a-Si/SiC:H superlattice APD with a high optical gain has been demonstrated by plasma-enhanced CVD *[Jwo et al., 1988]*.

Work on GaAs MSM photodiodes has been stimulated for optical transmission systems and integrated optical switching *[Prank et al., 1989]*. In order to extend this approach to longer wavelengths, MSM structures have been investigated and wide bandwidth (> 11 GHz), low capacitance, and acceptable responsivity have been achieved *[Soole et al., 1989]*. High-efficiency photodiodes with indium tin oxide/GaAs structure have been fabricated with bandwidths over 110 GHz *[Parker et al., 1987]*. To test the possibility of deriving special properties such as strong electro-optic and nonlinear effects by molecular engineering technology, integrated planar photoconductive detectors have been studied using organic and polymeric materials *[Reuter and Franke, 1989]*.

2.3. Integrated Optics

According to the original concept of integrated optics, the advantages of optical information processing are combined with the advantages of integrating many devices into a single chip. Integrated optics has subsequently evolved into two relatively distinct technologies: one based on guided wave devices, and the other utilizing optoelectronic devices as interfaces between ICs and optical signals. These technologies are often referred to as photonic integrated circuits (PICs) and OEICs, respectively.

The optical modulator is one of the fundamental guided wave devices. Recently, as the materials technology of III—V compounds has matured, high-speed waveguide modulators have been fabricated in AlGaAs/GaAs *[Wang and Lin, 1988]* and InP/InGaAs *[Koren et al., 1987]*. A significant breakthrough for III—V compound modulators has been the development of multiple-quantum-well modulators based on the quantum confined Stark effect *[Wood, 1988]*. A variety of guided optical wave devices such as focusing and dispersive planar components *[Smit, 1988]*, grating and holographic integrated-optical elements *[Miler et al., 1989]*, and integrated nonlinear optical devices for frequency conversion *[Sohler, 1989]* have also been proposed and demonstrated. A study of electro-optic polymers has been presented for integrated optics applications *[Horsthuis and Krijnen, 1989]*.

Currently, guided-wave structures have become more complex, combining more than one type of device on a substrate. A $LiNbO_3$ guided-wave device has been fabricated for an optical coherent receiver *[Heidrich et al., 1989]*. There has also been a shift toward III—V compunds due to the possibility of integrating emitters and detectors with the waveguide devices. Monolithic integration of a GaInAs photoconductor with a GaAs/GaAlAs optical waveguide on a GaAs semi-insulating substrate has been reported *[Mallecot et al., 1988]*. A distributed feedback laser with a Y structure waveguide integrated with a front-face photodiode has also been reported *[Liou et al., 1989]*.

Optoelectronic circuits have also progressed rapidly in the past few years, both in number of circuit elements and performance relative to hybrid circuits. Monolithically integrated transmitter and receiver chips for the 1.5 μm wavelength region *[Winzer et al., 1989]*, fabrication technology for long-wavelength receiver OEICs *[Spear et al., 1989]*, and an optical amplifier module for single-mode fiber optic systems *[Luc et al., 1989]* have been reported. Optoelectronic logic devices using quantum-well structures have been studied, including a hard limiting logic device with an optical gain of over 10 *[Wheatley et al., 1987]*. For optical interconnection and information processing, a new class of low-power-consumption electro-photonic functional devices has been proposed and 1-kbit monolithic integration successfully achieved *[Kasahara et al., 1989]*.

2.4. Optical Fibers And Applications

Optical fiber techniques or fiber-optics are now widely applied in telecommunications, sensors, medicine, data transmission, and measurements in adverse environments. The progress in optical fibers for telecommunications is aimed at economical fiber production, and at dispersion shifted or dispersion flattened single-mode fibers employing complex index profiles and requiring a high-precision preform fabrication. Further research in trunk communications systems resulted in multi-Gbit/s data transmission, based particularly on coherent transmission and detection techniques.

As for basic properties of various optical fibers, a nondestructive measuring technique has been reported for polarization maintaining fibers based on stress induced birefringence *[Calvani et al., 1987]*. It has also been reported that a fiber can be utilized as a distributed compressor for a weak pulse due to the cross-phase modulation from an intense pump pulse which chirps a weak pulse propagating simultaneously in a fiber *[Jaskorzynksa and Schadt, 1988]*. Sub-threshold flaws in optical fibers, which figure more quickly than cracks, have been shown to be the critical flaws determining the failure lifetime of proof-tested optical fibers in long-haul communications cables *[Donaghy and Dabbs, 1988]*. A statistical method of treating these flaws in real applications is indicated to be more realistic than current analytic methods based on an alternative theory of crack growth.

The exploration of various nonlinear effects in optical fibers continues to be a fruitful area of research and development *[Dianov et al., 1988]*. These include semiconductor crystallite-doped fibers with picosecond response times, soliton compression in Raman ring fiber lasers, and linewidth narrowing in a diode-laser pumped, all-fiber Brillouin ring laser *[Bayvel et al., 1989]*. Progress in optical fiber sensor technology and applications has also been reported in a variety of fields, and this technology is now recognized practically. As a good example, an all-optical remote sensing system for low-level CH_4 and other gases has been developed using 20-km-long optical fiber links and near infrared LED/laser diodes *[Chan et al., 1987]*.

For optical communications, two tpyes of transmission systems have been implemented: incoherent and coherent transmission. The primary research and development thrust for incoherent transmission systems, which utilize direct detection, has been for higher bit rates. Coherent transmission systems are still relatively immature and a significant effort has been expended to investigate various modulation formats and optimize the system components.

In direct detection systems, transmission quality and performance of injection locked laser (ILL) repeaters employed in optical frequency shift keying (FSK) communications have been reported *[O'Byrne and O'Reilly, 1988]*. Transmission bit rate-span length has been increased to 10 Gbit/s-100 km by using a multi-quantum-well (MOQ) DFB laser diode and a high-speed APD, together with dispersion shifted optical fibers *[Fujita et al., 1989]*. Optical FSK transmission with pattern-independent receiver sensitivity and arbitrary polarization control has also been demonstrated *[Noe' et al., 1989]*. Furthermore, with the use of Er-doped optical amplifiers as preamplifiers and post amplifiers, the span length has increased over 210 km at 1.8 Gbit/s in a direct detection system *[Takada et al., 1989]*. The Er-doped fiber amplifiers have also been used as repeater amplifiers in a 904-km transmission link at 1.2 Gbit/s *[Edagawa et al., 1989]*. A transimpedance/p-i-n receiver with high-transconductance HEMT FETs has been operated at bit rates as high as 16 Gbit/s for 64-km fiber transmission *[Gnauck et al., 1989]*.

Coherent detection systems offer increased sensitivity compared to direct detection and the prospect for very-high-density frequency multiplexing. Coherent optical multicarrier systems have been discussed *[Bachus et al., 1989]*, and a scheme for phase and polarization diversity reception in coherent fiber communication systems has been implemented by 3-way or 4-way directional couplers *[Siuzdak and Van Etten, 1989]*. A coherent star network providing six SFK channels at 200 Mbit/s, spaced 2.2 GHz apart, with a receiver sensitivity of 74 photons/bit at a bit-error ratio of 10^{-9}, has been demonstrated recently *[Glance et al., 1989]*.

3. PHYSICS AND MATERIALS

The growing interest in high-performance devices resulted in material research all around the world. New structures and technologies are now emerging and because of shrinking dimensions, new problems have to be solved.

3.1. Physics

Rapid progress in microelectronics and optoelectronics requires a sound physical background and increasing knowledge of ultimate properties of solids to provide for new communications needs. There are still three important research areas for physicists: optics, heterostructures and superlattices, and ultrafast phenomena.

Significant development has occurred in quantum optics during this period. It is now possible to explore nonclassical properties of radiation. *Reynaud et al. [1987]* describe how a two-mode optical parametric oscillator can generate nonclassical states of light with a large average number of photons, while *Yamamoto and Haus [1986]* propose a new scheme for generating an amplitude-squeezed state. With computer simulation, *Mollenauer et al. [1986]* have studied soliton propagation in an all-optical, long distance communications system where fiber loss is periodically compensated by Raman gain. They demonstrate that, in the gain-compensated system, multiplexing can yield rate-length products greater than 300,000 GHz.km!

The success of photonic switching depends on the development of materials and devices able to process light signals without converting them into electric form. Therefore, nonlinear optics, bistability, and the photorefractive effect have seen intense activity in research laboratories. A recent review of photonic materials has been published by Gunter and Huignard [1986]. Optical nonlinearities in semiconductors have many potential advantages for applications in optical logic due to wavelength compatibility with optical communications systems. The photorefractive effect in semi-insulating seminconductors has been studied by *Gravey et al. [1989]* who demonstrated great interest in InP:Fe for two-beam coupling at wavelengths in the near infrared region. Work on the sillenite family, such as BGO and BSO, is always of great interest. Degenerate four-wave mixing strongly depends on the polarization characteristics of the interacting waves. *Erdmann et al. [1988]* present theoretical calculations and experimental measurements which characterize this dependency.

A better understanding of the behaviour of light also requires the development of a large variety of measurements and modeling. *Francois et al. [1989]* have presented a universal measurement procedure of chromatic dispersion, birefringence, and nonlinear susceptibilities in optical fibers. Three possible uses of the interferograms have been illustrated, depending on the spectral width of the source illuminating an interferometer. *Van de Velde et al. [1988]* have extended the effective index method to calculate the physical characteristics of arbitrarily shaped inhomogeneous optical waveguides.

In solid-state physics, heterojunctions are always the topic of one of the fundamental research areas stimulated by the wide applications in micorelectronics and optoelectronics. A general description of electronic states in semiconductor heterostructures has been given by *Bastard and Brum [1986]*. Numerous theoratical and experimental studies have been made on multi-quantum wells and superlattices due to the progress of epitaxial technology. The physics of tunneling in quantum well heterostructures and its device applications have been discussed by *Capasso et al. [1986]*. Interesting device applications ranging from novel transistors to lasers and detectors are made possible with these new structures. Localization and oscillatory electro-optical properties of semiconductor superlattices have also been intensively studied. *Mendez et al. [1988]* have shown that a strong electric field in a superlattice produces a "blue" shift of its interband optical transitions, whereas at moderate fields, additional transitions reflect the presence of a Stark ladder.

A new area in physics derives from the possibility of generating short optical pulses. It is now possible to improve the temporal resolution of kinetics meausurements. The world record for producing short optical pulses seems to be 6 fs as described by *Fork et al. [1986]*. It is obtained by compressing 30-fs pulses from a colliding pulse mode-locking (CPM) laser. Double barrier resonant tunneling diodes have been studied by using these short pulses. The most remarkable result has been obtained by *Whitaker et al. [1988]*. In this experiment, a double barrier tunnel junction was biased with a CW voltage just at the limit of the negative differential region. A short pulse was sent to the device and switching was observed to occur within less than 3 ps. *Becker et al. [1988]* have used ultrashort pulses to determine time variations of interaction with injected carrier density in GaAs.

Very interesting information can be obtained on vertical transport in superlattices by analyzing the shape of the luminescence spectrum as a function of time delay. *Deveaud et al.* [1987] have used this technique to study the transport in superlattices of different graded compositions. Finally, the potential use of the soft-mode ferroelectric effect in electrooptical devices has been described by *Andersson et al.* [1988]. Notable features and possibilities are fast electrooptic switching, linear modulation of transmitted light, spatial modulation, and generation of continuous gray-scale by an applied voltage.

3.2. Materials

There is always extensive research activity in materials for electronics and photonics. Although most of the publications concern III-V semiconductors and related compounds, today we see literature on new classes of materials such as organic molecules or polymers, glasses, and dielectrics with some interesting properties for exploratory devices.

Vogel [1989] presents a detailed review on glasses as nonlinear photonic materials. Confinement of light in the small core area, and diffractionless propagation over long distances in optical fibers increase the efficiency of the nonlinear interaction and allow the use of relatively weak nonlinearities. *Monerie et al.* [1989] show the wide possibilities arising from the use of rare earth doped fluorozirconate fibers for lasers or optical amplification. The possibility of designing new optical materials at the molecular level has created substantial interest in recent years. *Badan et al.* [1986] have developed a new molecular organic crystal for highly efficient quadratic nonlinear optics.

Exceptional progress in epitaxial growth techniques, such as MBE and MOCVD, has stimulated wide investigations of the epitaxy, homoepitaxy or heteroepitaxy of III—V and II—VI compounds. *Nakwaski* [1988] has presented a phenomenological approach to calculate the lattice thermal conductivity of binary, ternary, and quaternary systems. *Marzin et al.* [1986] have compared properties of III—V superlattices on GaAs or InP substrates, *Novvak et al.* [1989] describe technological conditions for the preparation of epitaxial layers for high-speed photodetectors. New materials and graded interfaces have also been actively studied. *Guivarc'h et al.* [1989] show that metallic compounds such as ErP and ErSb can be epitaxially grown on InP and GaAs. These rare earth monoarsenides with an NaCl crystal structure may be an interesting class of compounds giving both thermodynamically stable and epitaxial contact metallization on III—V semiconductor substrates. Epitaxial group IIa fluoride layers (CaF_2, SrF_2, BaF_2, and mixtures thereof) have now been grown on common semiconductor materials with uniform composition. However, by grading the composition across the thickness of the layer, further general applications become possible. Using BaF_2—CaF_2 graded buffer layers, *Zogg et al.* [1987] have demonstrated the possibility of growing CdTe on Si.

Finally, amorphous siliconcarbon hydrogen alloy has been prepared by *Chang et al.* [1987] and used in amorphous Si/SiC heterojunctions. The structure of this device is glass/ITO/a-Si (n^+-i) /a-SiC(p^+-i-n^+)/Al. Very high optical gain is obtained under weak light illumination and hence the device is suitable as a sensitive light detector.

4. DEVICE MODELING AND CAD

Semiconductor device models are required by engineers primarily to give accurate predictions of performance for new devices, operation under unusual conditions, and/or realization of new functions. Moreover, device modeling is systematically used for the design and optimization of discrete devices, to determine the influence of technological parameters on device characteristics, and to predict expected performance. Finally, device modelling is very useful for device physicists to increase the understanding of device behaviour and to study the influence of various physical effects.

During the past few years, research activities in device modelling and CAD have undergone extensive development for several reasons. First, a great number of new device structures have been proposed and realized, primarily based on III—V materials and heterostructures. As a consequence, it becomes more and more difficult to determine the optimum values of technological parameters and to define the best one for a specific application. On the other hand, the dramatic increase in computer power and speed allows the systematic use of device and circuits models in the semiconductor industry.

Semicondustor device models can be classified as physical device models and equivalent circuit models. Physical device models are based on the device physics and usually describe the carrier transport process. Alternatively, equivalent circuit models can be used to describe the electrical and optical properties of the device; they are derived from theoretical considerations of the device operation or from an empirical approach. They have been the foundation of electronic circuit design, and the majority of existing CAD software uses the equivalent circuit model as the basis of the design work.

Significant progress has been achieved for each model, mainly in terms of accuracy, but the most important aspect of their evolution is their improving capability to accommodate numerous new devices, and to account for new physical effects that occur mainly in submicronic structures or in very high frequency ranges, for instance. Of course, this improvement is offset by an increase in software complexity.

We will now describe for each kind of optoelectronic device the significant aspects of this evolution during the past few years.

4.1. Photodetectors

The use of photodetectors resulted in optoelectronic components in the high-frequency range: hence, new applications such as microwave optical links have appeared thanks to the dynamic characteristics of these optoelectronic components. For microwave applications, high-intensity optical signals can be used, and nonlinear effects can occur under intense illumination. New numerical modelling has been proposed for such a purpose. The pioneer theoretical work of *Dentan and de Cre'moux* [1989] shows that nonlinear effects are minor phenomena for a III—V PIN photodiode under intense illumination.

For high-speed applications, another component which is being intensively studied is the III—V MSM photodetector. Its main feature is its technological compatibility with the MESFET reducing the technological difficulties of monolithically integrating the photodetector with an amplifier. Therefore, thoretical analysis of III—V MSM photodetectors is now being proposed for deducing the speed from the design of a photodetector *[Koscielniak et al., 1989]*.

For the more classical optical communications system applications (digital signals), III—V APDs are promising devices. Two types of research can be distinguished: use of a superlattice to improve performance and planarization of the device.

For the former, the theoretical work of *Brennan et al.* [1988] is well-known. For device planarization, it is important to predict the electrical field behavior under the guard-ring, for example to overcome breakdown occurring from the tunneling effect caused by an anomalous electric field increase under the guard-ring. The corresponding theoretical studies have been developed simultaneously with technological and experimental ones, such as the typical work of *Chi et al.* [1987]. Finally, for coherent applications, monolithic integration of the photodetector with an optical waveguide is required. Two types of techniques based on III—V materials have benn proposed: the butt coupling and the evancest field coupling. However, it is still necessary to predict the coupling efficiency between the photodetector and the optical waveguide, i.e., the fraction of light absorbed by the photodetector. From a theoretical point of view, the works of *Erman et al.* [1988] and *Vinchant et al.* [1989] based on the beam propagation method should be noted.

4.2. Lasers

In the past three years, the growing importance of semiconductor lasers has stimulated intense modelling of these devices, However, most properties of semiconductor lasers are analyzed by specific models, depending on the basic phenomena that are included, because a general and complete model would be too complicated to be of practical interest *[Baets et al., 1988]*.

As metal organic vapor phase epitaxy and MBE have become more widespread, the attractive features of quantumwell lasers are being explained by more realistic calculations which include the effects of spectral broadening by the intraband scattering process and well width fluctuations, reduction in the bandgap due to many-body effects at high injection, and the presence of nonradiative barrier recombination processes *[Blood et al., 1989]*. The purpose of these models is to predict the laser wavelength, the gain current relations, the threshold current, and the differential quantum efficiency for specific laser structures at different temperatures and for several semiconductor materials *[Chinn et al., 1988]*.

As a result of research and development on optical communication systems, considerable attention continues to be directed toward InGaAsP/InP lasers. Two-demensional models solving both optical and electrical equations in a selfconsistent way have been recently proposed *[Ohtoshy et al., 1989]*, and may be a useful tool for designing buried heterostructures with improved current confinement and high frequency performance. Other models dealing with single-frequency laser structures incorporating grating have been developed. Refined numerical analysis, including the effect of longitudinal mode spatial hole burning, gives an estimate of the linewidth and the changes in the spectrum, and can therefore be applied to performance optimization of phase-shifted DFB lasers *[Witheaway et al., 1989]*.

AlGaAs/GaAs high-power lasers continue to be an important topic. Several models examine the ability of the arrays to operate in a single-lobed diffraction-limited beam that remains stable at high power levels. The purpose of the array designs has been to reduce the effect of spatial hole burning *[Buus, 1987]* and the need for comprehensive numerical models in oder to describe the complex behaviour of three-dimensional structures. Another interesting topic is the analysis and design of surface emitting lasers for high-power operation or parallel optical computing. A wide range of structures have been proposed, and many important new concepts will need more refined models for detailed analysis *[Iga et al., 1988; Corzine at al., 1989]*.

In conclusion, during the last three years, research activities in device modeling and CAD allowed the evolution of numerous accurate models and the improvement of more conventional ones. They will be used now for the design and optimization of the majority of devices and circuits presently known, and for improving our knowledge of device behavior. However, new devices in which quantum effects are of primary importance appear every day: 2D, 1D, and OD electron gas, tunnel resonant structures. In these cases, not only computational but also conceptual problems will appear, to be solved in the next few years. It will constitute an exiting task, especially as the increasing capabilities and decreasing cost of computer simulations will make device modeling more and more attractive.

REFERENCES

"Review of Radio Science" (Editor E. Hyde) Ch.4. "Electronic and Optical Devices and Applications" (Ed. J. Hénaff) *URSI Publishing*, Brussels, 1990, D1-D23.

Amann, M. C. ,S. Illek, C. Schauen, W. Thielke and H. Lang, 1989, "Continuously tunable single-frequency laser diode utilizing transverse tuning scheme", *Electron. Lett.*, 25, 837.

Andersson, G. I. Dahl, W. Kuczinski, S. T. Lagerwall, K. Skarp and B. Stebler, 1988, "The soft-mode ferroelectric effect", *Ferroelectrics*, 84, 285.

Arakawa, Y. and Yariv, 1987, "Quantum well lasers-gain, spectra, dynamics", *IEEE J. Quantum Electron.*, QE-22.

Bachus, E. J., R. P. Braun, C. Caspar, H. M. Foisel, E. Grossmann, B. Strebel and F. J. Westphal, 1989, "Coherent optical multicarrier systems" *J. Lightwave Tech.*, LT-7, 375.

Badan, J., I. Ledoux and J. Zyss, 1986, "A new molecular organic crystal for highly efficient quadratic nonlinear optics, NPP", *Proc. European Materials Res. Soc.*, E-MRS'86, 421.

Baets, R., J. P. Van de Capelle and P. Vankwilkelberge, 1988, "The modelling of semiconductor laser diodes", *Ann. Telecomm.*, 43, 1459.

Baryshev, V. I., E. LG. Golikova and V. P. Duraev, 1988, "Distributed feedback CW injection heterostructure InGaAsp lasers (λ=1.55 μm)", *Sov. Phys.: Quantum Electron.*, 15, 2196 (in Russian).

Bastard, G. and J. A. Brum, 1986, "Electronic states in semiconductors heterostructures" *IEEE J. Quantum Electron*, QE-22, 725.

Bayvel, P., and I. P. Giles, 1989, "Linewidth narrowing in semiconductor laser pumped all-fibre Brillouin ring laser", *Electron Lett.*, 25, 260.

Becker, P. B., H. L. Fragnito, C. H. Britocruz, J. Shah, R. L. Fork, J. E. Cunningham, J. E. Henry and C. V. Shank, 1988, "Femtosecond intervalley scattering in GaAs" *Appl, Phys., Lett.*, 53, 2089.

Blood, P., E. D. Fletcher, K. Woodbrige, K. C. Heasman and A. R. Adams, 1989, "Influence of the barriers on the temperature dependence of threshold current in GaAs/AlGaAs quantum well lasers", *IEEE J. Quantum Electron.*, QE-25, 1459.

Bornholdt, C., W. Döldissen, F. Fiedler, R. Kaiser and W. Kowalsky, 1987, "Waveguide-integrated pin photodiode on InP", *Electron. Lett.*, 23 2.

Bowers, J. E., C. A. Burrus and F. Mitschke, 1986, "Millimeter-waveguide-mounted InGaAs photodetectors", *Electron. Lett.*, 22, 663.

Bowers, J. E., and M. A. Pollack, 1988, "Semiconductor lasers for telecommunications", *Optical Fiber Telecomm.* II. Academic Press.

Brennan, K. F., Y. Wang, M. C. Teich, B. E. A. Saleh and T. Khorsandi, 1988, "Theory of the temporal response of a simple multiquantum well avalanche photo diode", *IEEE Trans, Electron. Devices*, ED-35, 1456.

Buus, J., 1987, "Semiconductor laser arrays with enhanced mode stability," *IEEE J. Quantum Electron.*, QE-23, 757.

Calvani, R., R. Caponi and C. Coppa, 1987, "Fiber birefringence measurements with external stress method and heterodyne polarization detection", *J. Lighwave Tech.*, LT-5, 1176.

Campbell, J. C., B. C. Johnson, G. J. Qua and W. T. Tsang, 1989, "Frequency response of InP/InGaAsP/InGaAs avalanche photodiodes", *J. Lightwave Tech.*, LT-7, 778.

Capasso, F., K. Mohamed and A. Y. Cho, 1986, "Resonant tunneling through double barriers, perpendicular quantum transport phenomena in superlattices, and their device applications", *IEEE J. Quantum Electron.*, QE-22, 1853.

Chan, K. P., H. Ito and H. Inaba, 1987, "All optical-fiber-based remote sensing system for near infrared absorption of low level CH_4 gas", *J. Lighwave Tech.*, LT-5, 1706.

