Supplement of the translation of Kogelnik's "Introduction to Integrated Optics" [IEEE, MTT-23, 2 (1975)]

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It would seem that a brief review of the current advances in the field of thin-film optical apparatus and integrated systems based on them during the two years that have elapsed since G. Kotel'nikov wrote his review should start with listing the books and reviews that have been published in this time. Foremost among them are the monograph,[1] in which practically all the problems bearing on integrated optics were reflected, the book by Marcuse,[2] which treats the theory of asymmetric plane waveguides and fiber optics, as well as the theory of coupled modes as applied to thin-film waveguides, and the book by Goncharenko and Red'ko,[3] which mainly dealt with propagation of surface waves in anisotropic waveguides. An entire set of reviews has been published on general problems and prospectives of integrated optics, e.g.,[4–6] nonlinear phenomena in thin films[7,8] and lasers with distributed feedback.[9]

In line with the development of integrated optical systems, interest has grown considerably in optical thin films and in methods and technology of preparing them. This requires the most varied materials, both amorphous and monocrystalline.

A large number of studies has been devoted to organic materials, an important property of which is their rather small radiation losses and photosensitivity, i.e., a tendency toward changes in physicochemical characteristics due to photochemical reactions (refractive index, rate of diffusion, etc.). The most varied functional elements can be built from such materials: strip (channel) waveguides, thin-film lenses, prisms, diffraction gratings that operate as elements for the entry or exit of radiation, narrow-band filters and mirrors, and film waveguide lasers. The methods of preparing integrated-optics elements and the technology of preparing polymer waveguides are reviewed in[10]. One can obtain single-mode strip waveguides with very small losses down to 0.2 dB/cm by applying the photolocking method,[11] while the method itself ensures high resolution and is suitable for manufacturing thin-film holographic gratings. It has been possible to obtain thin-film waveguides with losses less than 0.13 dB/cm[12] by using acrylic resin (refractive index $n=1.485$ at $\lambda=0.63$ μm). Clair *et al.*[13] deal with optimizing