Chandrasekhar, S., J. C. Campbell, F. G Storz, A. G. Dentai, C. H. Joyner and G. J. Qua, 1988, "Balanced dual photodiodes integrated with 3 dB directional coupler for coherent lightwave receivers", *Electron. Lett.*, 24, 1457.

Chang, K. C., C. Y. Chang, Y. K. Fang and S. C. ow, 1987, "The amorphous Si/SiC heterojunction color-sensitive phototransistor" IEEE Electron. Dev. Lett., EDL-8, 64.

Chi, G. C., D. J. Muehlner, F. W. Ostermayer Jr, J. M. Freund, R. Pawelik, R. J. McCoy, L. J. Peticolors and V. D. Mattera Jr., 1987, "Planar avalanche photodiode with a low-doped reduced curvative junction", *Appl. Phys. Lett.*, 50, 1158.

Chinn, S. R., P. S. Zory and A. R. Reisinger, 1988, "A model for GRIN-SCH-SQW diode lasers", *IEEE J. Quantum Electron.*, QE-24, 2191.

Corzine, S. W., R. S. Geels, J. W. Scott, R. H. Yan and L. Coldren 1989, "Design of Fabry-Perot surface-emitting laseres with a periodic gain structure", *IEEE J. Quantum Electron.*, QE-25, 1513.

Dentan, M., and B. de Cremoux, 1989, "Numerical simulation of the non linear response in a PIN InGaAs wave guide type photodiode under intense illumination" Proc, *Sixth European Conf. on Integrated Optics (ECIO 89).*

Deveaud, B., T. C. Damen, J. Shah, B. Lambert and A. Regreny, 1987, "Block transport of electrons and holes in superlattice minibands: direct measurement by subpicosecond luminescence spectroscopy", *Phys. Rev. Lett., 58, 2582.*

Dianov, E. M., P. V. Mamyshev and A. M. Prokhorov, 1988, "Nonlinear fiber optics", *Sov. Phys.: Quantum Electron.*, 15,5 (in Russian).

Donaghy, F., and T. Dabbs, 1988, "Subthreshold flaws and their failure prediction in long distance optical fibre cables", *J. Lightwave Tech.*, LT-6, 226.

Edagawa, N., Y. Yoshida, H. Taga, S. Yamamoto, K. Mochizuki and H. Wakabayashi, 1989, "904 km, 1.2 Gbit/s non-regenerative optical transmission experiment using 12 Er-doped fiber amplifiers", *Proc. ECOC'89*, 3, 33.

Erdmann, A., R. Kowarschik and L. Wenke, 1988, "Polarization effects of degenerate four-wave mixing in photorefractive Bi_{12} GeO_{20} crystals", *J. Mod. Opt.*, 35, 1727.

Erman, M., P. Jarry, R. Gamonal, J. L. Gentner, P. Stephan and C. Guedon, 1988, "Monolithic integration of a GaInAs PIN photodiode and an optical waveguide: Modeling and realization using chloride vapor phase epitaxy", *J. Lightwave Tech.*, LT-6, 399.

Fork, R. L., C. H. Brito Cruz, P. C. Becker and C. V. Shank, 1986, "Compression of optical pulses to six femtosecond by using cubic phase compression", *Opt. Lett.*, 12, 483.

Forrest, S. R., V. S. Ban, G. Gasparian, D. Gay and G. H. Olsen, 1988, "Reliability of vapor-grown planar $In_{0.53}Ga_{0.47}As$/InP p-i-n photodiodes with very high failure activation energy", *IEEE Electron Dev. Lett.*, EDL-9, 217.

Francois, P. L., M. Monerie, C. Vassallo, Y. Durteste and F. R. Alard, 1989, "Three ways to implement interferential techniques: application to measurements of chromatic dispersion, birefrigence and nonlinear susceptibilities", *J. Lighwave Tech.*, Lt-7, 500.

Fujita, S., M. Kitamura, T. Torikai, N. Henmi, H. Yamada, T. Suzaki, I. Takano and M. Shikada, 1989, "10 Gbit/s 100 km optical fiber transmission experiment using high speed MQW DFB LD and back illuminated GaInAs APD", *Electron. Lett.*, 25, 702.

Glance, B., T. L. Koch, O. Scaramucci, K. C. Reichmann, L. D. Tzeng, U. Koren and C. A. Burrus, 1989, "Densely spaced FDM optical coherent system with near quantum-limited sensitivity and computer-controlled random acess channel selection". *Proc. Opt. Fiber Comm. Conf.* 81.

Gnauck, A. H., R. Jopson, J. D. Evankow, C. A. Burrus, S. J. Wang, N. K. Dutta and H. M. Presby, 1989, "16-Gbit/s 64-km optical fiber transmission experiment using an optical preamplifier receiver", Proc. ECOC'89, 3, 25.

Gravey, P., G. Picoli and J. Y. Labandibar, 1989, "Stabilization of photorefractive two-beam coupling in InP: Fe under high dc fields by temperature control", *Opt. Comm.*, 70, 190.

Guivarc'h, A., J. Caulet and A. Le Corre, 1989, "Epitaxial growth of metallic ErP, ErSb and lattice-matched ErPxSb(1-x) layers on (001)InP and (001) GaAs", *Electron. Lett.*, 25, 1050.

Gunter, P., and J. P. Huignard (ed.), 1986, "Photorefractive materials and their applications: Fundamental phenomena", *Topics in Applied Physics*, Springer-Verlag.

Heidrich, H., D. Hoffmann, C. H. V. Hemolt and H. Ahlers, 1989, "Lithium niobate guided-wave network for a coherent receiver", *Lett.*, 14, 99.

Horsthuis, W. H. G., and G. J. M. Krijnen, 1989, "Simple measuring method for electro-optic coefficients in poled polymer waveguides", *Appl. Phys. Lett.*, 55, 616.

Iga, K., F. Koyama and S. Kinoshita, 1988, "Surface emitting semiconductor lasers", *IEEE J. Quantum Electron.*, QE-24, 1845.

Jaskorzynska, B., and D. Schadt, 1988, "All-fiber distributed compression of weak pulses in the regime of negative group velocity dispersion", *IEEE J. Quantum Electron.*, QE-24, 2117.

Joindot, I. M., and C. Y. Boisrobert, 1987, "Analysis of crosscorrelation coefficients between mode fluctuations in semiconductor lasers", *IEEE J. Quantum Electron.*, QE-23 1059.

Jwo, S. C., M. T. Wu, Y. K. Fang, Y. W. Chen, J. W. Hong and C. Y. Chang, 1988, "Amorphous silicon/silicon carbide superlattice avalanche photodiodes, *IEEE Trans. Electron Devices*, ED-35, 1279.

Kakimoto, S., Y. Nakajima, A. Takemoto, N. Yosida and W. Susaki, 1989, "High output power and high temperature operation of 1.5 μm DFG-PPIBH laser diodes", *IEEE J. Quantum Electron.*, QE-25, 1288.

Kasahara, K., Y. Tashiro, I. Ogura, M. Sugimoto, S. Kawai and K. Kubota, 1989, "Vertical to surface transmission electrophotonic device for the application of optical interconnection and processing", *Ext. Abstracts, 21 st Conf. Solid State Devices and Materials*, 433.

Kobayashi, K., and I. Mito, 1988, "Single frequency and tunable laser diodes", *J. Lightwave Tech.* LT-6, 1623.

Koch, T. L., U. Koren and B. I. Miller, 1988, "High performance tunable 1,5 μm InGaAsP multiple-quantum-well distributed-Bragg-reflector lasers", *Appl. Phys. Lett.,* 53,1036.

Koren, U., B. I. Miller, T. L. Koch, G. Eisenstein, R. S. Trucker, I. Bar-Joseph and D. S. Chemla, 1987, "Low-loss InGaAs/InP multiple quantum well optical electroabsorption waveguide modulator", *Appl Phys. Lett.,* 51, 1132.

Koscielniak, W. C., J. L. Pelouard and M. A. Littlejohn, 1989, "Dynamic behavior of photocarriers in a GaAs metalsemiconductor-metal photodetector with sub half micron electrode spacing, *Appl. Phys. Lett.,* 54, 567.

Larsson, A., P. Andrekson, S. Eng and A. Yariv 1988, "Tunable superlattice p-i-n photodetectors: Characteristics, theory and applications", *IEEE J. Quantum Electron.,* QE-24, 787.

Liou, K. Y., U. Koren, S. Chandrasekhar, T. L. Koch, A. Shahar, C. A. Burrus and R. P. Gnall, 1989, "Monolithic integrated InGaAsP/InP distributed feedback laser ith Y-blanching waveguide and a monitoring photodetector grown by metalorganic chemical vapor deposition", *Apl. Phys. Lett.,* 54, 114.

Loepfe, R., A. Schaelin, H. Melchior, M. Blaser, H. Jaeckel and G. L. Bona, 1988, "2 ps InGaAs photoconductors and their speed-of-response evaluation by optical pulse mixing at inherent nonlinearities", *Appl. Phys. Lett.,* 52, 2130.

Luc, V. V., V. P. Duraev, P. G. Eliseev, M. A. Manko, N. Th. Phuong and N. T. Th. Nhet, 1989, "Optical amplifier module and its optoelectronic properties", *Tech. Dig. IOOC'89,* 2OB1-24, 86.

Mallecot, F., J. F. Vichant, M. Razeghi, D. Vandermoere and J. P. Vilcot, 1988, "Monolithic integration of a short length GaInAs photoconductor with a GaAs/GaAlAs optical waveguide on a GaAs semi-insulating substrate", *Appl. Phys Lett.,* 53, 2522.

Van de Velde, K., H. Thienpont and R. Van Geen, 1989, "Extending the effective index method for arbitrarily shaped inhomogeneous optical waveguides", *J. Lightwave Tech.,* LT-6, 1153.

Marzin, J. Y., L. Goldstein, F. Glas and M. Quillec, 1986, "Optical study of MBE grown (InAs)m(GaAs)n superlattice alloy on GaAs and of InxGa(1-x)As/InyGa(1-y)As structures on InP", *Surface Science,* 174, 586.

Mendez, E. E., F. Agullo-Rueda and J. M. Hong, 1988, "Stark localization in GaAs-GaAlAs superlattices under an electric field", *Phys. Rev. Lett.,* 60, 2426.

Miler, M., V. N. Morozov and A. N. Putilin, 1989, "Diffractional integrated-optical elements", *Sov. Phys.: Quantum Electron.,* 16, 415 (in Russian).

Miura, S., H. Kawatsuka, T. Mikawa and O. Wada, 1987, "Planar embedded InP/GaInAs p-i-n photodiode for very high speed operation", *J. Lightwave Tech.,* LT-5, 1371.

Mollenauer, L. F., J. P. Gordon, and M. N. Islam 1986, "Soliton propagation in long fibers with periodically compensated loss", *IEEE J. Quantum Electron.* QE-22, 157.

Monerie, M., J. Y. Allain, H. Poignant and F. Auzel, 1989, Fluorescence, upconversion and lasing in erbium-doped quasisinglemode fluorizirconate fibers, *Proc, ECOC'89,* TuB 12—6.

Nakwaskik, W., 1988, "Thermal concuctivity of binary, ternary and quaternary III—V compounds", *J. Appl. Phys.,* 64, 159.

Nishimoto, H., M. Yamaguchy, I. Mito and K. Kobayashy, 1987, "High-frequency response for DFB-LD due to a wavelength detuning effect", *J. Lightwave Tech.,* LT-5, 1399.

Noé, R., Rodler, A. Ebberg, G. Gaukel and F. Auracher, 1989, "Optical FSK transmission with pattern-independet 119 photoelectrons/bit receiver sensitivity and endless polarization control", *Electron. Lett.,* 25, 757.

Novvak, J., M. Kuliffayova, M. Morvic and P. Kordos, 1989, "Growth and properties of low-doped InO.53GaO. 47As LPE layers using rare earth oxides", *J. Crystal Growth,* 96, 645.

O'Byrne, V., and J. J. O'Reilly, 1988, "Transmission quality and performance of ILL repeaters used in optical FSK communications", *J. Lightwave Tech.,* LT-6, 695.

O'Mahony, M. J., 1988, "Semiconductor laser amplifiers for use in future fibre systems" *J. Lightwave Tech.,* LT-6, 531.

Ohtoshi, T., K. Yamaguchi and N. Chinore, 1989, "Analysis of current leakage in InGaAsP/InP buried heterostructure lasers", *IEEE J. Quantum Electron.,* QE-25, 1369.

Okuda, H., M. Ishikawa, H. Shiozawa, Y. Watanabe, K. Itaya, K. Nitta, G. Hatakoshi, Y. Kokubun and Y. Uematsu, 1989, "Highly reliable InGaP/InGAlP visible light emitting inner stripe lasers with 667 nm lasing wavelength", *IEEE J. Quantum Electron.,* QE-25, 1477.

Parker, D. G., P. G. Say, A. M. Hansom and W. Sibbett, 1987, "110 GHz high-efficiency photodiodes fabricated from indium tin oxide/GaAs", *Electron. Lett.,* 23, 527.

Prank, U., W. Kowalsky, T. Hackbarth and K. J. Ebeling, 1989, "Al-GaAs Schottky reflection modulator and detector for Gbit/s optical transmission systems", *Electron. Lett.,* 25, 847.

Reinhoudt, C. J., and C. J. Van der Poel, 1989, "Array modes of longitudinally varying laser array geometries", *IEEE J. Quantum Electron.,* QE-25, 1553.

Reuter, R., and H. Franke 1989, "An integrates organic photoconductive detector for optoelectronics", *J. Appl. Phys.,* B48, 219.

Reynaud, S., C. Fabre, and E. Giacobino, 1987, "Quantum fluctuations in a two-mode parametric oscillator", *J. Opt. Soc. Am. B,* 4, 1520.

Sasaki, Y., J. Ohya and M. Ogura, 1989, "Spectral linewidth and resonant frequency characteristics of InGaAsP/InP multi-quantumwell lasers", *IEEE J. Quantum Electron.* QE-25, 662.

Siuzdak, J., and W. Van Eten, 1989, "BER evaluation for phase and polarization diversity optical homodyne receivers using noncoherent ASK and DPSK demodulation". *J. Lightwave Tech.,* LT-=, 584.

Smit, M. K., 1988, "New focusing and dispersive planar component based on an optical phased array", *Electron. Lett.,* 24, 385.

Sohler, W., 1989, "Recent development of integrated optical devices for nonlinear frequency conversion", *Proc. ECOC' 98,* 2, 85.

Soole, J. B. D., H. Schumacher, H. P. Leblanc, R. Bhat and M. A. Koza, 1989, "High-speed performance of MOCVD grown InAlAs/In-GaAs MSM photodetectors at 1.5 μm and 1.3 μm wavelengths", *IEEE Photonics Lett.,* 1, 250.

Spano, P., A. d'Ottavi, A. Mecozzi and B. Daino, 1988, "Experimental measurements and theory of first passage time in pulse-modulated semiconductor lasers", *App. Phys. Lett.* 52, 2203.

Spear, D. A. H., P. J. G. Dawe, G. R. Antell, W. S. lee and S. W. Bland 1989, "New fabrication technology for longwavelengt receiver OEICs", *Electron. Lett.,* 25, 156.

Rakada, A., K. Hagimoto, K. Iwatsuki, K. Aida, K. Nakagawa and M. Shimizu, 1989, "1.8 Gbit/s transmission over 210 km using an erbium-doped fiber laser amplifier with 20 dB repeater gain in a direct detection system", *Tech. Dig. 100C'89,* 21B3-3, 30.

Torikai, T., K. Makita, S. Fujita, H. Iwasaki and K. Kobayashi, 1988, "Small area planar InGaAs avalanche photodiode with 75 GHz wide bandwidth", *Opt. Fiber Commun. Conf., Tech. Dig.,* TCU5.

Tucker, R. S., A. J. Taylor. C. A. Burrus, G. Eisenstein and J. M. Wiesenfeld, 1986, "Coaxially mounted 67 GHz bandwidth InGaAs PIN photodiode", *Electron. Lett.,* 22, 917 1986.

Marclay, E., D. J. Arent, C. Harder, H. P. Meier, W. Walter and D. J. Webb, 1989, "Scaling of GaAs/AlGaAs laser diodes for submilliampere threshold current", *Electron.Lett.,* 25, 892.

Vinchant, J. F., F. Mallecot, D. Decoster and J. P. Vilcot, 1989, "Photodetectors monolithically integrated with optical waveguides: Theoretical and experimental study of absorbing layer effects", *Porc, IEEE,* J136, 72.

Vogel, E. M., 1989, "Glasses as nonlinear photonic materials", *J. Am. Soc.,* 72, 719.

Wang, S. Y., and S. H. Lin, 1988, "High-speed III—V electro-optic waveguide modulators at 1.3 μm", *J. Lightwave Tech.,* LT-6, 758.

Wheatley, P., P. J. Bradley, M. Whitehead, G. Parry, J. E. Midwinter, P. Mistry, M. A. Pate and J. S. Roberts 1987, "Novel nonresonant optoelectronic logic device", *Electron. Lett., 23, 92.*

Whitaker, J. F., G. A. Mourou, T. C. L. G. Sollner and W. D. Goodhue, 1988, "Picosecond switching time measurement of a resonant tunneling diode", *Appl. Phys. Lett.,* 53, 385.

Winzer, G., C. Cremer, H. Hedrich, G. Heise, S. Illek, R. März, H. F. Mahlein, R. Matz, M. Schienie, G. Schulte-Roth, W. Thulke, H. Unzeitig, U. Wolff, W. Döldissen, F. Fiedler, R. Kaiser, L. Mörl, H. P.Nolting, W. Rehbein and G. Unterbörsch, 1989, "Monolithically integrated transmitter and receiver chips for a two-channel undirectional WMD-link at 1=1.5 μm", *Tech. Dig. 100C'89,* 19B3-14, 2, 72.

Witheaway, J. E. A., G. H. B. Thompson, A. J. Collar and C. J. Armistead, 1989, "The design and assessment of 1/4 phase shifted DFB laser structures", *IEEE J. Quantum Electron.,* QE-25, 1261.

Wood, T. H., 1988, "Multiple quantum well (MQW) waveguide modulators", *J. Lightwave Tech.,* LT-6, 743.

Yamada, H., H. Watanabe, H. Ito and H. Inaba, 1988, "Surface emitting GaAs light-emitting diode/laser diode with modified coaxial transverse junction (CTJ) structure", *Electron. Lett.,* 24, 77.

Yamamoto, Y., and H. A. Haus. 1986, "Preparation, measurement and information capacity of optical quantum states", *Rev. Mod. Phys.,* 58, 1001.

Zogg, H., P. Maier, and H. Mechior, 1987, "Graded IIa fluoride buffer layers for heteroepitaxy of lead-chalcogenides and CdTe on Si", *J. Crystal Growth,* 80, 408.

REAL TIME R. F. SPECTRUM ANALYZER USING A FIVE-CHANNEL ACOUSTO-OPTIC BRAGG CELL

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A phase sensitive acousto-optic Fourier processor with a five-channel Bragg cell is described. The advantage of a periodic transducer segment structure for radio frequency application is shown. The phase difference sensitivity of the system is improved by special output optics containing commercially available prisms and lens.

1. INTRODUCTION

The basic acousto-optic signal processing system is realized by a power spectrum analyzer with a Bragg cell producing light intensity spectrum vs. diffraction angle from the incident light beam as a function of input frequency. The angular intensity dirstribution is converted by a Fourier lens to spatial intensity distribution which can be measured by a detector array in the back focal plane of the Fourier lens. The system gives a one dimensional Fourier spectrum of the input electric signal with the advantages of good resolution and very high speed [1].

On the other hand, it can be easily extended to produce a two-dimensional Fourier transform applying a multichannel Bragg cell and a detector matrix [2]. This system is capable to determine simultaneously the frequency spectrum of the input signal and the phase difference between the input channels. Combining the system with an antenna array, the direction of electromagnetic waves incident on the antenna can be determined from the phase differences produced by the array characterizing the angle of arrival [2]. Experimental and theoretical analysis of this system was given in [2] and [3] for microwave applications.

The total phase difference produced by the antenna array is

$$\phi_M = \frac{2\pi d}{\lambda_e} \sin\alpha \qquad (1)$$

where

- d is the base distance of the array
- λ_e is the wavelength of the electromagnetic wave
- α is the angle of arrival for waves propagating in the horizontal plane
- ϕ_M is the phase difference.

The phase difference produced by an antenna array is inversely proportional to the wavelength of the electromagnetic wave and is proprotional to the basis distance of the antenna array. The length of the array is limited in practical applications, therefore it will be shown that the phase sensitivity of the optical system must be improved to achieve the desired 1 to 2° resolution in azimuth in the radio frequency range below 100 MHz.

In this paper, analysis of such a system is given for radio frequency application (30 to 60 MHz). The advantages of the periodic array structure will be shown, and a simple output optical system will be experimentally examined to improve the phase difference sensitivity of the system.

The achieved resolution with a five-element antenna array on 10 m base distance is 70 kHz in frequency, and 1 to 2 degrees in azimuth in the 30 to 60 MHz frequency band.

2. DESCRIPTION OF THE SYSTEM

The basic arrangement of the system is shown in Fig. 1. The ultrasound transducer of the multichannel Bragg cell is driven by the signals of the antenna array. The expanded laser beam is diffracted by the Bragg cell in such a way that in the z direction, the angle of diffraction depends on the input frequency, and in the x direction, the angle of the maximum intensity diffracted light beam is determined by the phase difference between the input signals. The angle distribution of the diffracted beam is transformed by the Fourier lens into an intensity distribution in the back focal plane of the lens. Here both the frequency and the direction of the incident wave can be determined from the position of the intensity maximum.

For the analysis of the system diffraction properties in the x direction where the position of the intensity maximum is a function of phase differences, we use the complex transmission function of the Bragg cell for Bragg diffraction [3]:

$$T(x,t) = \sum_{n=1}^{N} j \operatorname{rect}\left(\frac{x-(a_i-L/2)}{w}\right)\Psi_B \exp(-j\omega_a t+\Phi_i) \qquad (2)$$

where

- $T(x,t)$ is the complex transmission function for the maximum first order diffracted beam, neglecting the accoustic attenuation and the effect of transient signals,
- N is the number of segments,
- L is the aperture of the Bragg cell,
- w is the height of the segments, and the acoustic profile, is assumed to be uniform in the x dimension,
- ψ_B is the efficiency of the cell, usually $\ll 1$,
- ω_a is the angular frequency of the acoustic beam,
- ϕ_i is the phase of the input channels,
- a_i is the position of the segments on the x axis.

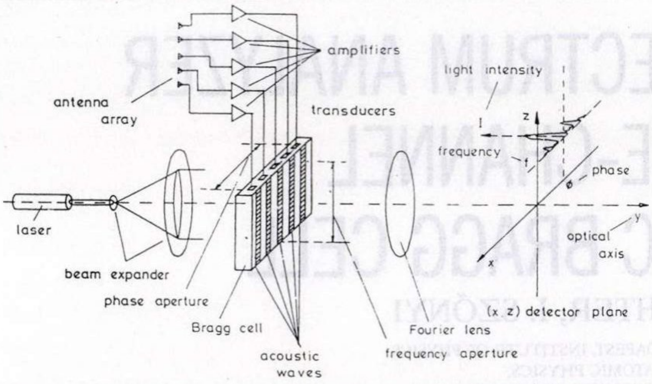

Fig. 1. The basic arrangement of a multichannel two dimensional acousto-optic Fourier transforming system

The electrical field in the back focal plane of the Fourier lens is

$$U(X_D,t) = \frac{1}{j\lambda F}\int E_0 \exp(-j\omega t)T(x,t)\exp\frac{-jkxx_D}{F} \tag{3}$$

where

- E_o is the incident field
- F is the focal length of the Fourier lens
- k is the wave number of the light wave
- λ is the wavelength of the light wave.

Substituting (2) into (3), the light intensity distribution in the focal plane, $|U(x_D, t)|^2$ can be easily determined. Assuming that the phases ϕ_i of the input signals are proportional to the position of the segments a_i (i.e. the antenna array has the same segment distribution as the Bragg cell), the effect can be explained as a reconstruction of the incident eletromagnetic wave by a light wave. The direction of the incident wave can be determined from the direction of the diffracted light beam, i.e. from the position of the intensity maximum

$$x_D = \frac{\phi_M \lambda}{2L} \tag{4}$$

which depends on the phase difference between the first and last segment.

3. NUMERICAL CALCULATIONS

In our calculations, the acoustic (electrical) frequency is 45 MHz which is the center frequency of the 30 to 60 MHz band, the light wavelength is 633 nm, the Bragg cell phase aperture, L is 10 mm, the base distance of the antenna array is 10 m, the focal length of the Fourier lens is 1 m which proved to be feasible.

The calculated light intensity curves from (1), (2) and (3) for 0° and 60° angle of incidence are shown in Fig. 2 and in Fig. 3, with aperiodic and periodic segment structure, respectively. The aperiodicity of the transducer (a_1=0, a_2/a_4=.56, a_3/a_4=.75) was chosen to minimize the first order peak intensities (which are out of picture), as usual in the literature [2], [3].

The input voltage dynamic range of the system for one frequency channel can be determined as the ratio between the maximum background sidelobe level and the peak intensity. It is 7 dB for the aperiodic and 13 dB for the periodic arrangement, so the periodic structure was chosen.

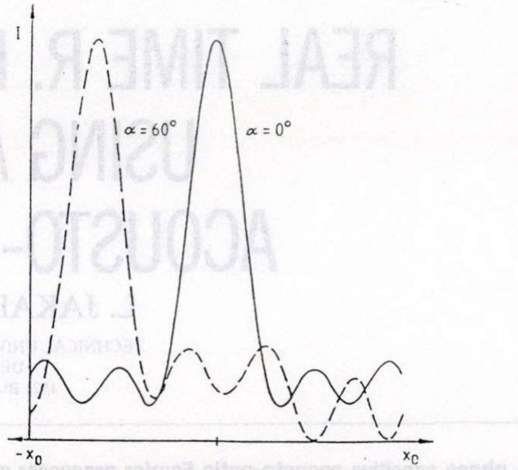

Fig. 2. The light intensity distribution for a four element aperiodic structure at 0° and 60° angle of incidence

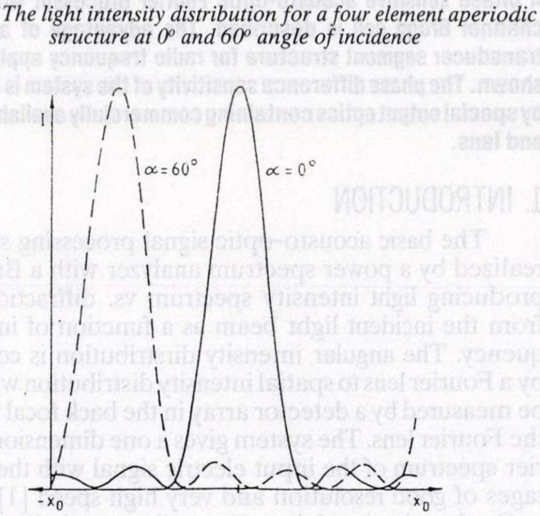

Fig. 3. The light intensity distribution for a five element periodic structure at 0° and 60° angle of incidence

4. EXPERIMENTAL RESULTS

The maximum change in the position of the intensity maximum can be derived from (4). We use the system pa-

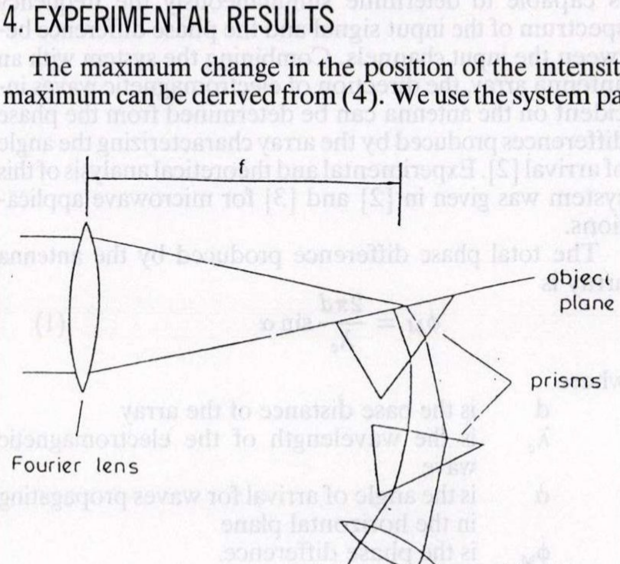

Fig. 4. The output optical system to match the frequency and phase axis to the detector matrix

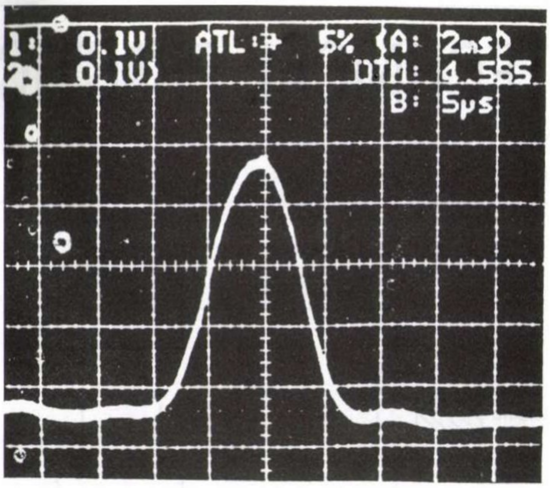

Fig. 5. The measured light intensity distribution for a 45 MHz signal at 0° angle of incidence

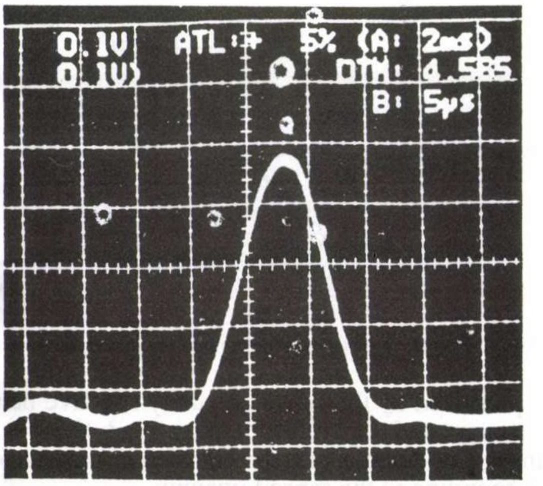

Fig. 6. The measured light intensity distribution for a 45 MHz signal at 10° angle of incidence

remeters above limiting the examined angle range to $\pm 45°$ in order to use the quasi-linear part of (1). In this case,

$$\Delta x_{Dmax} = 0.1 \text{ mm}$$

This is very small compared to the length of the frequency axis (30 mm for the 30 to 60 MHz range). A simple optical arrangement was used to increase Δx_{Dmax} as can be seen in Fig. 4. The length of the phase axis was magnified by prisms that do not influence the deflection along the frequency axis, and then the complete frequency-phase image was matched to the detector matrix area (CDD videocamera using an F/1.6 objective). One line of the measured image is shown in Figs. 5 and 6, for 45 MHz frequency, 0° and 10° direction. Comparing the pictures with the numerical results of Fig. 3, it can be seen that the small maxima around the peak disappeared because of the Gaussian apodization of the expanded input beam, further decreasing the optical noise limiting the dynamic range. Completing the measurement with an IBM PC/AT, image processing card and maximum finding software, and simulating the 10 m long antenna array with coaxcables in the laboratory, 1 to 2° angle resolution was achieved within the $\pm 45°$ range from the video output curves of Figs. 5. and 6. The measured 70 kHz frequency resolution was limited by the number of lines of the detector matrix.

5. SUMMARY

A five channel acousto-optic Fourier processor was described for application in the 30 to 60 MHz radio frequency range. The effect of the periodic and aperiodic transducer segment arrangement was examined showing the dynamic range limiting effect of the aperiodic structure in this frequency range. To improve the phase sensitivity of the system, a simple output optics was used, reaching a good 1 to 2° angle resolution with a CCD camera and maximum finding software.

REFERENCES

[1] D. L. Hecht, *Opt. Eng.* 16, 461—466 (1977).

[2] R. A. Coppock and R. F. Croce, *Proc. SPIE* 214, 124—129 (1979).

[3] J. P. Y. Lee, *Appl. Opt.* 22, 876—872, 15, March (1983).

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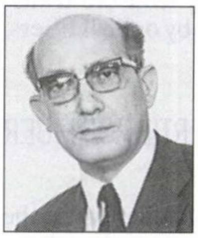

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FIBER OPTIC SENSORS IN TECHNICAL PRACTICE

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Fiber optic technology is applied for sensor and measurement systems for automation in industrial production, and is a result of the development of fiber optic communications. In the last twenty years, there has been considerable development in the use of fiber optic sensors for the monitoring of physical (and also chemical or "biological") parameters, and fiber optic telemetry systems are readily available. The classification and basic properties of fiber optic sensors are first presented, followed by the discussion of sensor systems, together with typical applications and future development trends.

1. INTRODUCTION

The stormy development of automation in industrial production demands an increasing use of special sensors, sensor systems, or intelligent sensors. In these systems, the components of fiber optics and partially integrated optics find ever increasing applications. Thus, a new class of sensors have come into existence — the Fiber Optic Sensors (FOS) [4], [12], [15], [17], [18], [20], [21].

During the short period since the discovery of the first FOS, there has been a rapid development in this field. FOS use opens up qualitatively new possibilities in sensor technology. The universality of their design principles has attained a level at which practically any physical quantity can be sensed by FOS'S (the only problem is that of price reduction) [6], [24]. It is often required in industry to sense position (20%), force (20%), flow (20%), pressure (15%) and temperature (15%), and all these quantities may be sensed by FOS. A FOS display has a number of advantages over the corresponding classic sensors: higher sensitivity, geometrical adaptability (FOS generation in different shapes, sensing a point, a surface etc.), a common technological base for sensors of various physical quantities (acoustic, electrical, magnetic, mechanical, thermal etc.), possibilities of application in aggressive conditions, high voltages, under the effect of electromagnetic interference, and high temperatures. They are also advantageous due to their compatibility with the transmission of primary measurement signals by optical fibers, i.e. fiber optic telemetry [18], [21].

2. CLASSIFICATION AND BASIC PROPERTIES OF FIBER OPTIC SENSORS

A FOS has an input source of optical radiation — the light (LED, semiconductor laser, or some other laser source of radiation) which injects a continuous or pulsating optical signal into the optical fiber. At the output of the FOS, there is a photodetector (PIN diode, APD, or PIN-FET structure) which receives the optical signal modulated by the sensor. Active parts of the FOS are the electronic components and circuits which control the source and light detector, and process the detected signal. The sensor itself is an electrically passive component (i.e. there is no need for electrical energy), connected by one or more optical fibers to the source and photodetector. The principle of a FOS is the physical (optical) phenomenon produced by the sensed quantity effective between the source and the photodetector, and the resulting changes (modulation) in the transferred optical signal, corresponding to the sensed quantity.

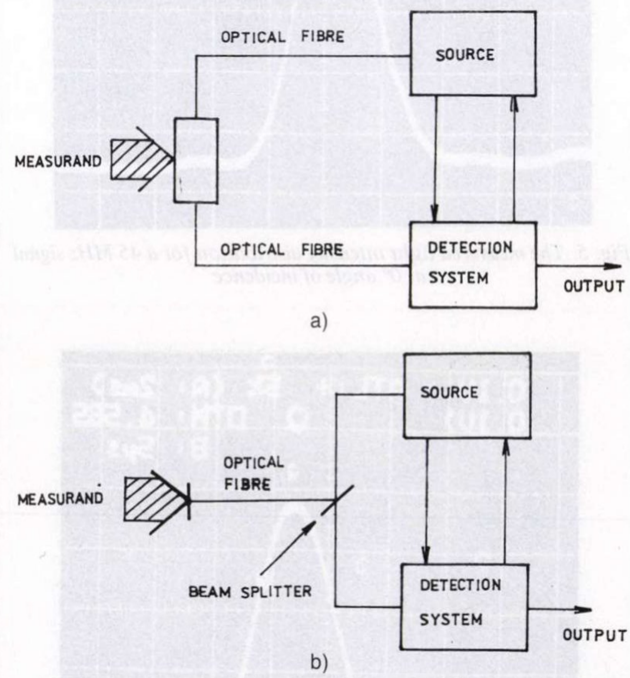

Fig. 1. Transfer type (a) and reflex type (b) fiber optic sensors

The optical fiber sensor is called transfer sensor if it is possible to physically distinguish between the input and the output optical fibers (Fig. 1a). On the other hand the optical fiber sensor in which it is impossible to physically distinguish between the input and the output optical fibers is called reflex sensor (Fig. 1b).

Fig. 2 is a schematic diagram of three types of FOS construction. Fig. 2a illustrates the variant using the optical fiber itself as a sensing device. In Figs. 2b and 2c, optical fibers are used only as input/output components. The fiber optic sensor in Fig. 2b utilizes the optical effect outside the optical fiber. The FOS in Fig. 2c utilizes a non-optical phenomenon, and the optical fiber is used only for measurement signal transmission. By the type of the optical fiber used, FOS's may be classified as follows:

a) Single-mode sensors using single mode operation optical fibers and coherent sources of optical radiation.

b) Multi-mode sensors using multi-mode operation optical fibers and incoherent sources of optical radiation.

The FOS classification has recently been configured on the basis of the modulation of optical signals characterizing the construction of the sensor itself and its electronic detection system [24].

A) Amplitude FOS's use intensity (amplitude) modulation of the light propagating through the optical fiber. Optical signal amplitude modulation in these FOS's may be carried out in the following ways [24]:

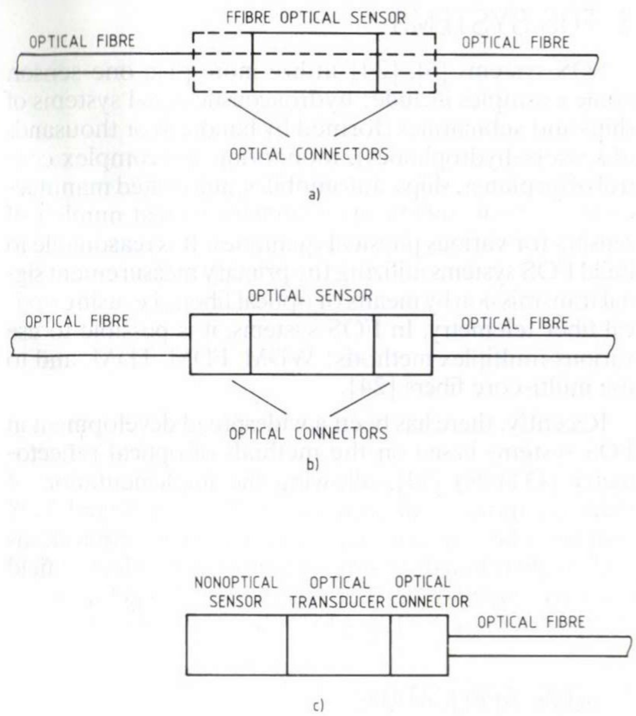

Fig. 2. Fiber optic (a), optical (b) and non-optical (c) construction of fiber optic sensors

1. direct attenuation of light in optical environment, caused by changing of the attenuation coefficient;
2. cross-sectional changes in the optical channel;
3. changes in the reflective properties, caused by the changing of the reflection coefficients and not meeting the condition of total internal reflection in the optical fiber core;
4. optical signal control in the optical fiber (e.g. by influencing the waveguide link);
5. generation of additional radiation.

B) Phase FOS's are based on phase modulation of a light wave propagating in the optical fiber [19] due to the sensed quantity on the optical fiber material. The phase changes of the light wave are measured by interferometric methods (Fig. 3). As these methods allow the measurement of phase changes of the order of 10^{-5} to 10^{-8} rad, the phase FOS's are extremely sensitive [4], [5], [13], [19], [21], [22], [23], [24]. This principle is applied in optical fiber interferometers which may be divided into three basic groups:

1. Double-arm single mode interferometer (Mach-Zehnder or Michelson) based on the phase comparison of the light waves propagating in the sensor optical fiber and in the reference optical fiber. A homodyne or heterodyne method of detection is used. Fig. 4 is a schematic diagram of a construction of FOS using Mach-Zehnder interferometer.
2. Inter-mode interferometers utilize the interference between two or more modes of the light wave propagating in a given optical fiber. Its advantage is the possibility to use multimode optical fibers while the disadvantage is the difficulty of evaluating the interference pattern.
3. Single fiber interferometer with a two-way optical link (Sagnac interferometer), comparing the phases of two light waves propagating in opposite directions in an optical fiber coil.

C) Polarization FOS's utilize the effect of the sensed quantity on the polarization state of the light wave trans-

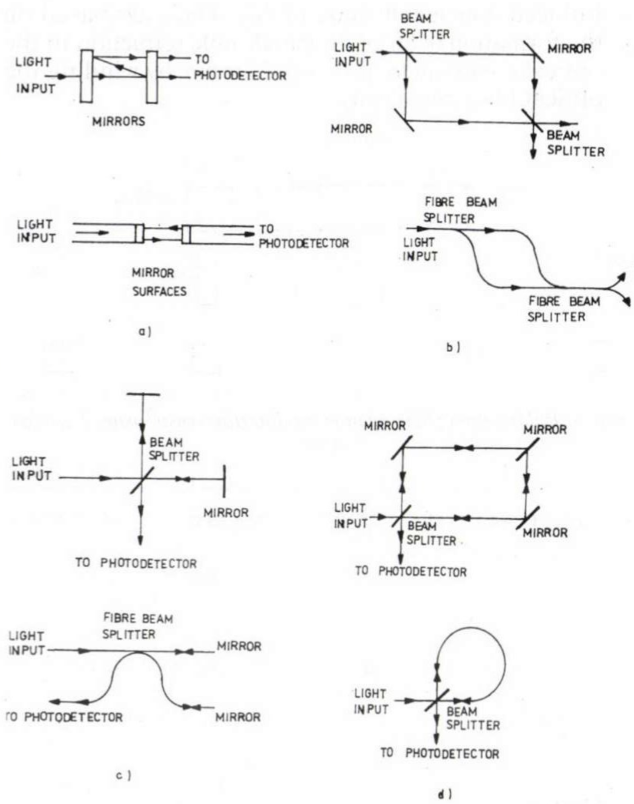

Fig. 3. Interferometers. Top line: optical components. bottom line: fibre equivalents. (a) Fabry Perot, (b) Mach Zehnder, (c) Michelson and (d) Sagnac

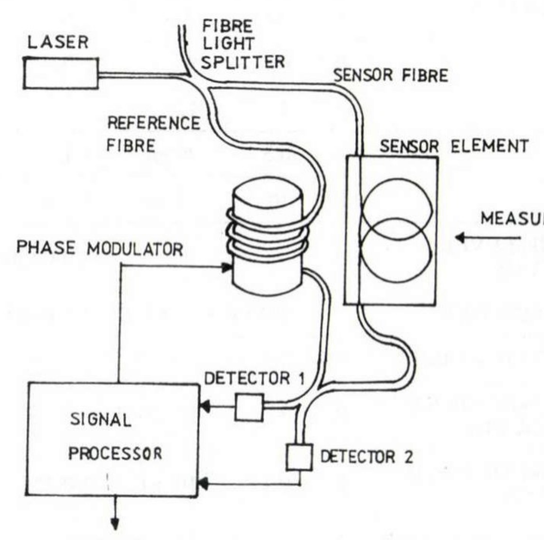

Fig. 4. Construction of sensor using Mach Zehnder interferometer

ferred by the optical fiber [2], [4], [19], [22]. The polarization of light passing through the optical environment may change under the influence of various physical quantities (intensity of the magnetic and electric fields, pressure, etc.). The sensed physical quantity can cause either a rotation of the polarization ellipsoid without a change in its shape, or the ellipsoid may be deformed. Accordingly, polarization FOS's can be classified as follows:

1. Polarization plane rotation FOS's. These include, for example, Faraday effect sensors (i.e., polarization plane rotation due to magnetic field, Fig. 5), used as a sensor for magnetic field intensity and electric current.

2. Induced double refraction FOS's. These are based on the formation of an additional double refraction in the optical environment (it may occur e.g. by winding the optical fiber into a coil).

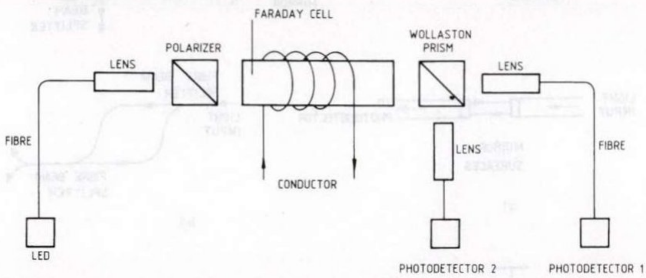

Fig. 5. Polarization plane rotation modulation sensor using Faraday effect

Table 1.

SENSED QUANTITY	FOS TYPE	RANGE		ACCURACY
TEMPERATURE	A	300	2000 °C	± 1 °C
		−50	+150 °C	± 0.2 °C
	B	0	100 °C	± 0.001 °C
PRESSURE	A	0	35 MPa	± 0.5%
POSITION	A	ROTARY: 0	40°	± 0.04°
		DISPLACEMENT: 0	15 cm	± 0.003 cm
ACCELERATION (VIBRATION)	A	0.01	32 g	± 0.1%
	B	10^{-6}	10 g	± 1%
pH	E	6	8	± 0.02
		7	12	
FLOW	A	0.5	20 ms^{-1}	± 1%
	D	10^{-6}	10^5 ms^{-1}	± 1%
LIQUID LEVEL (SWITCH)	A		—	± 0.05 mm
(CONTINUOUS)	A	SEVERAL METERS		± 1 mm
ELECTRIC CURRENT	C	20	5000 A	± 0.24%
ACOUSTIC SIGNAL (PRESSURE)	B	3	170 dB/μPa	—
MAGNETIC FIELD INTENSITY	B	0.1	10^5 nT	± 0.1%
RATE OF ROTATION	B	10^{-3}	10^2 °/h	± 0.1%
OIL CONCENTRATION IN WATER	A	0	1000 ppm	± 20%
METHANE CONCENTRATION	E		≧ 2600 ppm	

D) Frequency FOS's utilize frequency modulation of optical signals (e.g. Doppler effect) propagating in the optical fibers [2], [4], [19].

E) Wavelength distribution (e.g. spectral) modulation FOS's based on the detection of spectrum dependent changes in absorption, light emission or refractive index [4], [8], [9], [11], [18].

Table 1 is a review of parameters of some FOS types.

3. FOS SYSTEMS

FOS systems [6], [24] utilize more than one sensor. Some examples include: hydroacoustic aerial systems of ships and submarines (formed by hundreds or thousands of sensors-hydrophones), monitoring and complex control of airplanes, ships, automobiles, automated manufacturing systems, robots, etc.) applying a great number of sensors for various physical quantities. It is reasonable to build FOS systems utilizing the primary measurement signal transmission by means of optical fibers, i.e. using optical fiber telemetry. In FOS systems, it is possible to use various multiplex methods: WDM, FDM, TDM, and to use multi-core fibers [24].

Recently, there has been a widespread development in FOS systems based on the methods of optical reflectometry (OTDR) [14], allowing the implementation of multi-component (discrete) as well as distributed FOS systems. These systems may be used in many applications such as distributed sensing of temperature, electric field intensity, pipeline defects (gas lines, oil pipelines), security systems, etc. [12], [15], [16], [17], [18], [21].

4. SOME APPLICATIONS

In the following, some industrial applications of commercially available FOS's [7], [17] will be summarized. Fig. 6 shows typical industrial applications of simple amplitude FOS. The most widely used FOS's are for displacement, vicinity, pressure, force and other quantities that can be transformed into displacement [7], [15]. The displacement sensitivity of the optimized microbending FOS (Fig. 7) is 10^{-12} m. Based on this sensor, it is possible to develop sensitive sensors of pressure (~ 60 dB/μPa), temperature (~ 4.10^{-6} °C), acceleration (~ 3.10^{-7} g), electric field intensity (~ 0.17 Vm^{-1}), and other quantities.

For some years now, temperature FOS's have been commercially available [10], [12], allowing the measurement of wide temperature ranges, from cryogene up to 2000 °C, with a relatively high accuracy. They find applications under laboratory conditions, in medicine, airplane engine monitoring, gas turbines, induction furnaces, gas burners, etc.

FOS's are industrially applied in spectrometric systems (Fig. 8) for chemical analysis of gases and liquids [9], [11]. They may be used to measure the concentration of methane, O_2, CO_2, H_2, CO, SO_2, etc., even in distant areas (several kilometers). Similar FOS systems may be used in laboratory practice, in chemical and mining industries, environmental monitoring, etc. [4], [9], [11], [21].

There are FOS applications for measuring voltage, current (Fig. 9), electric and magnetic field intensity. They present very sensitive magnetometers capable of monitoring high voltages and power lines [19], [22].

There has been wide industrial use of various types of coding disks using optical fibers. These rotation and displacement coding devices may be used in systems for optical control of servo-valves [12].

FOS's are also used in robotics [1], [7], [12], [15]. Let us mention tactile sensors and special visual systems of robots. To sense pattern information, optical fibers are used which transfer optical signals proportional to the bright-

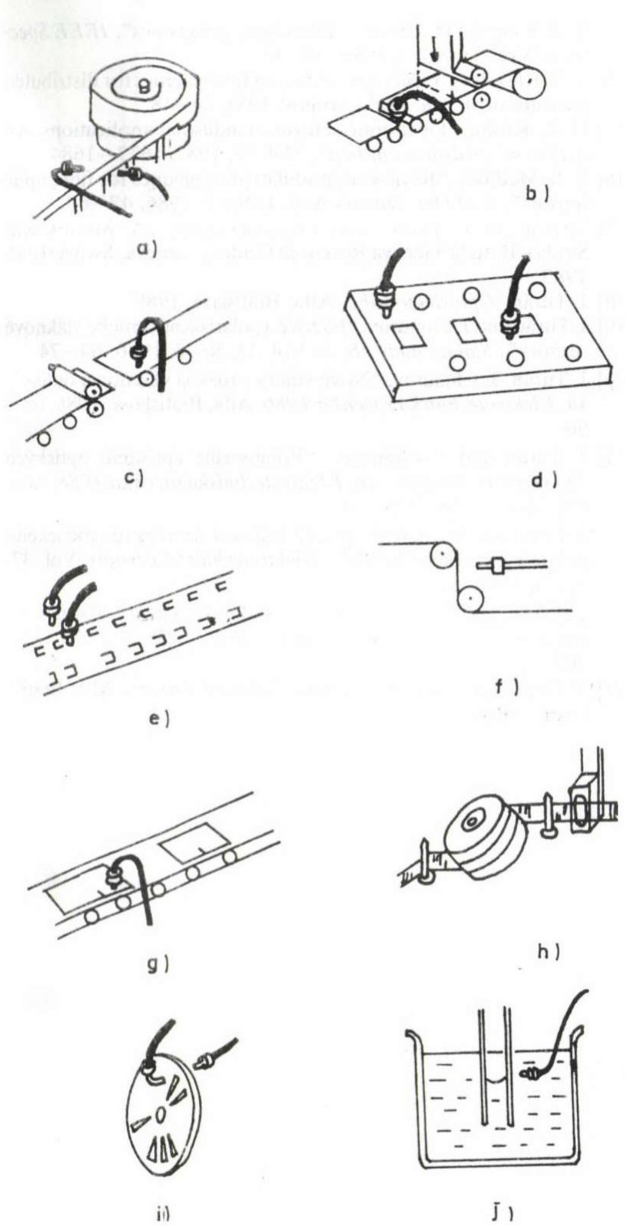

Fig. 6. Some applications of simple amplitude fiber optic sensors

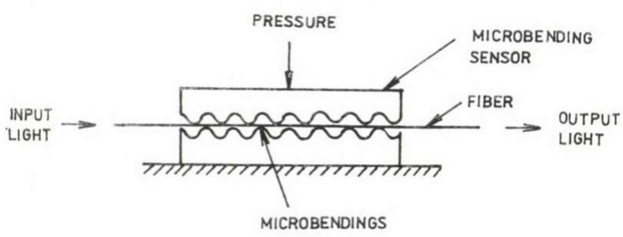

Fig. 7. Microbending pressure sensor

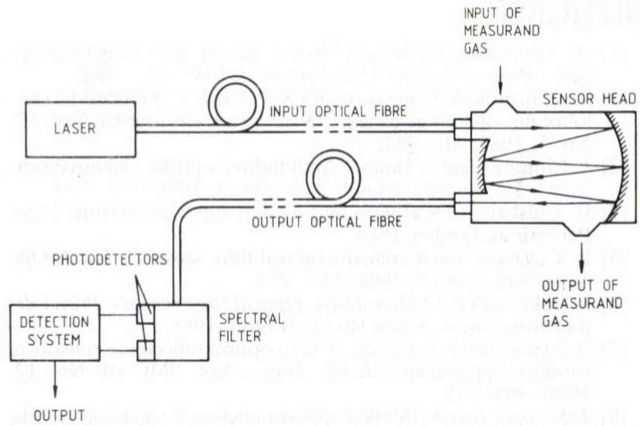

Fig. 8. Remote fiber optic spectrometric system for chemical analyses of gases

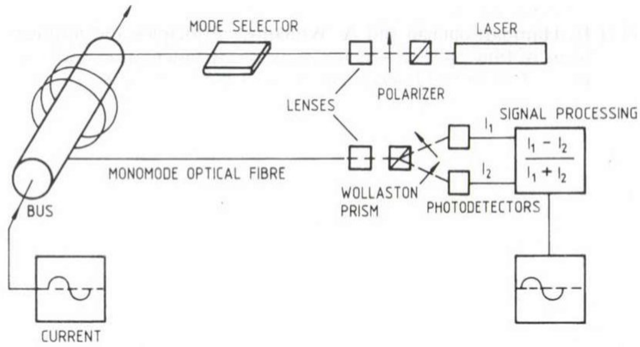

Fig. 9. A device for current measurement using single mode optical fiber

Fig. 10. Fiber optic visual system of robots

ness intensity of the corresponding picture element. For scene illumination, it is also possible to use optical fibers. Such visual systems of robots (Fig. 10) have a number of advantages over the visual systems using cameras such as allowing the spatial separation of the optical and electronic systems and thus increasing the resistance against electromagnetic interference, aggressive environmental effects, radioactive radiations and insuring the low weight of the sensor head (fine manipulation, possible mounting on the arm, etc.). By selecting the shape of the illumination and observation area, it is possible to perform a picture pre-processing.

5. CONCLUSION

In spite of certain conservatism avoiding the introduction of new technologies into industrial practice, FOS's present a revolutionary change in measurement technology utilizing optical fiber telemetry. The main directions of further research and deelopment in this field are oriented to the research into new FOS construction, special fibers designed for FOS's, signal processing methods, and integrated optics applications.

REFERENCES

[1] A. Agraval and M. Epstein, "Robot eye- in hand using fiber optics", *Proc. of 3rd conf. on robot vision,* 1983, 257—262.

[2] V. I. Busurin, A. S. Semenov and N. P. Udalov, "Opticeskije i volokonno- optičeskije datčiki", *Kvantovaja elektronika,* Vol. 12, No. 5, 1985, 901—944.

[3] J. Chmúrny and J. Turán, "Aplitdúdové optické vláknové senzory", *Slaboproudý obzor,* Vol. 47, No. 5. 1986, 223—231.

[4] B. Culshaw, *Optical fibre sensing and signal processing,* Peter Peregrinus, London, 1984.

[5] B. Culshaw, "Interferometric optical fibre sensors", *Int. J. Opt. Sens.,* Vol. 1, No. 3, 1986, 237—252.

[6] J. Dakin and B. Culshaw (eds), *Optical fiber sensors, Principles and components,* Artech House, Boston, 1988.

[7] B. Espian and J. Y. Catros, "Use of optical reflectance sensors in robotics applications", *IEEE Trans.,* Vol. SMC-10. No. 12, 1980, 903—912.

[8] *Fibre optic sensors,* (Market opportunities and technology trends, ERA Technology Ltd, Leatherhead, England, 1983.

[9] G. Graff , "Fiber optics analyze chemical processes", *High Technology,* Vol. 3, 1983, 24—25.

[10] K. T. V. Grattan, "The use of fibre optic techniques for temperature measurement", *Measurement and Control,* Vol. 20, July, 1987, 32—39.

[11] A. J. Guthrie, R. Narayanaswamy and D., A. Russell, "Optical fibres in chemical sensing", *A review. Trans. Inst. MC,* Vol. 9, No. 2, 1987, 71—80.

[12] E. Hampartsoumian and A. Williams, "Principles and applications of fibre optic sensors for process instrumentation and control", *J. of Inst. of Energy, December* 1985, 159—168.

[13] Y. B. Kim and H. J. Shaw, "Fiber optic gyroscopes", *IEEE Spectrum,* Vol. 23, No. 3, 1986, 54—60.

[14] S. A. Kingsley, "Fiber optic sensors, Opportunities for distributed measurement", *In. Tech.,* August 1985, 44—48.

[15] D. A. Krohn, "Fiber optic sensors in industrial applications, An overview", *Advances in Instr.,* Vol. 37, 1982, 1673—1684.

[16] R. S. Medlock, "Review of modulation techniques for fibre optic sensors", *J. of Opt. Sensors,* Vol. 1, No. 1, 1986, 43—68.

[17] *Optical fibre sensors and instrumentation,* (A Multi-Client Study), Battelle Geneva Research Centres, Geneva, Switzerland, 1983.

[18] J. Turán, *Optoelektronika,* Alfa, Bratislava, 1988.

[19] J. Turán and J. Chmúrny, "Fázové a polarizačné optické vláknové senzory", *Slaboproudý obzor,* Vol. 47, No. 2, 1986, 64—74.

[20] J. Turán, J. Chmúrny, "Nové smery v rozvoji vláknovej optiky", *In, Elektrotechnická ročenka 1986,* Alfa, Bratislava, 1986, 65—96.

[21] J. Turán and J. Chmúrny, "Priemyselné aplikácie optických vláknových senzorov", *In, Elektrotechniská ročenka 1988,* Alfa, Bratislava, 1988, 205—230.

[22] J. Turán and S. Petrík, "Optické vláknové senzory magnetického pola a elektrického prúdu", *Elektrotechnický časopis,* Vol. 37, No. 3, 1986, 224—231.

[23] J. Turán and S. Petrík, "Optické vláknové senzory akustických signálov", *Elektrotechnický časopis, Vol.* 38, No. 4, 1987, 297—307.

[24] J. Turán and S. Petrík, *Optické vláknové senzory,* Alfa, Bratislava, 1990.

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A PLANE WAVE SPECTRAL ANALYSIS OF REFLECTANCE IN INTEGRATED OPTICAL WAVEGUIDE PROBLEMS

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A method for three-dimensional analysis of reflection problems in integrated optical devices is presented. The propagating optical beams are represented as a two-dimensional angular spectrum of electromagnetic plane waves. The connection between the plane wave spectrum and the electromagnetic field is given by two-dimensional Fourier-transformation. Using the discrete approximation of the Fourier spectrum, a set of linear equations yields the relation between the plane wave components of the electromagnetic field in different planes perpendicular to the direction of the propagation. The inhomogeneous waveguide can be taken into consideration with the presented method. The results of the reflectance calculation of an optical waveguide-ending is compared in two different approximations. In the first case, the waveguide is replaced by a homogeneous medium, and in the second case, the inhomogenity of the waveguide is taken into consideration through the weakly guiding waveguide approximation. The modal reflectance of an optical waveguide ending terminated by a tilted antireflection coating is finally presented.

1. INTRODUCTION

Good quality antireflection coatings have great importance in different integrated optical applications. The nature of antireflection coatings deposited on semiconductor laser facets is important e.g. in short pulse generation, optical amplification, or external cavity design applications [1]—[7]. For the calculation of radiation properties of semiconductor lasers, the laser is usually modelled by an optical waveguide [2]—[7]. Different approximations are used to determine the modal reflection, and numerical results are presented when the laser mode is approximated by a single plane wave [2]. For other calculations, the laser is represented as a medium with homogeneous refractive index [3]—[6]. Results are presented for reflectance calculation of parallel antireflection coatings that take into consideration the inhomogenity of the laser structure [7]. In this papar, a method is presented that can treat the refractive index variation not only in one direction but in three dimensions as well. The presented method is useful for the analysis of antireflection coating.

The theory is based on the following considerations. The known electromagnetic field distribution of the waveguide modes is represented as the angular spectrum of electromagnetic plane waves.The relation between the electromagnetic field and the plane wave spectrum is given by a two-dimensional Fourier-transform [8]. The plane wave spectrum is approximated by its discrete representation. A linear equation system is obtained by fulfilling the boundary conditions at the interfaces of the materials with different refractive indices. The solution of this linear equation system gives the discrete representation of the reflected field. The matching of the reflected field to the guided mode of the waveguide determines the reflectance.

The theory of the calculation is presented in Sec.2 In Sec.3, examples are presented. The first example is the comparison of the reflected fields of a plane waveguide end,

1) when the waveguide is considered as a homogeneous medium, and

2) when the inhomogeneous material of the waveguide is taken into consideration by using the weak guidance approximation.

The difference between the calculated electric fields resulting from two approximations is plotted depending on the refractive index step between the film and the cover material, and depending on the refractive index step between the two films and the reflecting layer. As a second example, the reflectance of a tilted antireflection coating is calculated. The modal reflectivity versus the angle of the coating and versus the wavelength of light is plotted.

2. THEORY

The investigated structure is shown in Fig. 1. The waveguide medium of refractive index n_f is embedded in a material with a lower refractive index n_c. The refractive index distribution of the waveguide is described by the function $n_0(x,y)$. The direction of propagation in the waveguide is parallel to the co-ordinate axis z, and the waveguide is assumed to be infinite in the negative-z direction. The optical waveguide is terminated at the z=0 plane with a medium

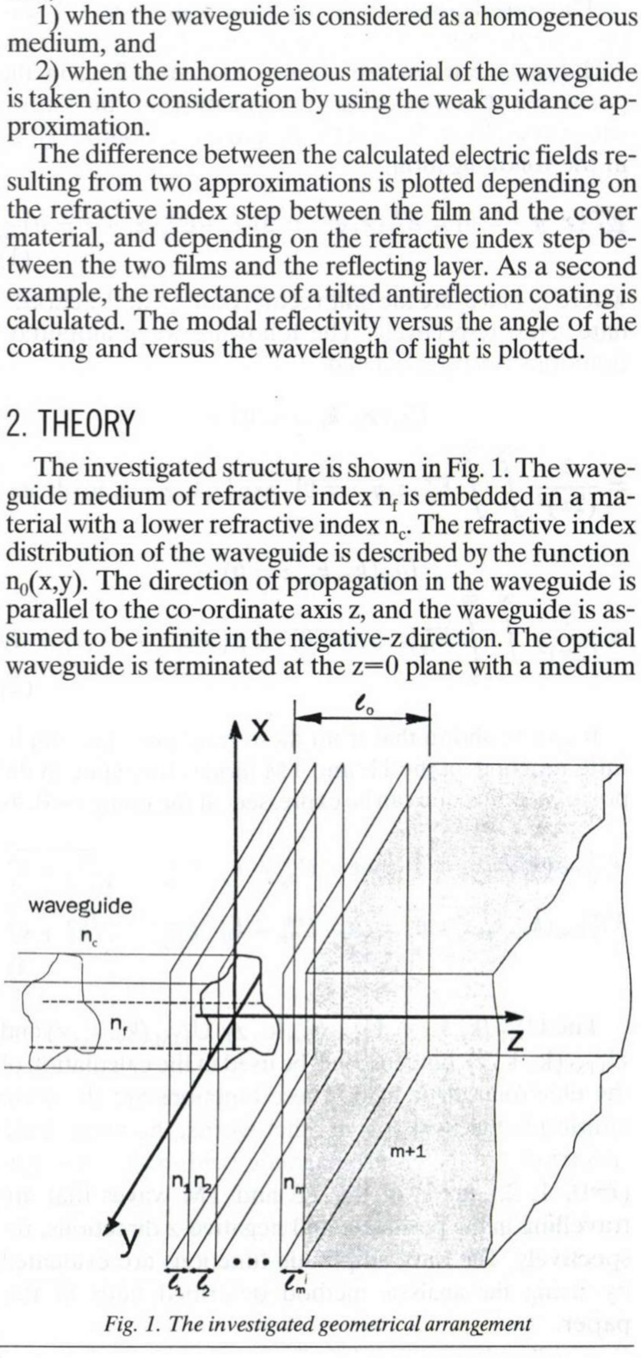

Fig. 1. The investigated geometrical arrangement

which has layers perpendicular to the z axis. The layers and the waveguide are made of linear isotropic materials, the layers are homogeneous with different thicknesses and refractive indices (l_i, n_i, i=1, 2, ... m). The waveguide ending is referred to with i=0. The (m+1)-th layer is infinite in the positive-z direction, and its refractive index distribution n(x,y,z) is arbitrary. The electromagnetic wave travelling in the waveguide in the positive-z direction is assumed to be given. Analytical or numerical descriptions of this wave are given for most of the arrangements in the literature.

The electromagnetic field can be represented as the angular spectrum of TE and TM plane waves (perpendicular to the z direction). For calculating the propagation of the two polarizations, the separation of the TE and TM wavespectrum is required. This can be done for arbitrary electromagnetic fields in the following way.

The time dependence of the wave is sinusoidal. Using the complex notation and suppressing the exp($j\omega t$) time variation, the transverse electric field travelling in the positive-z direction in the z=0 plane (i.e. the known transverse electric field of the propagating mode) is given in the following form:

$$\underline{E}_t^+(x,y,z=0) = E_{tx}^+(x,y,z=0)\cdot\underline{e}_x + E_{ty}^+(x,y,z=0)\cdot\underline{e}_y \tag{1}$$

where e_x and e_y are the unit vectors of the x and y coordinate axes, respectively. The following wave amplitude functions can be calculated:

$$U_{0x}(k_x,k_y,z=0) = $$

$$= \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_{tx}^+(x,y,z=0)\cdot\exp\{j(k_x x + k_y y)\}dx\,dy$$

$$U_{0y}(k_x,k_y,z=0) = $$

$$= \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_{ty}^+(x,y,z=0)\cdot\exp\{j(k_x x + k_y y)\}dx\,dy \tag{2}$$

It can be shown that from these functions, the amplitude functions of the TE and TM modes travelling in the positive-z direction can be expressed, at the plane z=0, as

$$U_{0TE}^+(k_x,k_y,z=0) = (k_x\cdot U_{0y}^+ - k_y\cdot U_{0x}^+)\ /\ \sqrt{k_x^2+k_y^2}$$

$$U_{0TM}^+(k_x,k_y,z=0) = (k_x\cdot U_{0x}^+ + k_y\cdot U_{0y}^+)\ /\ \sqrt{k_x^2+k_y^2} \tag{3}$$

The U^+_{iTE} (k_x, k_y, z), U^-_{iTE} (k_x, k_y, z), U^+_{iTM} (k_x, k_y, z) and U^-_{iTM} (k_x, k_y, z), functions will be used in the calculation of the electromagnetic field. These functions are the wave amplitude functions (or, in other words, the plane wave spectrums) of the electromagnetic field in the ith layer (i=0, 1, 2,...m+1) of the TE and TM waves that are travelling in the positive-z and negative-z directions, respectively. The wave amplitude functions are evaluated by using the analysis method described later in this paper.

Using these wave amplitude functions, the transverse electric field in the ith layer at the $z=l$ plane can be written as

$$E_x(x,y,l) = $$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{k_x\cdot U_{iTM} - k_y\cdot U_{iTE}}{\sqrt{k_x^2+k_y^2}}\cdot e^{-j(k_x x+k_y y)}dk_x dk_y$$

$$E_y(x,y,l) = $$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{k_x\cdot U_{iTE} + k_y\cdot U_{iTM}}{\sqrt{k_x^2+k_y^2}}\cdot e^{-j(k_x x+k_y y)}dk_x dk_y$$

$$U_{iTE}(k_x,k_y,z=l) = $$

$$= [U_{iTE}^+(k_x,k_y,z=l) + U_{iTE}^-(k_x,k_y,z=l)]$$

$$U_{iTM}(k_x,k_y,z=l) = $$

$$= [U_{iTM}^+(k_x,k_y,z=l) + U_{iTM}^-(k_x,k_y,z=l)] \tag{4}$$

The electromagnetic field in the waveguide and in the layered medium is well concentrated within a finite area in any cross section. Considering this fact, it can be seen that using the connection between the discrete and continuous Fourier transformation, (2) and (4) can be evaluated by FFT [9].

For the numerical evaluation of the electromagnetic field, the discrete approximation of the plane wave spectra are used. The calculus is made for the TE and TM mode separately. The notations used in the calculations will be the followings. $U^{\pm}$ vector contains the discrete values of the plane wave spectrum of the electromagnetic field:

$$U_i^{\pm}\begin{bmatrix}\vdots\\ U_{i,q}^{\pm}\\ \vdots\end{bmatrix};\quad (U_{i,q}^{\pm})_p = U_i^{\pm}(p\cdot k_{x0}, q\cdot k_{y0});\quad \begin{array}{l} i=0,1,\dots m\\ q=0,1,\dots q_0\\ p=0,1,\dots p_0\end{array} \tag{5}$$

where $U_i^{\mp}$(p · k_{x0}, q · k_{y0}) is the value of the plane wave spectrum at k_x=p · k_{x0} and k_y=q · k_{y0}, in the plane separating the ith and the (i+1)th layer. The + and − sings represent the waves travelling in the positive-z and negative-z directions, respectively. U^-_{m+1}=0 and U^+_{m+1} are defined in the (m+1)th layer at the plane separating the mth and the (m+1)th layer. p_0 and q_0 are the number of the sampling points in the space window used for the discrete Fouriér-transformation in the x and y direction. k_{x0}=2 · π/l_x, k_{y0}=2 · π/l_y, where l_x and l_y are the size of the space window in the x and y directions, respectively.

The propagation matrix is a diagonal matrix defined in the ith layer as a supermatrix in the following way:

$$\begin{array}{l} P_i = <\ P_i^q\ >\\ P_i^q = <\dots\exp(j\cdot k_{z,i}^{p,q}\cdot l_i)\dots>\end{array}\quad \begin{array}{l} i=1,2,\dots m\\ q=0,1,\dots q_0\\ p=0,1,\dots p_0\end{array} \tag{6}$$

where

$$k_{z,i}^{p,q} = (k_{0i}^2 - p^2 \cdot k_{x0}^2 - q^2 \cdot k_{y0}^2)^{1/2}$$
$$\text{if} \quad k_{0i}^2 > p^2 \cdot k_{x0}^2 + q^2 \cdot k_{y0}^2 \tag{7}$$
$$k_{z,i}^{p,q} = -j(p^2 \cdot k_{x0}^2 + q^2 \cdot k_{y0}^2 - k_{0i}^2)^{1/2}$$
$$\text{if} \quad k_{0i}^2 < p^2 \cdot k_{x0}^2 + q^2 \cdot k_{y0}^2$$

$k_{0i}=n_i \cdot 2\pi/\lambda$, where n_i is the refractive index and l_i is the length of the ith layer; λ is the wavelength of light in vacuum.

The admittance matrix is a diagonal matrix defined in the ith layer as a supermatrix in the following way:

$$Y_i =< \ldots Y_i^q \ldots > \quad i = 1,2,\ldots m$$
$$Y_i^q =< \ldots Y_i^{p,q} \ldots > \quad q = 0,1,\ldots q_0 \quad p = 0,1,\ldots p_0$$

$$Y_i^{p,q} = \frac{k_{z,i}^{p,q} \cdot \lambda}{2 \cdot \pi \cdot c \cdot \pi_0} \quad \text{for TE mode} \tag{8}$$

$$Y_i^{p,q} = \frac{2 \cdot \mu \cdot n_i^2}{k_{z,i}^{p,q} \cdot \lambda \cdot c \cdot \mu_0} \quad \text{for TM mode}$$

where c is the speed of light in free space, and μ_0 is the permeability of the vacuum.

The $\mathbf{Y}_0$ matrix can be calculated by considering that the $\mathbf{Y}_0 \cdot U_0^+$ product gives the magnetic field component of the wave in the z=0 plane, perpendicular to the z coordinate axis, travelling in the positive-z direction:

$$Y_0 = [\ldots Y_0^q \ldots] \quad q = 0,1,\ldots q_0$$
$$Y_0^q = [\ldots Y_0^{p,q} \ldots] \quad q = 0,1,\ldots p_0 \tag{9}$$

Utilizing the weak guidance approximation (small refractive index differences in the waveguide structure), the $Y_0^{p,q}$ vector contains the two-dimensional discrete Fourier-transform of the following discrete function:

$$y^{p,q}[a,b] = f^{p,q}[a,b] \cdot \exp\{-j(p \cdot k_{x0} \cdot a \cdot x_0 + p \cdot k_{y0} \cdot b \cdot y_0)\}$$

$$f^{p,q}[a,b] = \frac{k_{z,0}^{p,q}(a \cdot x_0, b \cdot y_0) \cdot \lambda}{2 \cdot \pi \cdot c \cdot \mu_0} \quad \text{for TE mode}$$

$$f^{p,q}[a,b] = \frac{2 \cdot \pi \cdot n_0^2(a \cdot x_0, b \cdot y_0)}{k_{z,0}^{p,q}(a \cdot x_0, b \cdot y_0) \cdot \lambda \cdot c \cdot \mu_0} \quad \text{for TM mode} \tag{10}$$

$$a, p = 0, 1 \ldots p_0; \quad b, q = 0, 1, \ldots q_0$$

where $x_0=l_0/p_0$ and $k_{z,0}^{p,q}(a \cdot x_0, b \cdot y_0)$ is defined in (7) by considering that $k_{z,0}(a \cdot x_0, b \cdot y_0) = n_0(a \cdot x_0, b \cdot y_0) \cdot \cdot 2 \cdot \pi/\lambda$.

The relation between the plane wave spectra of the electromagnetic waves travelling in the positive-z and negative-z direction in the ith layer is given by the $\mathbf{R}_i$ reflection matrix ($U_i^-=\mathbf{R}_i \cdot U_i^+$). When $\mathbf{R}_m$ is given, $\mathbf{R}_i$ matrices can be calculated recursively. The $\mathbf{R}_m$ matrix, to be given for the particular geometrical arrangement, has the following structure:

$$\mathbf{R}_m = [\ldots R_m^q \ldots] \quad q = 0,1,\ldots q_0$$
$$R_m^q = [\ldots R_m^{p,q} \ldots]^T \quad p = 0,1,\ldots p_0 \tag{11}$$

where the number of the elements of the $\mathbf{R}_m$ vector is $p_0 \cdot q_0$, and this vector contains the discrete representation of the plane wave spectrum of the wave reflected from the plane separating the mth and (m+1)th layer (see Fig. 1), assuming that the exciting field is generated by the following plane wave:

$$E(x,y,z) = \exp\{-j \cdot [p \cdot k_{x0} \cdot x + q \cdot k_{y0} \cdot y + k_{z,m}^{p,q} \cdot (z - l_0)]\} \tag{12}$$

where E is the electric field of the given plane wave. The reflected field for a plane wave excitation can be determined in most cases analytically.

Once U_0^+ is known, the plane wave spectrum of the electromagnetic field can be calculated by fulfilling the boundary conditions at the planes separating the layers:

$$U_i^+ + U_i^- = P_{i+1} \cdot U_{i+1}^+ + P_{i+1}^{-1} \cdot U_{i+1}^-$$
$$Y_i \cdot U_i^+ - Y_i \cdot U_i^- = Y_{i+1} \cdot P_{i+1} \cdot U_{i+1}^+ - Y_{i+1} \cdot P_{i+1}^{-1} \cdot U_{i+1}^-$$
$$i = 0, 1, \ldots m-1;$$
$$U_m^+ + U_m^- = U_{m+1}^+$$
$$U_m^- = R_m^+ \cdot U_m^+ \tag{13}$$

where $\mathbf{I}$ is the unit matrix.

Solving the linear set of equations (13), U_0^- can be calculated by evaluating $\mathbf{R}_i$ matrices recursively in the following way ($\mathbf{R}_m$ is assumed to be known):

$$R_{i-1} = 2 \cdot (P_i + P_i^{-1} R_i) \cdot$$
$$\cdot [(\mathbf{I} + Y_{i-1}^{-1} Y_i) \cdot P_i + (\mathbf{I} - Y_{i-1}^{-1} Y_i) \cdot P_i^{-1} R_i]^{-1} - \mathbf{I} \tag{14}$$
$$i - 1, 2, \ldots m$$

where the dimension of the matrices in equation (14) is $p_0 \cdot q_0 \cdot$ Utilizing the orthogonality of the propagating modes, the modal reflectance can be determined [8].

3. EXAMPLES

Example 1: The effect of homogeneous waweguide approximation

The investigated structure is seen in Fig. 2. The dimension of the waveguide in the direction perpendicular to the plane of the paper is much greater, so it is considered infinite (dielectric slab waveguide). In this case, one-dimensional Fourier-transform is to be used. The waveguide-end is terminated by a homogeneous medium with refractive index n_r. The modal reflectance of the 0th order TE mode is investigated. First, the reflectance is calculated using the approximation of replacing the waveguide with a homogeneous medium with a refractive index equal to the index of the film layer. Next, the inhomogeneous matter of the refractive index of the waveguide is considered, using the $\mathbf{Y}_0$ matrix as given in (9). For the numerical calculation, 128 sampling points represented the plane wave spectrum, and the space window was 32 μm.

In Fig. 3, the relative error of the homogeneous approximation depending on the refractive index step be-

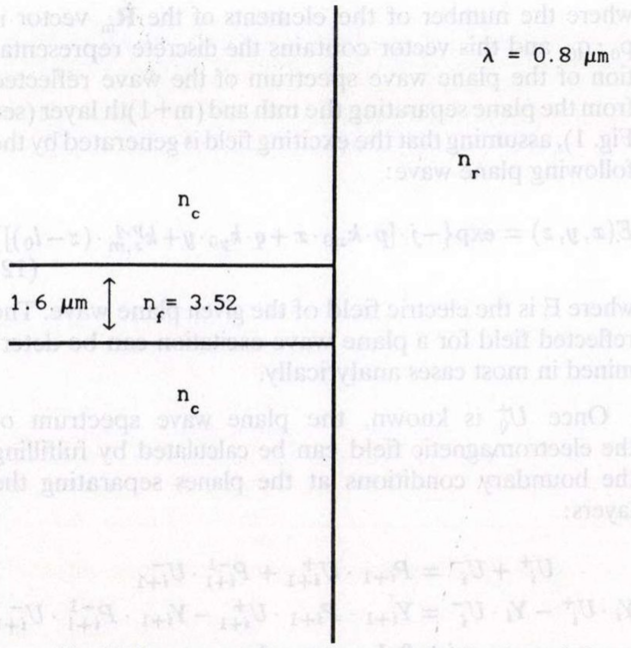

Fig. 2. The geometrical structure considered in Example 1

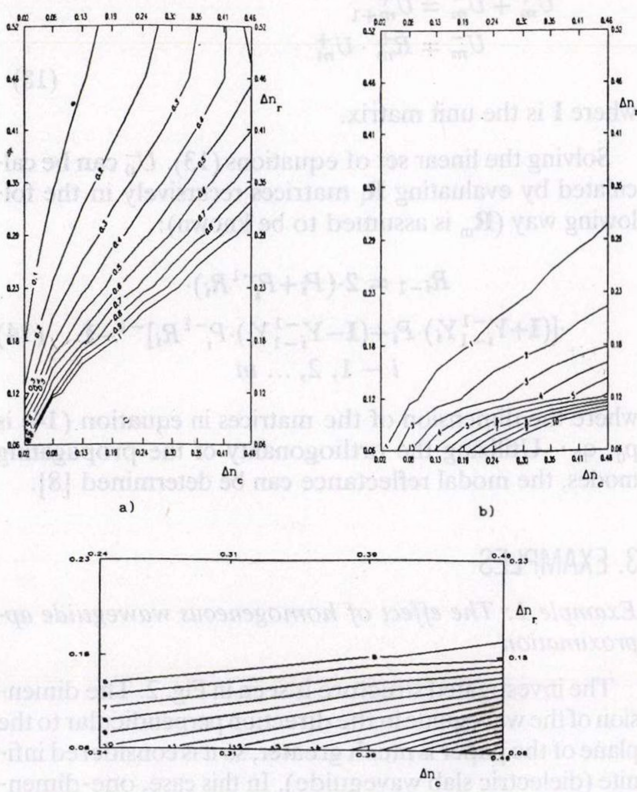

Fig. 3. The normalized error (E) in the Δn_r, Δn_c plane
a) for E < 1%
b) for the range of 1% < E < 10%
c) for E > 5%

tween the film and cover material ($\Delta n_c = n_f - n_c$) and on the refractive index step between the film and the reflecting layer ($\Delta n_r = n_f - n_r$) is shown. The error is defined as the square integral absolute value of the difference between the reflected electric field, calculated by the weak guidance approximation, and the homogeneous approximation, normalized to the square integral absolute value of the reflected electric field, calculated by the weak guidance approximation. The lines of constant error are

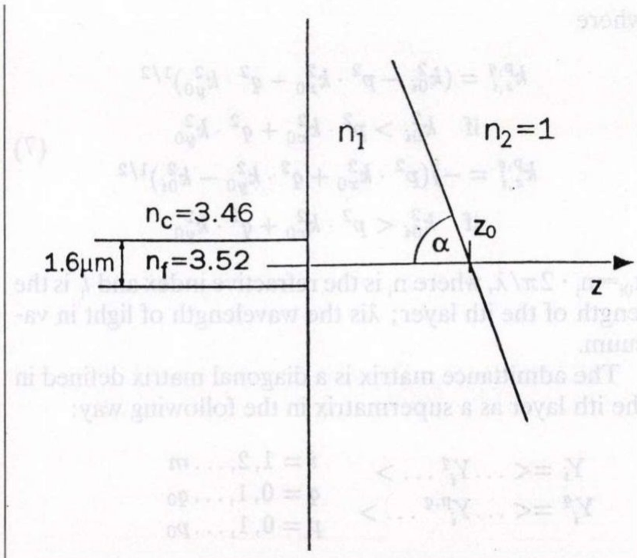

Fig. 4. The geometrical arrangement of the tilted antireflection coating investigated in Example 2

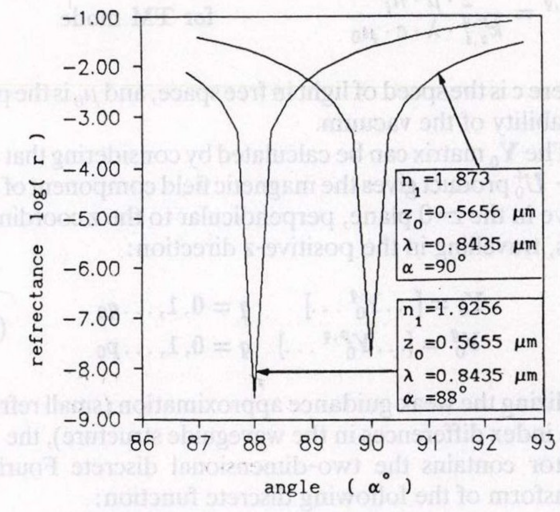

Fig.5. Modal reflectance versus the angle of the tilted layer (α°) when the layer is optimal for α=88° and for α=°

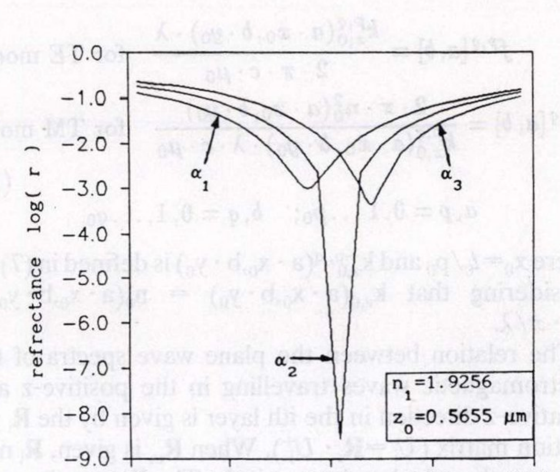

Fig. 6. Modal reflectance versus the wavelength of the tilted layer with angles or α_1=87°, α_2=88° and α_3=89° (the layer is optimal for α=88°)

plotted in Fig. 3. It is seen that the error is considerable when Δn_r is comparable to Δn_c.

Example 2: Calculation of the reflectance of tilted antireflection coatings

The investigated two-dimensional geometrical arrangement is shown in Fig. 4. The integrated optical slab waveguide-end is covered by a tilted antireflection coating. The geometrical sizes and refractive indices are given in Fig. 4. The $\mathbf{R}_m=\mathbf{R}_1$ matrix will have the following form:

$$R_1 = [\ldots R_1^p \ldots] \quad p = 0, 1, \ldots p_0 \tag{15}$$

where R_1^p contains the discrete values of the plane wave spectrum of the following electromagnetic wave in the z=0 plane:

$$\begin{aligned} E_p(x) = {} & \frac{k^p_{\alpha,1} - k^p_{\alpha,2}}{k^p_{\alpha,1} + k^p_{\alpha,2}} \cdot \\ & \cdot \exp\{-2 \cdot j \cdot (k^p_{z,1} \cdot \sin^2\alpha + p \cdot k_{x0} \cdot \sin\alpha \cdot \cos\alpha) \cdot z_0\} \\ & \cdot \exp\{j[k^p_{z,1} \cdot \sin(2\cdot\alpha) + p \cdot k_{x0} \cdot \cos(2\cdot\alpha)] \cdot x\} \end{aligned} \tag{16}$$

where

$$k^p_{\alpha,s} = k^{p,0}_{z,s} \sin\alpha + p \cdot k_{x0} \cdot \alpha \quad (p = 0, 1, \ldots p_0;\ s = 1, 2)$$

$k^{p,0}_{z,s}$ is defined in (7)and α is the angle of the tilted layer. $\Delta n_r \ll \Delta n_c$, and subsequently, the homogeneous approximation is used for the calculations.

Considering that $\mathbf{P}_0=\mathbf{I}$ and using equation (14), $\mathbf{R}_0$ can be determined. When the arrangement shown in Fig. 4 is investigated, the space window has to be chosen to fulfill the following additional requirement: $l_x < 2 \cdot z_0 \cdot \tan\alpha$. In this example, 128 points were again used for the discrete representation, and the space window was 12.8 μm. The calculation process being fast enough, a simple optimizing procedure was used to find the optimal thickness and refractive index of the tilted antireflection coating. The Downhill simplex method in two dimensions [10] was used for the minimization of modal reflections.

The dependence of the modal reflectance versus the angle of the tilted layer is shown in Fig. 5. Fig. 6 shows the modal reflectance vs. the wavelength of light for tilted layers with different angles.

4. CONCLUSION

A method is presented for the analysis of the reflected field supplied by an optical waveguide ending that is separated by a layered medium from a three-dimensional object. The method is based on the representation of the electromagnetic field as a superposition of TE and TM plane waves. The electromagnetic wave propagating in the waveguide is assumed to be given. Formulas are presented giving the relation between this arbitrary wave and its TE and TM plane wave spectrum. For further calculations, the discrete approximation of the spectrum is used, and the propagation of plane wave components are analyzed. If the electromagnetic field, reflected by the three-dimensional object, can be given for each plane wave component of the waveguide, the relation between the electromagnetic wave supplied by the waveguide and the reflected field is given by a linear equation system. The modal reflectance is calculated using the orthogonality of the waveguide modes.

Two-dimensional examples are also presented. The first example is for the estimation of the error caused by the homogeneous approximation of the waveguide in the reflectance calculus. In the second example, the reflectance of tilted antireflection coatings is calculated.

5. ACKNOWLEDGMENT

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REFERENCES

[1] M. Serenyi H., U. Habermeier, "Directly controlled deposition of antireflection coatings for semiconductor lasers", *Appl, Opt.* 26 (1987), 845

[2] E. Marcaly, D. J. Webb, P. Buchmann and P. Vetiger, "Stepwise-graded-index multilayer broadband low-reflectivity coating for AlGaAs/GaAs power lasers", *Appl. Phys. Lett.*, 55(10) (1989), 942—944

[3] G. Eisenstein, "Theoretical design of single-layer antireflection coatings on laser facets", *AT&T Bell Lab. Techn. J.*, 63 (1984), 357—364

[4] R. H. Clarke, "Theory of reflection from antireflection coatings", *AT&T Bell Lab. Techn. J.*, 62(1983), 2885—2891

[5] M. C. Farries, J. Buus and D. J. Robbins, On angled semiconductor laser amplifiers", *Electron. Lett.*, 26(1990), 381—382

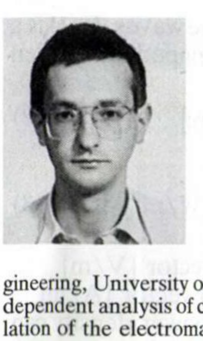
[6] D. Marcuse "Reflection loss of laser mode from tilted end mirror", *J. Lightwave Technol.*, LT-7(1989), 336—339

[7] L. Atternas and L. Thylen, "Single-layer antireflection coating of semiconductor lasers: polarization properties and the influence of the laser structure", *J. Lightwave Technol.*, LT-7(1989), 426—430

[8] H. A. Haus, *Waves and fields in optoelectronics* (Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1984)

[9] J. Pávó, "Transient analysis of lossy transmission line system by discrete Fourier transform", *Periodica Poltechnica Ser. El. Eng.*, 33(1989), 117—134

[10] W. H. Press, B. P. Flannery, S. A. Teukolsky and W. T. Vetterling, *Numerical recipes in C,* (Cambridge University Press, Cambridge, 1988)



József Pávó graduated from the Department of Telecommunication of the Faculty of Electrical Engineering, Technical University of Budapest in 1987. From 1987 until 1990, he was employed by the Hungarian Academy of Sciences. During this period, his research took place at the Department of Electromagnetic Theory of the Technical University of Budapest. From 1990 to 1991, he was an assistant at the same department. Since October 1991, he has been with the Department of Nuclear Engineering, University of Tokyo. His research interests include the time dependent analysis of coupled transmission line systems and the calculation of the electromagnetic field in integrated optical network elements.

POWER DENSITY METER

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This paper presents a power density meter developed by the Department of Microwave Telecommunications of the Technical University of Budapest, and deals with both the theoretical and developmental aspects of this instrument.

1. INTRODUCTION

In the past ten years, equipments utilising the thermal effect of microwave radiation (microwave ovens, industrial heaters and dryers) have been istalled in Hungary. Most of them operate at 2450 MHz, and their RF power range is between 500 watts and some kilowatts. In general, because of their imperfect shielding, the microwave radiation in the vicinity of these equipments may be hazardous to the operating persons.

When characterizing hazardous electromagnetic fields, a distinction should be made between emission levels and exposure levels. In most cases where an emission standard is applied, the sources of radiations are small apertures, giving rise, for example, to leakage around the periphery of a microwave oven door. In this case, the intensity of the radiated power emission will be approximately inversely proportional to the squared distance from the source. However this rapid decay of emission may not be applicable to exposure levels near a typical microwave oven, if the leakege is due to a large radiating aperture, for example the viewing window. In general, the potential level of exposure to personnel will not be equivalent to the emission level.

The Hungarian National Standard MSZ 22013/1, similarly to the IEC standard 325-25/1976, allows an emission level of 5 mW/cm^2 at a distance of 5 cm from the surface of a microwave oven.

Safety levels with respect to human exposure to RF electromagnetic fields significantly differ from each other in individual countries [1]. For example the Hungarian National Standard MSZ 16260-86 allows a value of 10 μW/cm^2 for the power density in the safety zone for a fixed source of radiation, while this value in the American National Standard ANSI C.95. 1-1982 is 5 mW/cm^2 in the frequency range of 1.5 GHz to 100 GHz.

The effects of RF fields on biological systems depend on the differential rate of energy deposition, hence modern RF exposure standards are expressed in terms of specific absorption rate (SAR), i.e the power absorbed per unit mass. The International Radiation Protection Association (IRPA) recommends an exposure limit of 0.4 W/kg for frequencies above 10 MHz when averaged over any 6 minutes over the whole body. This limit, expressed in terms of equivalent plane wave power density, is 5 mW/cm^2.

In general, the upper end of the most sensitive measurement range of commercial power density meters is about 0.2 mW/cm^2. These power density meters can measure the value of 10 μW/cm^2 only with a very large uncertainty so a more sensitive power density meter has been developed.

2. MEASUREMENT PROBLEMS OF HAZARDOUS RF RADIATON

Radiation leakage from microwave equipment presents special problems because the source of energy may not be clearly defined. The polarization of the electromagnetic field and the location of the leak are not generally known and can only be found by trial and error. Radiation leakage is usually measured in the near field region.

In general, the near fields of RF sources comprise both reactive and radiation components. These components will exhibit both temporal and spatial variations which will depend on the type of the radiation source and the physical environment.

In the region immediately surrounding the equipment, reactive components of the field predominate over the radiating near field and far field components. Although the reactive components do not contribute to the net flow of radiated energy they can still affect energy absorption.

Multipath interference due to the reflection and scattering of energy from other objects or surfaces is an additional complicating factor, and is nearly always present to some degree. Multipath interference can also affect the field polarization.

Because of above mentioned effects, several measurements carried out carefully are needed to obtain sufficient information on the temporal and spatial variations of the electromagnetic field. However, the radiation monitor immersed into the field to be measured and the monitoring personnel will perturb the electromagnetic field.

In the near field, there are no plane waves, so the the power density is difficult to evaluate. In fact, no existing instrument actually measures power density directly, they all measure one or more components of the electrical field or magnetic field, or both, and then infer the power density from the far field plane wave relationship. This is the so called equivalent plane wave power density.

3. RELATIONSHIP BETWEEN E, H AND POWER DENSITY

The power density is the magnitude of the Poynting vector:

$$S = EH \quad [\mathrm{W/m^2}] \tag{1}$$

Taking into account that in case of plane waves, E/H is a constant (the free-space characteristic impedance) given by

$$\eta = E/H = 120\pi \quad [\mathrm{Ohm}] \tag{2}$$

expression (1) can be written as

$$S = E^2/\eta \quad \text{or} \quad S = \eta H^2 \quad [\mathrm{W/m^2}] \tag{3}$$

where

E—magnitude of the electric field vector [V/m]

H—magnitude of the magnetic field vector [A/m]

In case of plane wave propagation, power density can be calculated from E^2 or H^2 in a very simple manner.

4. PRINCIPLE OF POWER DENSITY METERS

As may be seen from Eqs. (1) and (3), there are three possibilities for the determination of power density: jointly from E and H (the measuring antenna is an aperture antenna), from only E or only H (the measuring antenna is a small dipole or loop). In all the three cases, a square law detector or power sensor is needed.

Power sensors utilize either thermosensitive elements (bolometric, thermometric devices) or semiconductor diodes. Thermosensitive elements are used as loads of measuring antennas or, in some cases, the electromagnetic wave impinges directly on the thermosensitive device. In both cases, a thermal conversion of electromagnetic energy takes place, and the true RMS value is measured. But this transfer is intrinsically slow, the time constant being some seconds. The point contact diodes and the low barrier Shottky (zero bias Shottky) diodes are applicable as power sensors in the square law region of their I vs V characteristic because they have low forward voltage. The square law region is limited by the tangential sensitivity of the diode (tipically −55 dBm) and the transition between square and linear law region (tipically −20 dBm).

Chosen the diode as power sensor, it can be shown that in case of an input RF power close to the tangential sensitivity the detected voltage will be some times ten μV. However, offset, drift and noise problems will arise in the amplification of low DC voltages. To solve these problems, AC amplifiers have to be used instead of DC amplifiers. To obtain an AC voltage, either the DC voltage or the RF voltage has to be chopped as can be seen in Fig. 1. Chopping the DC voltage is simpler and cheaper, because availability of choppers in integrated circuit form.

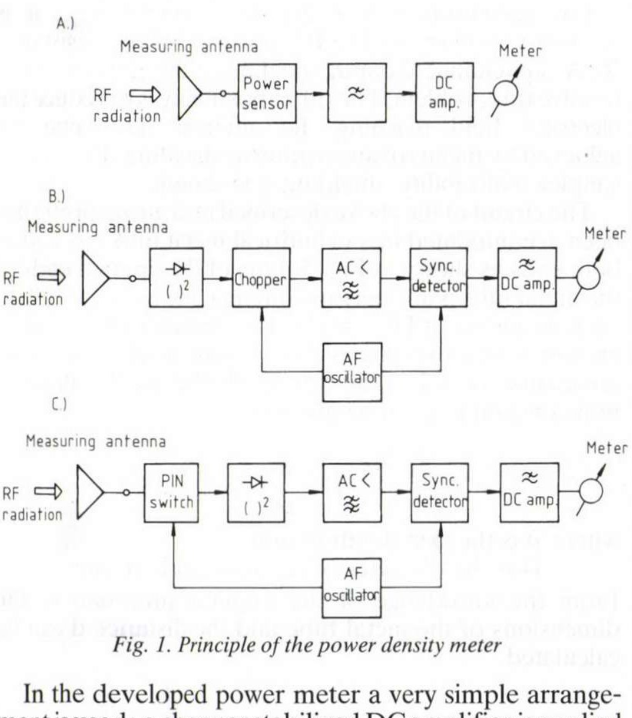


Fig. 1. Principle of the power density meter

In the developed power meter a very simple arrangement is used: a chopper stabilized DC amplifier is applied in the measuring probe, working as preamplifier.

5. DESCRIPTION OF THE DEVELOPED POWER METERS

The first developed power density meter has been used for the measuring the radiation of microwave ovens, as commissioned by the Hungarian Institute of Commercial Quality Control (KERMI). This power density meter consists of an aperture antenna made of an open ended R32 type waveguide, wo calibrated attenuators (30 dB and 50 dB), a power measuring head with four point contact diodes operating in the square law region, a low-noise preamplifier, and a signal processing unit with the meter. Main technical data: power density range of 3.16 nW/cm^2 to 100 mW/cm^2, accuracy of measurement ± 0.8 dB in the frequency band 2415 MHz to 2485 MHz. Its main disadvantage is the large weight of the antenna, attenuator and the power measuring head.

The new power density meter developed in 1990 eliminates the above disadvantage: it has light-weight measuring probes, each of them functioning as an electrical field sensor.

5.1. Measuring Probe

A) Measuring probe with single dipole antenna

Fig. 2 shows the shematic of the measuring probe. In case of a continuous-wave incident electrical field parallel to the dipole, the received voltage U_r will be given by

$$U_r = EL_{\text{eff}} \tag{4}$$

where

$$L_{\text{eff}} = 2l\frac{1-\cos\beta l}{\beta l \sin\beta l} \tag{5}$$

is the effective length of the dipole, and $\beta = 2\pi/\lambda$

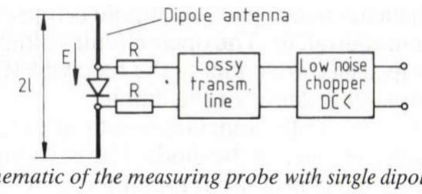


Fig. 2. Shematic of the measuring probe with single dipole antenna

When the diode is operating in its square law region, a direct current component is also present, in addition to fundamental and harmonic components. This current is passed through the low-pass filter formed by the lossy transmission line to the chopper stabilized preamplifier. Thus the output signal of the preamplifier is proportional to the square of the received RF voltage, i. e. proportional to the power density. The lossy transmission line consisting of discrete resistors reduces the signal received directly by the line and transmitted to the diode. Additionally, it reduces the scattering of the incident field by the transmission line. The values of resistances of the lossy transmission line are decreased gradually towards the preamplifier. The highest two resistances nearest the diode are shown separately in Fig. 2.

Design features of the measuring head:

- application of an electrically and physically small antenna,
- choice of an LBS diode with wide dinamic range and low temperature dependence,
- choice of a lossy transmission line with a minimum value of the resistances providing an acceptable scattering of the incident field and a sufficiently low noise level,
- choice of a preamplifier having low noise, drift and offset.

If the half length of the dipole is smaller than $\lambda/10$, the frequency dependence of the effective length will be negligible. From equation (5), $L_{\text{eff}} = l$, so the received voltage is given by

$$U_r = El \tag{6}$$

The input impedance of the electrically short dipole is approximately capacitive [4]:

$$Z_A = R_A - j\frac{1}{\omega C_A} \approx -j\frac{1}{\omega C_A} \qquad (7)$$

Choice of a small dipole is also of advantage because it provides high spatial resolution of the field and because it receives lower RF voltage for a given power density. There is a practical limit in the reduction of the dipole length. Generally, the half length of the dipole is chosen to be equal to or larger than two times the length of the diode case. In case of l=10 mm, both conditions are satisfied.

The response of the measuring probe (the ratio of the output voltage to the power density as function of frequency) may be determined from the equivalent circuit shown in Fig. 3.

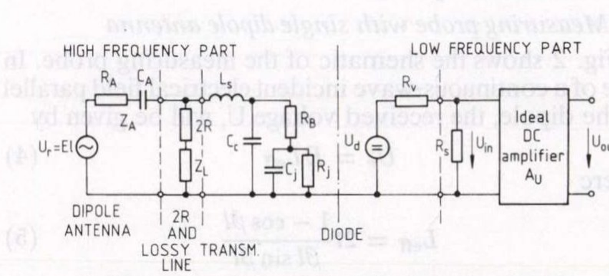


Fig. 3. Equivalent circuit of the measuring probe

In the high frequency part, the dipole is represented by its Thevenin equivalent. The open-circuit voltage and the internal impedance are equal to the received RF voltage and the input impedance of the dipole.

R_j, C_j and R_B are the junction resistance, capacitance and the bulk resistance of the diode. The case capacitance and the lead inductance are represented by C_c and L_s.

The input impedance of the lossy transmission line is Z_L. This impedance, in series with resistance 2R, appears across the diode. The role of these discrete resistors is to isolate Z_L from the diode. At high frequencies, Z_L represents a low impedance.

In the low frequency part, the diode is modelled by the voltage source in series with the video resistance R_V:

$$U_d = \gamma_0 P_j \qquad (8)$$

where γ_o is the voltage sensitivity at low RF frequencies and P_j is the time average of the high frequency power absorbed by the junction resistance R_j of the diode. The resistane R_s is the sum of two resistors nearest the diode, the resistors of the lossy transmission line and the input resistance of the preamplifier.

The element values used for the design of the measuring probe are summarized in Table 1.

Table 1. Parameters of the developed measuring probe

l	mm	10	
R_A	ohm	10	DIPOLE ANTENNA
C_A	pF	0.162	
R	kohm	1	RESISTOR
L_s	nH	3.6	
C_c	pF	0.06	
R_B	ohm	9.5	ZERO BIAS
R_j	kohm	.75	SHOTTKY DIODE
C_j	pF	0.15	(HP HSCH 3486)
γ_o	mV/μW	53	
R_V	kohm	2.75	

At the operating frequency, some of the elements in the equivalent circuit may be omitted (R_A, 2R, L_s, C_c and R_B). The equivalent circuit without these elements is shown in Fig. 4.

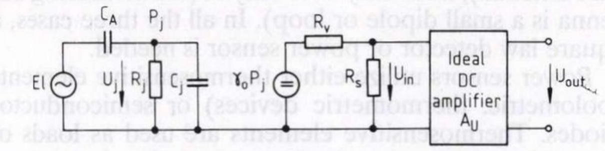


Fig. 4. Simplified equivalent circuit

Based on the simplified equivalent circuit and using equations (3) to (8), the response of the measuring probe is given by

$$U_{out} \approx \gamma_0 \frac{\eta S l^2}{R_j} \frac{(\omega R_j C_A)^2}{1+[\omega R_j (C_A + C_j)]^2} \frac{R_v A_u}{R_v + R_s} \qquad (9)$$

The frequency dependence of the output signal is ±0.01 dB in the frequency band of 2450 MHz ± 500 MHz. Eq. (9) is not valid if P_j is higher than −20 dBm, so it is necessary to determine the power density corresponding to this limit value. The relationship between P_j and S is given by

$$S = P_j \frac{R_j}{\eta l^2} \frac{1+[\omega R_j (C_A + C_j)]^2}{(\omega R_j C_A)^2} \qquad (10)$$

Substituting P_{jmax} = 0.01 mW and the circuit element values into Eq. (10) results in a maximum power density of S_{max} = 276.7 μW/cm^2. From the dynamic range of 35 dB, the maximum power density is calculated to be 87.5 nW/cm^2.

For measuring power densities beyond S_{max}, it is necessary to decrease the RF power reaching resistance R_j. A capacitance shunting the diode is the generally used to solve this problem. The other possibility is to reduce the electrical field reaching the antenna. This may be achieved by means of absorption or shielding. Because of simpler realizability, shielding was chosen.

The circuit of the above described measuring probe has been accomodated in a cylindrical metal tube opened at both ends as shown in Fig. 5. One of the opened ends of the metal tube is an aperture antenna, the incident E field exciting a wave in TE_{11} mode. The diameter of the tube is chosen so that the tube as a waveguide works as a cutoff attenuator. Based on the waveguide theory, the attenuation constant (α) can be given by

$$\alpha = \frac{31.984}{D}\left(1 - \frac{\delta}{D}\right) \quad [\text{dB/mm}] \qquad (11)$$

where δ is the skin depth in mm,

D is the diameter of the waveguide in mm.

From the knowledge of the required attenuation, the dimensions of the metal tube and the distance d can be calculated.

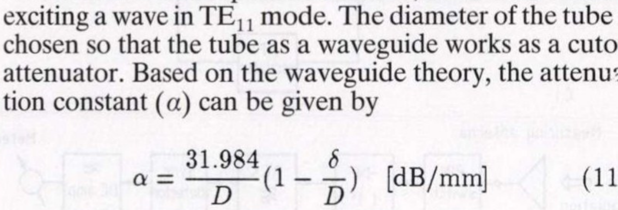


Fig. 5. Shematic drawing of the measuring head placed inside a metal tube

The measuring probe with a single diode was designed by utilizing the above considerations. It has a power density range of 10 $\mu W/cm^2$ to 10 mW/cm^2, an output voltage of 1 V for 10 mW/cm^2, and a frequency band of 2450 MHz ± 100 MHz. The accuracy of measurement of the power density is ± 0.8 dB, including the indicator.

B) Measuring probe with two dipole antennas

It may be convenient not to rotate the dipole antennas during the measurement of power density. This requirement may be satisfied by using a measuring probe comprising two perpendicular dipole antennas.

The shematic drawing of this measuring probe is shown in Fig. 6. The operation may be understood by referring to the probe with single dipole antenna. If the diodes operate in the square law region of their characteristics, the currents of the diodes have DC components proportional to E_x^2 and E_y^2. These currents flow through the input resistance of the preamplifier and produce an input voltage proportional to the sum of E_x^2 and E_y^2. Hence the output voltage is proportional to the power density.

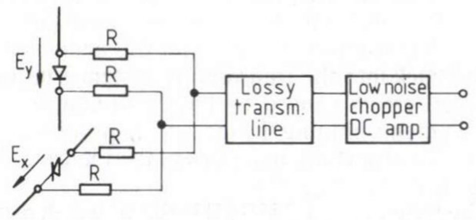


Fig. 6. Measuring head with two dipole antennas

Following additional requirements had to be satisfied in the design stage of the two-dipole antenna:

- to apply two antennas with identical geometrical dimensions,
- to insure that the axis of the two dipole antennas be exactly perpendicular to each other,
- to use two diodes with identical electrical and geometrical parameters,
- to insure that the two connecting resistor pairs be identical,
- to minimize the ovality of the shielding tube.

Any departure from the above ideal conditions results in a smaller crosspolarization attenuation and the measured value of the power density will change with the rotation of the measuring probe for a constant, linearly polarized electrical field. This change is less than ± 0.3 dB for the realized measuring probe, and the rest of the electrical parameters are identical with those of the measuring probe with a single dipole antenna.

5.2. Metering Assembly

The block diagram of the metering assembly, together with the measuring probe and power supply adapter, is shown in Fig. 7. It consists of three functional parts: DC amplifier with the meter, comparators with light emitting diodes, power supply with charger for storage batteries.

The main part of the metering assembly is the DC amplifier with the meter. This part comprises a low noise, band limited amplifier, range switch, integrating amplifier and indicator. The input voltage range is 60 dB (1 mV to 1 V), corresponding to the power density range from 10 $\mu W/cm^2$ to 10 mW/cm^2. The output voltage is 3 V at full meter deflection.

The first stage is an active low-pass filter with a cutoff frequency of 10 Hz and with an amplification of 10 dB.

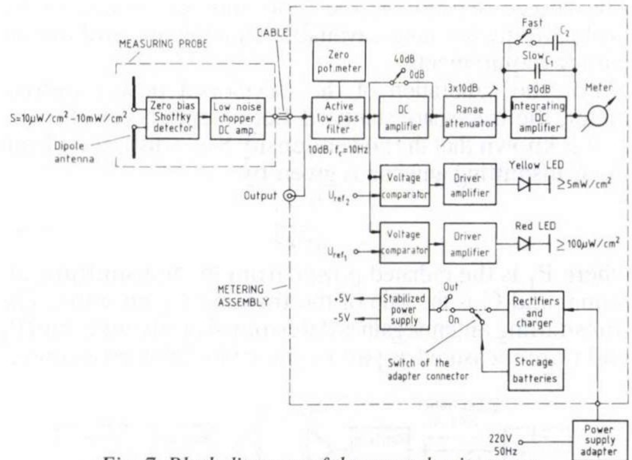


Fig. 7. Block diagram of the power density meter

The next stage has an amplification of 0 dB or 40 dB depending on the the input voltage. If the input voltage is lower than or equal to 10 mV, its amplification is 40 dB (the switch connected in parallel to the DC amplifier is linked to the range switch). The range attenuator has attenuations of 0 dB, 10 dB, 20 dB or 30 dB. The integrating DC amplifier has an amplification of 30 dB, and the time constant of the integration can be switch-selected to be either about 20 msec or 1 sec.

Each of the comparators activates light emitting diodes (LED). A red LED is turned on as soon as the power density exceeds 100 $\mu W/cm^2$. This limit value is declared to be a hazardous exposure level in MSZ 16260-86. A yellow LED is turned on at power densities exceeding 5 mW/cm^2.

The power supply provides a stabilized DC voltage of ± 5 V for the circuits of the instruments. The power supply is fed from two storage batteries (each 9 V, 100 mAh) or from the rectifiers. The charger charges the storage batteries with a constant current of 10 mA. The rectifiers are fed from the power supply adapter with an AC voltage of $2 \times 10.5\ V_{eff}$.

The photograph of the developed power density meter is shown in Fig. 8.

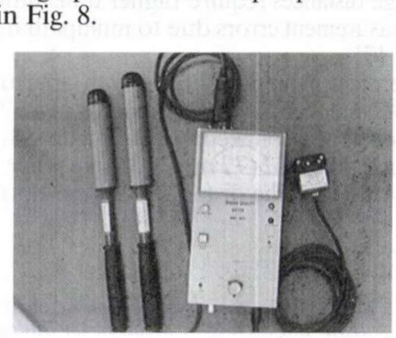


Fig. 8. Photograph of the power density meter

6. CALIBRATION

Existing calibration methods are based on the assumption that a known field strength can be established through measurement, calculation, or a combination of both. The power density meter to be calibrated is then placed in this known field, and the meter indication is compared with the known field value.

There are three basic methods of producing the standard field:

- free-space standard-field method,
- guided wave method (for example the Crawford cell),
- transfer-standard or standard-antenna method.

The choice depends on the type and size of measuring probe, frequency range, available equipments, and the accuracy requirements.

For the calibration of the developed power density meter, the free-space standard-field method was chosen.

It is known that the power density S at a distance r from the transmitting antenna is given by

$$S = \frac{P_T G}{4\pi r^2} \tag{12}$$

where P_T is the radiated power from the transmitting antenna, and G is the gain of the transmitting antenna. The transmitting antenna gain is determined in advance, and P_T and r are measured as part of the calibration procedure.

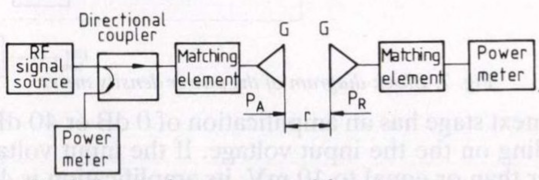


Fig. 9. Principal arrangement of the gain measurement

The antenna gain was measured by using the so-called two-antenna method (Fig. 9). The dimensions of the transmitting and receiving antennas are identical, hence their gains are equal.

The gain of the probe antenna can then be calculated by the equation

$$G = 10 \lg \frac{4\pi r}{\lambda} \quad 5 \lg \frac{P_T}{P_R} \quad [\mathrm{dB}] \tag{13}$$

where

r is the distance between antennas,

λ is the free-space wavelength,

P_T is the radiated power from the transmitting antenna. The accuracy of the determination of antenna gain is a function of the distance. The gain approaches a constant G_o as r approaches infinity, that is, G_o is the far-field gain. The gain reduction factor is -0.5 dB if $r = 2a^2/\lambda$, and only -0.1 dB if $r = 8a^2/\lambda$, where a is the aperture dimension [6]. In case of large distances, G approximates the far-field gain G_o, but large distances require higher transmitter powers, and the measurement errors due to multipath interference are greater [7].

Two identical pyramidal horns with aperture dimensions of 245 mm × 162 mm and lengths of 267 mm have been applied. Their connecting waveguide is a rectangular waveguide type R 32 (72 mm × 34 mm). The calculated gain was 14 dB, and the distance between horn antennas

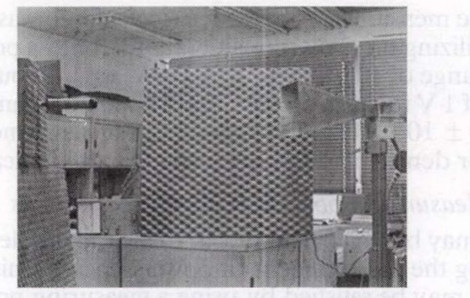


Fig. 10. Calibration of the power density meter

was 1.5 m. The measured gain was 13.83 dB at a frequency 2450 MHz. The frequency dependence of the gain is of ± 0.08 dB in the frequency band of 2450 MHz ± 100 MHz. One of the pyramidal horns was applied for the calibration of the power density meter. The photograph of the calibration set-up is shown in Fig. 10.

The calibration was achieved in the previously mentioned frequency band at a power density of 100 μW/cm^2. The required distance between the pyramidal horn and the aperture of measuring probe of the power density meter is 98 cm at $P_T = 500$ mW. In the case of this distance and the aperture dimension of D = 28 mm, the amount of energy reflected back into the transmitting system is insignificant. Additional errors caused by backscattering from cables and equipments holding the measuring probe was reduced by means of absorbing materials placed in front of all reflecting items (see Fig. 10).

At the frequency of 2450 MHz the power density meter was adjusted to 100 μW/cm^2 by means of adjusting the distance d at the measuring probe. Frequency dependence of the indicated power density is ± 0.3 dB in the frequency band of 2450 MHz ± 100 MHz.

Calibration of the power density meter was controlled by means of a NARDA radiation monitor of model 8321 (transfer standard method). Depature of the measured values was smaller than 0.4 dB in the previously mentioned frequency band.

7. CONCLUSION

Theoretical and experimental aspects of a power density meter have been discussed. It has been shown that the main characteristics of a power density meter are basically determined by the measuring probe. Two different types of measuring probes designed on the basis of this theory have been presented. In addition to the design aspects of measuring probes and the description of the power density meter, its calibration procedure has also been described.

REFERENCES

[1] Repacholi, M. H., "Radio frequency electromagnetic field exposure standards." *IEEE Engineering in Medicine an Biology Magazine,* March 1987. pp. 18—21.

[2] Gandhi, Om P., "The ANSI radio frequency safety standard: its rationale and some problems." *IEEE Engineering in Medicine and Biology Magazine,* March 1987. pp. 22—25.

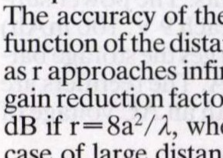
[3] Safety levels of high frequency electromagnetic fields, Hungarian National Standard, MSZ 16260-86.

[4] Smith, G. S., "Limitations on the size of miniature electric-field probes." *IEEE Trans. on MTT,* June 1984. pp. 594—600.

[5] Kanda, M. and Driver, L. D., "An isotropic, electric field probe with tapered resistive dipoles for broadband use, 100 kHz — 18 GHz." *IEEE EMC Conference,* pp. 256—261.

[6] Bassen, H. I. and Herman, W. A., "Precise calibration of plane-wave microwave power density using power equation techniques." *IEEE Trans. on MTT,* August 1977. pp. 701—706.

[7] Jull, E. W., "Finite-range gain of sectorial and pyramidal horns." *Electronic Letters,* October 15. 1970. pp. 680—681.



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His research subjects in addition to high frequency measuring techniques are techology of high frequency circuits, CATV systems, measurement of semiconductor parameters in the microwave band, measurement of hazardous microwave radiations.

RECOGNITION OF PRINTED MULTIFONT CHARACTERS BASED ON A NEURAL NETWORK ARCHITECTURE

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A simple neural network capable of high speed recognition of two dimensional patterns is described. Based on this architecture, computer simulation of a new generation optical character reader (OCR) is presented.

1. INTRODUCTION

Real time optical pattern recognition (OCR) devices would find many applications e.g. in paperless offices and desktop publishing. Present systems read approximately 200 characters in a second that takes about half a minute to process one page. Traditional recognition algorithms like contour analysis [1], [2], statistical methods, etc. use several features to describe and distinguish the incoming patterns. The recognition time strongly depends on the quality of the test and the number of patterns contained in the data base. To fulfill the requirements for a faster (500 cps) and accurate ((99,99%) device a new architecture is needed. In the last decades, several neural models were developed to solve pattern recognition tasks [3].

In this paper the computer simulation of a neural network based OCR system, capable of robust reading of poor quality texts at a high speed, is presented. Section 2 describes the overall methodology. In Section 3 and 4, results and conclusions are presented.

2. METHODOLOGY

Neural networks are mathematical models based on our present understanding of biological nervous systems. They have some special characteristics, like *associativity, generalization, fault tolerance, adaptibility* and *learning,* which make them desirable for pattern recognition. Nevertheless, practical limitations arise due to huge computational power needed for the simulation of densely interconnected real systems. The goal of this work is to reduce the number of steps executed by a computer in order to find the correct classification for an incoming pattern. After performing classical preprocessing steps, like position and size normalization, the pattern is processed by a heteroassociative neural network.

The main features of the network are the following:

- The proposed net contains as few interconnections as possible.
- To solve the problem of convergence and prescribed settling time, the architecture is feedforward.
- In order to achieve high speed mapping, two state neurons are used.

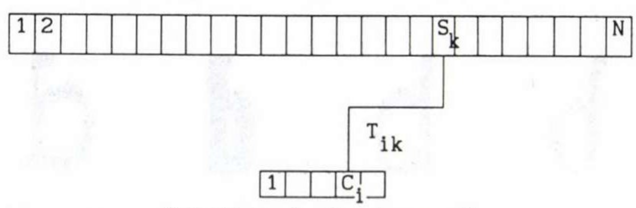


Fig. 1. Network structure

The operation of the system shown in Fig. 1 can be described by :

$$C_i = \mathrm{sign}\Big(\sum_{k=1}^{N} T_{ik} * S_k \Big)$$

where **S, C** and **T** are the pattern vector, the code vector and the weighted interconnection matrix, respectively ($S_k = \pm 1$, $C_i = \pm 1$).

A certain input pattern is assigned to a code defined earlier during the learning process. Each codebit can be computed independently. Due to the structure of this model $N * \log_2 P$ additions are needed to recognize the stored patterns.

In the experiments a resolution of N=20 * 20 neuros was used. To store P=26 English lowercase letters the network contains C=5 codebits. During the relaxation process the system executes 2000 additions. In comparison, a Hopfield net of the same number of neurons would contain *160 000* interconnections.

3. RESULTS

As the input patterns are highly correlated the network was trained using iterative learning rules [4], [5]. The training set contained 12 noisy versions for each letter of 3 different font styles. The 12 noisy versions were produced from 4 scanned samples using a contour noise superposition method. During the learning process each bit had a zero threshold. To improve the recognition rate, an additional threshold modification mechanism was proposed. In the second phase, numbers of noisy versions of known patterns were shown to the network. When the classification was not correct the threshold of wrong code neurons was modified according to the error. The system was tested on scanned versions of texts. Retrieval errors were about 1%.

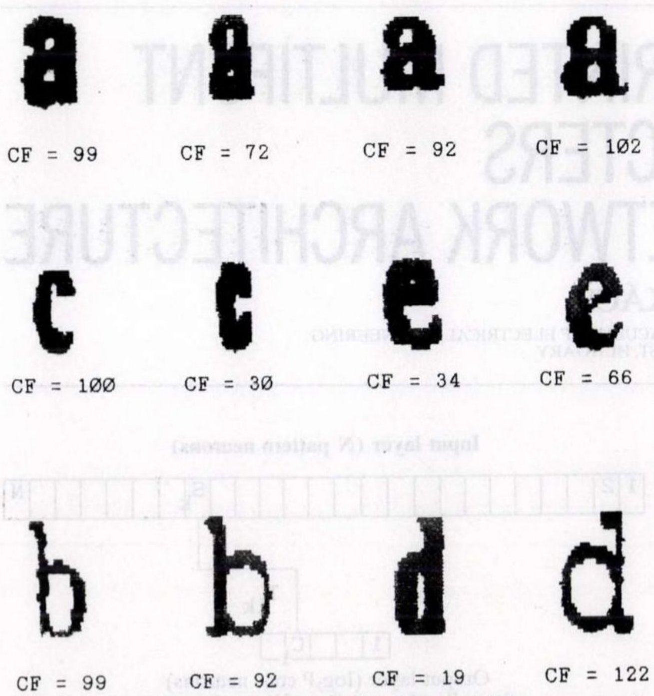


Fig. 2. Correctly recognized poor quality letters with the corresponding confidence values

REFERENCES

[1] Fu, K. S., *Syntactic Pattern Recognition and Applications* Prentice-Hall, 1982.

[2] Kahan, S., Pavlidis, T. and Baird, H. S. "On the Recognition of Printed Characters of Any Font and Size", *IEEE PAMI-9* no.2, pp. 274—286.

[3] Lippmann, R. P., "An Introduction to Computing with Neural Nets", *IEEE ASSP,* Apr. 1987, pp. 4—22.

Barnabás Takács was born in Budapest in 1966. He graduated in electrical engineering and computer science at the Technical University of Budapest in 1991. Now he is with the European section of the University of Houston (Texas, USA) earning a master's degree in computer science. He is interested in neural networks and pattern recognition, and is a holder of the ,Foundation for Hungarian Technical Progress' award. His work on a neural network based optical character reader was first presented at the Scientific Student Conference 1990 of the Technical University of Budapest.

Based on the local stability of the code neurons the program produces a confidence value. The highest the confidence the safer the correct classification. Fig. 2 shows some examples for correctly classified poor quality letters indicating the confidence value (CF).

4. CONCLUSION

A neural network capable of handling poor quality texts using minimum recognition time has been developed using computer simulation. The recognition speed is independent of the number of patterns stored in the network. The learning process being supervised, the overall performance of the net is strongly affected by proper code selection. Recognition rate can be improved by training with noise. Multifont recognition can be achieved using a training set of several font styles.

The average overlap of the letters is about 70%, thus pattern recognition is a hard task for this network architecture. To improve the performance of the structure, the possibilities to use the net itself in finding an optimal code set and a hierarchical classification method is now under investigation.

[4] Diederich, S. and Opper, M., "Learning of Correlated Patterns in Spin-Glass Networks by Local Learning Rules", *Phys, Rev. Lett.* vol. 58. no.9, 2nd March 1987, pp. 949—952.

[5] Krauth, W. and Mezard, A., "Learning Algorithms with Optimal Stability in Neural Networks", *J. Physics A. Math. Gen.* 20. 1987, L745—L752.

OPTOELECTRONICS R&D FOR COMMUNICATION AND INFORMATION TECHNOLOGY

Communication Technology

Systems

RF acousto-optic Fourier processors:
- power spectrum analysers
- interferometric spectrum analysers
- scanning spectrum analysers
- five channel power spectrum analyser

Acoustooptic spectrofotometer

Elements

Acousto-optic elements:
- deflectors (1D,2D)
- modulators
- Q-switches
- mode lockers
- tunable filters
- Bragg cells

Surface acoustic wave elements:
- filters
- despersive delay lines

Integrated optical elements:
- 10 Bragg cells

Information Technology

Systems

CD optical pick-up
Optical storage system
(capacity: 2 GByte)

Elements

Plastic precision aspheric lenses
Cube beam splitters
Diffractive optical elements
Diffraction limited
collimators and objectives
Polarizing cube beam splitters
Magnetooptical disk
(capacity: 625 MBytes,
ISO standard)

Examples

Optical signal processing

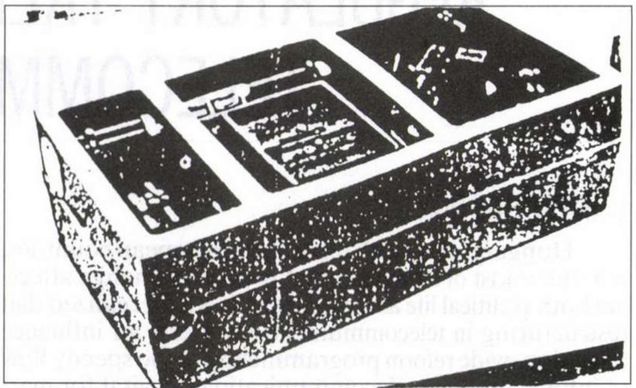


Fig. 1. Acousto-optic radio frequency spectrum analyser

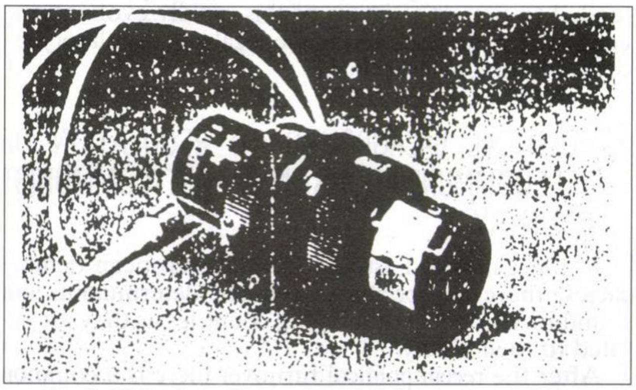


Fig. 2. Eight channel acousto-optic light intensity modulator

Optical data storage

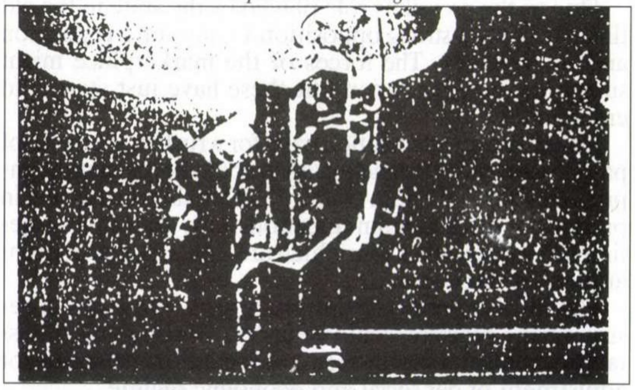


Fig. 3. MO read—write optical head

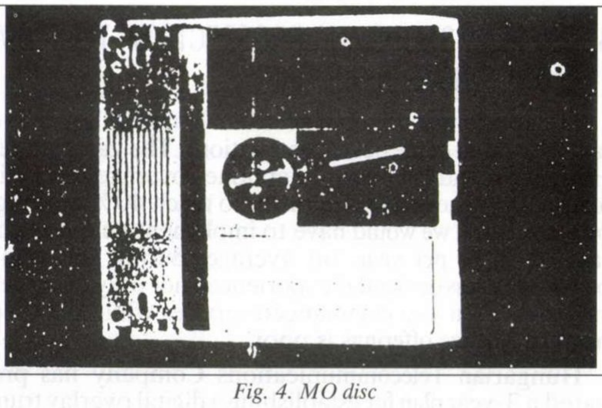


Fig. 4. MO disc

Department of Atomic Physics,
Technical University Budapest

REGULATORY TRENDS IN HUNGARIAN TELECOMMUNICATIONS

1. INTRODUCTION

Hungary, along with other East European countries, is in the midst of a fundamental process of change affecting both political life and economy. It is now realized that restructuring in telecommunications exerts an influence on nation-wide reform programmes since the speedy flow of information, via telecommunications, is vital for markets and democracy to function. In this report, it is intended to present a picture of this rapidly evolving and complex process as it affects the legal and regulatory aspects of telecommunications.

2. POLITICAL BACKGROUND TO REGULATION OF TELECOMMUNICATIONS IN A POST-COMMUNIST COUNTRY

In the emerging East and Central European democracies, there are specific forces and determinants not found in Western or developing countries as they are related to their history.

After the recent political turnover there is a common agreement between almost all forces, people and parties in favour of the removal of old things, laws, institutions, etc. although there is far less agreement on the nature and direction of these supposedly radical changes.

Due to the prevailing role played by the state in the old times there is a strong opposition to any state regulation and intervention. The forces of the marketplace might substitute state regulation but these have just started to emerge.

The fast pace of evolution calls for a rush in the work of parliament which is enacting an amount of legislation unprecedented in Western countries. This also means that in preparing the telecommunications law, one has sometimes to rely on other laws which are similarly under preparation or discussion.

Having European legislation in view, the pace of restructuring processes could be faster, assisting thus the establishment of a comprehensive legal infrastructure for adjustment of our social and economic regime.

3. PRESENT STATUS AND PROSPECTS OF TELECOMMUNICATIONS IN HUNGARY

The telecommunications sector in Hungary is at a level far below that of the developed nations. The gap between Hungarian and European telephone coverage can be illustrated by the fact that in order to reach 40% coverage by year 2000, we would have to implement an expansion rate of 20% per year, on average, during the whole period. Excess demand is experienced not only in universal service but also in enhanced services while the spectrum of service offerings is poor.

Hungarian Telecommunications Company has prepared a 3-year plan for establishing a digital overlay trunk network and increasing the number of main lines by about 50%. The necessary pace of upgrading the network can be financed only by heavily relying on external resources (loans and privatisation) since the national budget is exhausted. It will call for a specific evolutionary path with regard to both finance and institutions.

Pressure coming from local governments, would-be foreign investors and the business sector for the enhancement of the telecommunications network, and dissatisfaction with a monopolistic service provider which is insensitive to their needs, are shooting up to the political arena.

4. LEGAL BACKGROUND TO THE TELECOMMUNICATION REGULATORY REGIME IN HUNGARY

It is stated in the Hungarian Constitution that basic rights and duties can be imposed only by the force of laws or governmental orders. Ministerial orders can be prepared only for implementing the above-mentioned rules. This also means that

- all rights and duties related to players in the telecom sector (service providers, consumers and regulators) have to be included in rules stated in the before mentioned laws and orders, consequently,
- the ministries have much more responsibilities than those in Western countries, so there is greater political influence on telecommunications,
- the bottom-up control of society over public utilities has no specific legal basis as found, for example, in American public utilities,
- there is very little place for solving problems emerging from affairs not included in the rules. This could be dangerous in the coming transitional period.

The new telecommunications law due to be enacted later in 1992 will replace the so-called Post Law of 1964 which was a traditional PTT law. In accordance with the European directives, the new legislative regime for the Hungarian telecomms sector will, similarly to other sectors, be ruled by a number of general laws. The major governing laws are as follows:

- The Civil Code provides the framework for terms and conditions of contracts and for the use of private property by public utilities.
- The Concession Law is about activities which can be run exclusively on the initiative of the state.
- The Competition Law and the Price Law are generally applicable for telecommunications but specific tasks are assigned to the minister of communications in Telecom Law.
- The Criminal Law will penalize vandalism against public telecommunications facilities.
- The Enterprise Law, the Company Law and the Law About Transformation of Enterprise into Company and the emerging State Budget Law are bases for regulatingon operational entities, and legislative means for the state to exercise its property right.
- The Frequency Law, currently under preparation, will govern spectrum management and radio communications.

Telecommunications policy and process of restructuring will be formulated by the parliament. The competence of the parliament in this issue is a general rule in countries with developed democracies.

Although the policy-making process has not yet come to an end, a significant liberalization is envisaged through the implementation of the ONP (Open Network Provision) concept of the EEC as the principle governing a multi-player telecom sector. Unlike in most of the countries, it is expected that the ownership of the so-called "digital highway" will remain the exclusive right of the state but specific rules for exercising this property right have yet to be finalized.

5. INSTITUTIONAL FRAMEWORK OF TELECOMMUNICATIONS REGULATIONS

In Hungary, similarly to the European German-speaking countries, telecommunications have been run as a PTT embracing both operation and regulation of post and broadcasting in one single government entity, although since 1968, operations have been accounted as a business activity.

Out of the post-communist countries, Hungary was the first one to launch a restructuring process, essentaially consisting of the following steps:

- regulation and operation were split in 1989, leaving regulation for Ministry of Transport, Communications and Construction (from 1990 on Ministry of Transport, Communications and Watermanagement),
- the operational entity was split into three companies: post, telecommunications and broadcasting in 1990,
- telecommunications will be transformed into a shareholding company in 1991,
- regulatory functions of the government will be split when those of property rights are separated from those of the telecommunications-specific regulation in 1991,
- privatization of the Hungarian Telecommunications Company is going to be undertaken in 1992,
- floating of shares of the privatized Hungarian Telecommunications Company is going to be started in 1993.

6. FUNCTIONS OF TELECOMMUNICATIONS: FORMS OF EXECUTION IN LEGISLATION

6.1. Creating an Entrepreneurial Environment and Removing the Obstacles to Entering the Market

According to Hungarian legislation, free competition is limited by concessions which are the tool for regulating entry to, and operation in the market. The purpose of concessions is to give special rights and obligations in order to provide universal service or public utilities. Geographical barriers to concessions are subject to the principle that they must be economically viable.

The concessions have a civil contract nature where one party is the Minister of Transport, Communications and Watermanagement (hereinafter referred to as the Minister). Public bidding is compulsory before contracting.

There are only a few limitations of ownership rights. The basic network (which in practice will probably be the overlay digital network) is the exclusive property of the state. There are no other constraints except that for voice telephony, the service provider has to be the owner of the network infrastructure as well.

The clauses of the Hungarian Competition Law are fully applicable to telecommunications where abuse of monopoly power is of particular interest. Additionally, the Minister has the right to put limitations on entry in cases where this is justified by considerations of security of the network and services, and economic viability.

Accounting, and the organisational principles for separating the competitive and non-competitive sectors, have to be laid down by the Minister. Free entry is limited to the operation of the digital overlay network, voice telephony, public paging, mobile services, country-wide package switched data transmission, and broadcasting.

6.2. Correcting Defects of the Market: Keeping Tight Control of the Dominant Service Provider

A dominant service provider is in a position, due to its size and/or activity, to influence the operation of the market fundamentally instead of the market determining its own operation.

Keeping tight control over telecommunications organisations enjoying exclusive rights can be executed by means of concessions or via statute of state enterprise and price control. The Minister has the right to initiate modifications of a concession if the interests of users and efficient operation so require.

6.3. Consumer Protection

Protection of the telecommunications user is a considerably structured task which, in a wider sense, permeates almost the entire regulatory activity.

In the new draft of the Telecommunications Law, the relation between the service provider and the subscriber is transformed into a business contract. Major terms and conditions of public services are contained in the Law while others will be contained in government statements. In the competitive sphere, the terms and conditions of services are subject to the general rules relating to contracts in the Civil Code. This is true also for responsibility for damages caused by service providers.

For example, according to the new provisions, the service provider has an obligation to fix and keep to the time limit for connecting the subscriber to the network. If it fails to do so, it must pay a penalty. In case of claims for repayment of the bills, the obligation for proof lies with the service provider.

It is the general obligation of the Minister to ask for the opinion of the associations of users in cases where his order under preparation is going to affect the services provided.

Cases where a large circle of subscribers is hurt and the behaviour of a service provider has to be stopped and users compensated can be handled on the basis of the Competition Law if consumers are misled. In other cases, related to the terms and conditions of the contract, the Minister has the right to file a procedure in the Court.

6.4. Provision of public utilities

Although, according to he ideology of socialism, all needs of people are taken care of by the state, we have a very poor legislative framework for provision of public utilities. The existing Civil Code clause providing for public utilities has to be supplemented with a specific provision in the Telecommunications Law.

According to the Telecommunications Law, the government has the obligation to determine the required level of service coverage. According to present plans, in 1995 waiting time for a main line must not exceed one year. It is the obligation of the Minister to implement these obligations in the concessions.

In case the concessioner fails it is the obligation of the Minister to take on the responsibilities for public services, but practical means for doing so are still being elaborated.

Public utilities have special rights of way. According to the provisions of the Act, there has to be room for network infrastucture in any new settlement and building.

6.5. Connecting to Europe

The intention of the Hungarian telecommunications policy is to follow the directives of the EEC. The reason for this is not only because it is a political aim but also because EEC directives are based on large scale compromises between the various players, especially the pro- and anti-competitive ones.

Hungary would like to implement the ONP (Open Network Provision) concept so that the digital overlay network would have the function of a highway, and regional networks and service providers could connect to it through standardized interfaces. The problem is that implementing ETSI standards will take time and money—both of which are lacking.

6.6. Ensuring the Network's Interoperability and Integrity

The public telecommunications network is suitable for providing various telecommunications services and bearer services. The quality of the service provided to the user depends on numerous factors (operating characteristics, usefulness of the service, etc).

The key issue in ensuring the integrity of networks is the distribution of responsibilities between the players (regulator, network operators, sevice providers). The Law decrees the establishment of conditions of network integrity and interoperability to be the general obligation of the Minister while other participants are obliged to co-operate. The player failing co-operation should compensate for the total damage caused in consequence.

The problem is that implementation of standards takes some time, and in the mean time, the network would be practically without approved standards and conditions.

6.7. Determining Quality Requirements

In an environment where there are requirements imposed on a service provider as to efficiency, service obligations and prices, the circle of regulation can be closed if there are certain obligations for service quality as well.

According to Hungarian legislation, regulation of quality is the duty of the ministers in a process which is very similar to that of standardization. This ensures equal chances for every service provider and consumer.

6.8. Determining Prices

In Hungary, according to the Price Law, the ministers have the right to determine the so-called fixed prices (where only a very limited proportion of goods are subject to fixed prices). Indirectly, this is also the tool for regulating resources for financing investments.

According to the draft of the Telecommunications Law, we are going to implement a "price cap" mechanism accompained by an access charge which will be the means of cross subsidizing local network operation. By the force of this law, the Minister has the right to liberalize the prices of services having some sort of competition or excess supply.

6.9. Publicity and Interest Reconciliation

Telecommunications have proved to be a politically sensitive field. This is no accident since some groups strongly involved in it (large users, multinational firms, the energy sector) are able to assert their interests very effectively. The situation is complicated by the unquestionable existence of public interests which cannot be related directly to any single group but which, according to social needs, have to be taken into consideration.

Telecommunications, at the same time, is itself a particularly intricate technological system where technical issues dictate some aspects of progress, and the most important interests are often wrapped up in technical issues.

Although we were keen to establish a process for the reconciliation of interests, this has proved to be very difficult. We have realized that there is no generally applicable legislative framework for such actions. We have not had the opportunity, up till now, to learn the difference between the top-down hierarchical regulation of state administration and the bottom-up democratic control of society.

According to the Telecommunications Law, the Minister has the obligation in given cases to ask for the opinion of users associations. There is a Council to be made up of representatives of consumers, service providers and ministries operating for the government. We did not find it possible to establish a public hearing-like process which could have ensured true democratic rights for interested parties.

6.10. Maintaining Operability of the Existing Network

There is no doubt that the transformation of the telecommunications regime implies building on entirely new foundations. However, such a radical change in the regulatory framework of telecommunications puts the operability of the whole network at risk. Redistribution of rights and duties will inevitably result in unclear situations where network operation is at stake.

Due to the time-consuming process of preparing the regulatory framework needed for secure functioning of the network, Hungarian Telecommunications Company, as provided by the Telecommunications Law, maintains its position until 1994 in that it will not need a concession. Instead, the government has special rights to influence its activity in case it doesn't cope with the general requirements of the Law.

7. CONCLUSION

According to the emerging legislation, telecommunications in Hungary will be regulated by a series of laws, the most important being the Telecommunications Law which is going to be presented to the Parliament in 1992 for final decisions and contributions.

NOTE

This study is a teamwork under the financing of the Ministry of Transport, Communications and Watermanagement.

K. HELLER
HUNGARIAN TELECOMMUNICATIONS COMPANY

CENTENNIAL SCIENTIFIC DAYS OF PKI

In November 1991, the Postal Experimental Institute, recently named *PKI Telecommunication Institute* celebrated the 100-year anniversary of its foundation, and on this occasion, organized the traditional PKI Scientific Days. The meeting was supported by the *Hungarian Telecommunications Company* and the *Scientific Society* for *Telecommunications,* under the auspices of the *International Telecommunication Union* and the *Universal Postal Union.*

Following the opening address of *P. Horváth,* general director of HTC, 48 papers in 12 Sessions have been presented in course of the 3-day conference. During the conference and informal meetings, technical and strategic issues of telecommunication development have been widely discussed by Hungarian and foreign experts. From the 49 foreign delegates pariticipating, 26 presented papers, while from Hungary, the number of participants was 450.

During the conference, the 100-year history of PKI, firmly linked to the devolopment of Hungarian telecommunications. was recalled, and tribute was payed to the memorable achievements of outstanding PKI scientists as contributors to the development of Hungarian telecommunications. *Gy. Lajtha* presented an interesting paper about PKI research schools, and professor *J. Szentágothai* recollected the contributions of Nobel prize winning *Gy. Békésy* who was active in PKI from 1917 to 1947 in the research of the hearing mechanism.

In 1881, the Hungarian Royal Post and Telegraph Experimental Station has been established in Budapest, being the second of such institutions in the world. Throughout many decades, this Station was active in postal research work, telecommunications and broadcasting. In 1954, the Station was re-organized and became the Postal Experimental Institute.

Due to the continuity by the research schools and the early recognition of trends by the institute management, a well-educated staff of experts was available at the Hungarian PTT during the recent technical development phase. The achievements of this staff were manifested in the fields of optical communication, stored program controlled switching, cable TV, satellite communication, speech recognition and synthesis, computer aided network analysis and optimization procedures.

The year 1990 witnessed a re-structuring of the Hungarian PTT organization, resulting in three successor companies. As a consequence of this process, PKI functioned as a limited company for a year before becoming a member of the Hungarian Telecommunications Company (HTC) as PKI *Telecommunications Institute.*

Gy. Sallai, director of HTC's strategic department, emphasized that in this new configuration, PKI activities will be concentrated on telecommunications and broadcasting, but with additional reseach and development background activities focused on design and operational support, thus becoming a fundamental technical background institute. This concept requires activities for monitoring telecommunication world trends, processing the acquired information and feeding it to the company management for decision making and choice between technological options. Other activities of the institute cover investment support, operational support and network design. PKI strives to obtain internationally appreciated results, thereby maintaining international relations and reputation.

Gy. Perlaki, director of PKI, emphasized that the institute is now providing technical support for the entire telecommunication development process. Research activities are concentrated in the institute, while in other fields such as network development, a coordinating function is implemented. Institute activities are supporting regional telecommunication authorities, thereby intending to promote the development of the entire Hungarian telecommunication. By applied research and development, the domestic introduction of modern telecommunication technologies will be accelerated, and the quality of telecommunications will be improved by introducing up-to-date services.

Within the framework of the Centennial Scientific Days, the presented papers successfully illustrated the diverse achievements and international relations of the 100-year old institute, simultaneously outlining issues and challenges of this long-standing institution. ■

HUNGARIAN TELECOMMUNICATIONS COMPANY JOINS THE INTELSAT GLOBAL SATELLITE NETWORK

Overseas telephone communication of the Hungarian PTT or its successor, the Hungarian Telecommunications Company HTC is, at present, mainly implemented via foreign earth stations of the Intelsat global satellite network. In order to eliminate expenses resulting from the use of foreign earth stations and transit connections, HTC decided to establish its own earth stations, and to this end, issued an international tender call early 1991. Answering this call, nine foreign companies submitted delivery proposals from which HTC selected the proposal of NEC, Nippon Electric Company. Another tender call was issued to set up a microwave link connecting the site of these earth stations with the East-West fibre optic link, and the winner of this tender call was the Japanese Fujitsu company. End of September 1991, the delivery contracts have been signed by representatives of the Japanese Sumitomo and the Hungarian Elektroimpex foreign trading companies, further by representatives of NEC and HTC.

The new Hungarian earth stations will be installed at the site of the Intersputnik earth station which is already operating near the village of Taliándörögd in Western Hungary. The two stations will cover the Atlantic Ocean region (AOR) and the Indian Ocean region (IOR) according to the "modified A" standard, with following main technical data:

Receive frequency range	3625 to 4200 MHz
Transmit frequency range	5850 to 6425 MHz
G/T	35 dB/K°
Antenna diameter	18 m
Preamplifier	uncooled, noise temperature 55 K°
Telephone transmission	according to Intelsat IDR system (Intermediate Digital Rate)
Transmission rate	2 Mbps, with 5 carriers assigned for the AOR station, and some lower speed carriers assigned for the IOR station
Output amplifier for telephone transmission:	
AOR station	TWT, 700 W
IOR station	TWT, 400 W
Output amplifier for TV transmission, AOR station	klystron, 3 kW

In order to allow for future expansion, both stations will be capable to operate at both polarizations. Digital channel multiplication equipment (DCME) will be applied for the transmission of telephone channels in order to make better use of the rented space segment capacity.

According to plans, the telecommunication equipment will be delivered by NEC while the site preparation and the station assembly (under Japanese control) will be the responsibilities of HTC. At the station site, the necessary ground and infrastructure are available, with the exception of the uninterrupted power supply and the air conditioning of the new telecommunication equipment. Antennas will be supported by steel structure on reinforced concrete foundation at ground level, with adjoining containers holding the radio frequency equipment. All other station parts will be accomodated in the central Intersputnik building, and will be controlled by a computer aided central supervisory system.

Time schedule for starting operation:

- AOR station: 4th quarter, 1992.
- IOR station: 1st quarter, 1993.

G. HEGYI
HTC

■ 21ST EUROPEAN MICROWAVE CONFERENCE STUTTGART, SEPTEMBER 1991

This was the third occasion that after Hamburg and Nürnberg, the European Microwave Conference was held in Germany. Stuttgart is the highly industrialized capital of Baden-Württemberg, with a record number of companies specialized in electrical engineering, in RF and microwaves. Parallel to the Conference, there was a major exhibition where approximately 350 companies were exhibiting hardware and software products. Conference and exhibition took place at the International Congress Centre.

The call for papers solicited 456 summaries, the second highest number ever; this shows the increasing importance of the microwave field and of the topics chosen. By arranging three parallel oral sessions each day, complemented with four poster sessions, 229 papers in all have been presented. The topics dealt with range from antennas, submillimetre receivers, CAD and modelling to MMICs, field theory, passive components, microwave propagation, satellite communications, optical/microwave interaction and microwave measurement. Special sessions on the medical applications of microwaves and on microwave education have been arranged.

Invited papers are keystones within the architecture of any conference, and during the EuMC, they presented a general survey of the ever expanding field of microwaves. There were 15 invited papers, 6 of them delivered in the special USA and Japan sessions, with emphasis on the millimetre waves field. As a first speaker, David Olver (Queen Mary and Westfield College, London) gave an overview on millimetre wave antennas, reflectors, lenses, horns, planar antennas, travelling wave antennas and integrated antennas. In the field of mm-wave solid-state devices, E. Kollberg (Chalmers University, Göteborg) discussed the quantum well diode, back-to-back barrier n—n^+ doped varactor diode multipliers, and the newest achievements in the fabrication of Schottky diodes. With array oscillators, these can generate some Watts of power in the 20 to 200 GHz frequency range. Peter Russer (Technische Universität, München) discussed silicon monolithic mm-wave ICs. Complete receivers and transmitters may be integrated using IMPATT and Schottky diodes. He presented some experimental results in the frequency range up to 100 GHz. In the field measurement technique in the mm-wave range, Horst Groll (Technische Universität, München) presented an overview. He discussed network analyzers, spectrum analyzers and signal generators, and a coaxial connector with 1 mm O.D. which has an upper frequency limit of 100 GHz.

Other invited speakers discussed microwave devices (Pons et al, Thomson CSF) and MMICs (Ali, Pacific Monolitics, USA). O. G. Vendik (Electrical Engineering Institute, St. Petersburg, USSR) discussed the use of superconduction films as microwave transmission lines. He was dealing with the surface resistance of such films and showed experimental results of switches and limiters.

"Industrial applications of microwave imaging" was the topic covered by J. Detlefsen (Technische Universität, München). Current and potential future industrial applications, including the fields of robotics, microwave vision, biomedical applications, nondestructive testing and vehicular guidance were discussed.

Very interesting was the lecture of H. Brand (Universität Erlangen-Nürnberg): "Microwave technology in the Terrahertz region". He reviewed the state of the art of sub-millimetre wave technology with emphasis on molecular gas lasers as sources, and quasioptical waveguides for signal processing.

Because of the limited place for this review, only one paper is mentioned from the session papers: "Fully integrated 18 to 20 GHz phase locked DRO signal source for digital radio systems using chip and wire technology." It was presented by W. Konrath from the ANT Nachrichtentechnik GmbH, Backnang, Germany. The RF assemblies comprise the DR-VCO, a balanced amplifier, a ferrite isolator and a sampling phase detector. The control circuitry includes a PLL amplifier, voltage regulators and filters. The experimental results show that the chip and wire technology reaches the lower Ka-band with excellent results. For this paper and the excellent presentation W. Konrath received the 1991 EuMC Microwave Prize from the Management Committee of the Conference.

Following the Conference, three Workshops were organized:

1. Microwave optoelectronics dealing with interaction between the microwave and optical frequency range, taking into account system aspects as well as the properties of particular components.
2. Advanced car electronics and future traffic control systems related to microwaves. This workshop was useful for the engineers working in the microwave communication and automotive business.
3. CAD and modelling of microwave devices and circuits. Tools and models were discussed aiming at the accuracy of microwave devices to avoid lengthy and costly experiments.

The Conference and workshops were well organized due to F. M. Landstorfer and W. Mahler, the chairman and secretary of the Conference. The next EuMC will be held in Finland, August 1992.

M. KENDERESSY

■ INTERNATIONAL CONFERENCE ON INTELLIGENCE IN TELECOMMUNICATIONS NETWORKS

The second edition of ICIN (International Conference on Intelligence in Telecommunications Networks) will take place in Bordeaux, France, from 3 to 5 March 1992.

This event is being held under the patronage of the ITU and the French Ministry of Posts and Telecommunications as well as several scientific societies including IEEE/COMSOC which are acting as sponsors.

The international Steering Committee, chaired by John S. RYAN of AT&T Bell Labs, met in Geneva during TELECOM '91 and approved the programme and the campaign to launch this event.

The Programme Committee, chaired by Michel TREHEUX from the General Directorate of FRANCE TELECOM, has seledted 58 papers from the 130 that were proposed in reply to the call for papers. These papers, of which 44 originate from 14 countries other than France, have been divided into 11 sessions centred on the following themes:

- Network user needs.
- Intelligence in public networks.
- Intelligence in private/corporate networks.
- Intelligent network management.
- Personal telecommunications and mobility.
- Intelligent network applications.

Senior representatives from FRANCE TELECOM, NTT and BELLCORE will take part in the opening session, and to close the conference a round table has been organised with delegates from regulatory bodies on the theme of ONA/ONP.

The very high quality of the papers selected has led the organisers to propose a "tutorial" day. This day of initiation for newcomers, which has been prepared by Sup Telecom, will take place in Bordeaux on 2 March.

This conference is composed in such a way that its members represent different components in the field of intelligent networks: telecommunications operators, telecommunications and data processing equipment manufacturers, university researchers and teachers and network users. Many eminent foreign speakers have agreed to participate, thereby adding a representative international dimension to the conference.

In order to give a certain prestige to the conference the Program Committee wished to invite a few keynote speakers.

The conference will therefore be opened with speeches by S. SUSUKI, head of IN laboratories at NTT, D. P. WORRALL, Vice-President of the Network Control Technology Division at Bellcore, and J.J. DAMLAMIAN, Marketing Director at FRANCE TELECOM.

To close the Conference program there will be a debate led by J.P. ROY from the DIEBOLD Agency where representatives from regulatory bodies (FCC, OFTEL, DGXIII, ...), ministries and large companies will be invited to talk about intelligent networks, thereby posing fundamental questions concerning the structure of public networks.

This program brings together all the ingredients that are likely to make it a great international success. ■

■ LIGHT EMITTING SILICON CHIPS MAY SPEED COMPUTER LINKS

Specialists working in the UK have devised a way to modify silicon wafers that enables them to emit light when excited by a laser, a capability that could be used to provide high speed communication between computers and possibly bring nearer the day of the viable optical computer. It also offers the prospect of reducing the cost of connecting telecommunications equipment to the fibre optic cables that greatly increase network capacity compared with the traditional wires.

In curent technology, gallium arsenide chips are used as light-emitting diodes to convert electrical signals into light. This relatively exotic material is, however, much more expensive than silicon, and in addition, chips made from it cannot have the same degree of circuit density.

Now researchers at the Royal Signals and Radar Establishment (RSRE) at Malvern, Western England, have been able to demonstrate for the first time that very thin filaments of silicon will emit light when excited by a laser. The team is now concentrating on developing the concept to enable light to be emitted when an electric current is applied to the silicon.

Dr Leigh Canham, one of the project scientists, said that their aim was to design what would be the first silicon light-emitting diode, and later possibly to create a silicon solidstate laser. The researchers have already succeded in modifying an ordinary silicon chip into a network of strands of silicon, known as quantum wires, some 15,000 times thinner than a human hair, by using a type of etching process.

Quicker and less costly than methods involving epitaxy (depositing a thin layer) or lithography (another form of etching), their innovative approach involves dissolving most of a very thin surface layer in a bulk silicon wafer, to leave a network of isolated „wires" of the desired thickness. In this process, the silicon chip is exposed to hydrofluoric acid within an electrochemical cell. Small holes are thus eroded into the material, which can then be enlarged by further chemical dissolution until they inctersect, leaving the remaining wafer material in the form of strands.

The frequency of the light emitted by the silicon can be selected by varying the thickness of the wires. Mesoporous silicon layers (material in which the holes are 20—25 Angstroms wide) of about 80 per cent porosity (air:silicon ratio) has been shown to emit visible red light at room temperature when excited by unfocused blue or green laser light, said Dr Canham. He explained this was due to two-dimensional quantum size effects which do not occur in the case of bulk crystalline silicon.

Information from London Press Service

International Workshop

will be organized by the IEEE Joint Chapter of Societies Communication and Microwave Theory and Techniques and the Scientific Society for Telecommunications, on the topic of

PERSONAL COMMUNICATIONS AND INDOOR AND MOBILE RADIO

in Siófok, Hungary, 26—27 May, 1992

The workshop belongs to a series of regular Symposia in this topic; the previous was organized in London, September 1991, the next will be in Boston, October, 1992.

The subject of the Workshop covers any aspect of the topic, including networking, services, propagation phenomena and equipment design, problems of modulation, coding, etc.

International Technical Program Committee:

Frigyes, Fazekas, Aghvami, Baal-Schem, Berceli, Blake, Kato, Ohrvik, Pahlavan

A formal call for papers, including registration fees, accommodation possibilities, transport to Siófok and others, can be asked from the Scientific Society for Telecommunications, Budapest, Kossuth Lajos tér 6—8, 1055. Hungary, (Mrs. Katalin Mitók, phone: +361-153-1027, fax: +361-153-0451).

In the year 1992 we are continuing to publish the JOURNAL ON COMMUNICATIONS alternately in English and Hungarian, focusing each issue on a selected significant topic guest edited by an outstanding expert in the field. The planned issues are the followings:

Reliability in electronics — Computer aided circuit design — Speech processing — Personal communications — Optical communications — Medical electronics (in English)

Acoustics — IC testing — Telecommunication services — Telecommunication softwares — Digital audio broadcasting — Digital satellite communications (in Hungarian)

The subscription rates will not be changed in 1992.

Subscription orders can be sent to the publisher Typotex Ltd. H-1015 Budapest, Batthyány u. 14., phone: (361) 201-3317. Transfers should be made to the Hungarian Foreign Trade Bank, H-1821, Budapest. Account number: 203-21411

Informations for authors

JOURNAL ON COMMUNICATIONS is published monthly, alternately in English and Hungarian. In each issue a significant topic is covered by selected comprehensive papers.

Other contributions may be included in the following sections:

- INDUVIDUAL PAPERS for contributions outside the focus of the issue,
- PRODUCTS-SERVICES for papers on manufactured devices, equipments and software products,
- BUSINESS-RESEARCH-EDUCATION for contributions dealing with economic relations, research and development trends and engineering education,
- NEWS-EVENTS for reports on events related to electronics and communications,
- VIEWS-OPINIONS for comments expressed by readers of the journal.

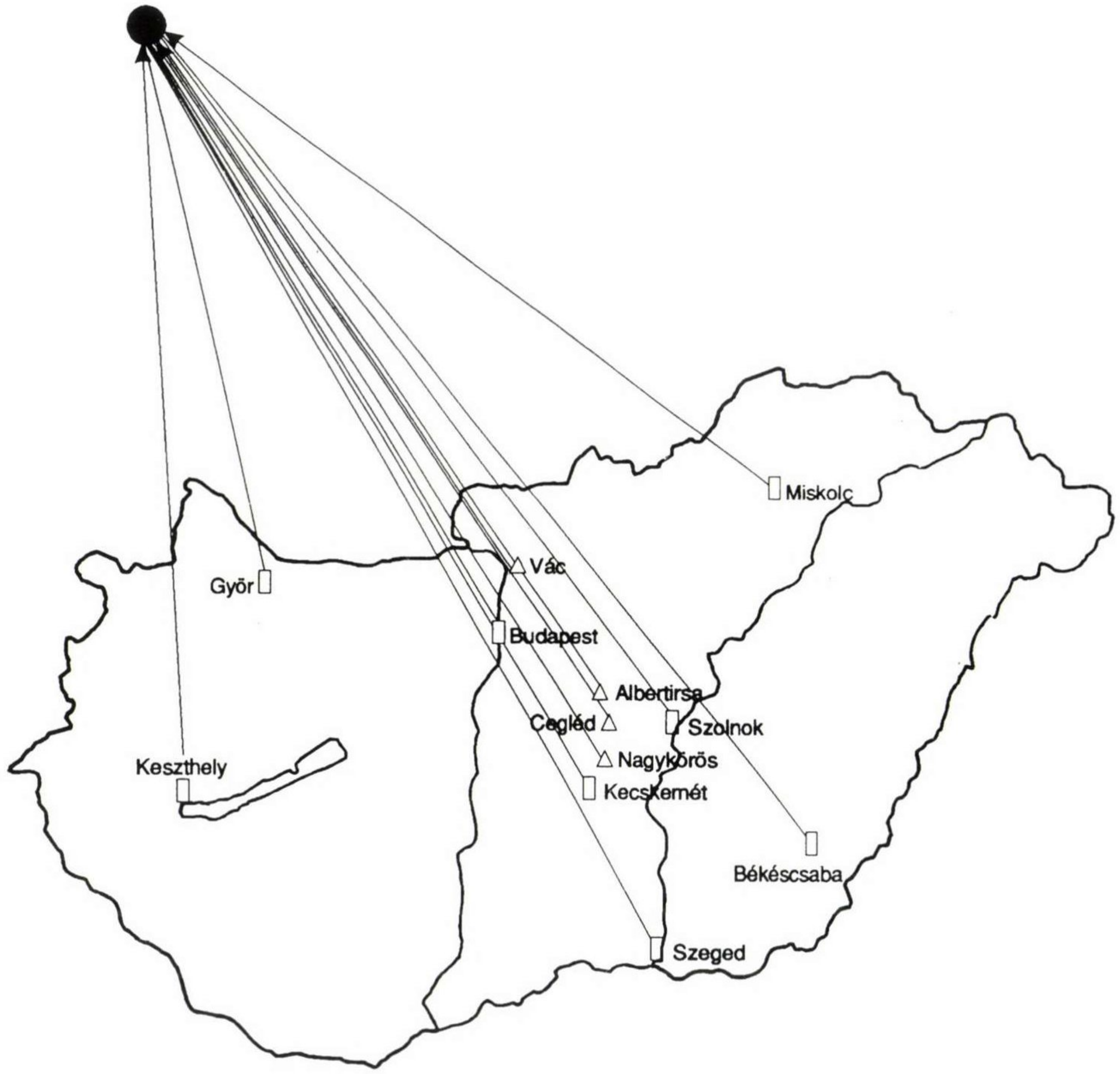
Manuscripts should be submitted in two copies to the Editor (see inside front cover). Papers should have a length of up to 30 double-spaced typerwritten pages (counging each figure as one page). Each paper must include a 100—200 word abstract at the head of the manuscript. Papers should be accompanied by biographies and clear, glossy photographs of the authors.

Contributions for the PRODUCTS-SERVICES and BUSINESS-RESEARCH-EDUCATION sections should be limited to 16 double-spaced typewritten pages.

Original illustrations should be submitted along the manuscript. All line drawing should be prepared on a white background in black ink. Lettering on drawings should be large enough to be readily legible when the drawing is reduced to one- or two-column width. On figures capital lettering should be used. Photographs should be used sparingly. All photographs must be glossy prints. Figure captions should be typed on a separate sheet.

For contributions in the PRODUCTS-SERVICES section, a USD 110 page charge will be requested from the authors company or institution.

HELLO...
SIEMENS SPEAKING...
HERE WE ARE...



△ EWSD Public Exchanges 1991
▯ EWSD Public Exchanges 1992

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KONTRAX TELEKOM: A NEW DYNAMIC COMPANY ON THE TELECOMMUNICATION MARKET

DEAR READER,

Welcome by the new company Kontrax Telekom. We hope we shall not only meet on the pages of this magazine but can also become business partners.

Perhaps you will find this letter peculiar because you have heard of Kontrax before. The explanation is simple.

Kontrax was founded in 1987. During a dynamic expansion period, in addition to traditional office techniques, new activities such as telecommunication and optics have been started. Therefore company management decided to create new independent companies for each of the profiles.

Kontrax Telekom Company has been registered this May. It follows from our name that our intention is to take part in the development of domestic telecommunication.

This kind of activity has not been unfamiliar for us. Besides the PTT, we have been the first dealers of telecommunication equipments such as phones, fax machines and PABX's.

But our aim is more than simple trading. One of our important tasks is to participate in organizing local phone companies. Besides, we intend to initiate the development of other telecommunication services.

Because perfect communication is essential for all of us, we are sure one day we shall be able to give you a specific offer. Perhaps we can help you already now by introducing Kontrax Telekom's acitivities and product ranges.

Ericsson BCS 90 digital PABX's are offered in two versions by Kontrax Telekom.

The BCS 90/24 handles 8 trunk lines and 16 extensions, and should be operated with Ericsson type phones.

The BCS 90/66 system can be extended up to 18 trunk lines and 48 extensions. It can handle traditional phones too but the special services are available only by phones developed for this system. The system can be applied as a partner system for another exchange, and is also suitable for computer data transfer.

The Ericsson BCS 150 digital system can handle up to 40 trunk lines and 150 extensions. The services can be established in a flexible way, taking into account the activity of the user, type and direction of internal information flow etc. The system is capable of transmitting voice, written text and data, and can be classified from the viewpoint of calls, trunk line usage and tariff counting, further the services available for all subscribers.

The Ericsson BCS 150/Hotel version is recommended by Kontrax Telekom for hotels. This system includes a special software and guest room phones.

The exchange systems of the world famous company Ericsson provide a wide selection of convenient services meeting even professional requirements.

For customers requiring only few lines, the Soolo 8 and Soolo 16 electronic systems of the Finnish company Nokia are recommended by Kontrax Telekom.

The Jazzi is a digital exchange with stored program control and has two versions. One has a maximum capacity of 4 trunk lines and 12 extensions while the other offers 10 trunk lines and 32 extensions.

The Soolo and Jazzi systems with their small space requirement, elegant outfit, reliability (assured by up-to-date components) and wide range of services are especially suitable for smaller offices, bureaus, agencies, motels, further for educational, health and cultural institutes.

The Nokia Dixi is a totally electronic, digital, stored program controlled system suitable for voice and data transmission so that computer devices can also be connected. It is offered in 3 versions. The capacity of MINI DIXI is 192 line endings. DIXI 700 can handle 150 trunk lines and 704 extensions while DIXI REMOTE handles 196 lines and connects to a central DIXI via PCM trunks.

Optimum configuration can be established by special software and hardware matched to the user requirements such as a stand-alone small system, a DIXI programmed for hotels, hospitals, or used by several companies.

A DIXI network of as many as 2400 lines can be established by interconnecting more PABX's. All extension users may benefit by the advantages of a digital system.

KONTRAX TELEKOM

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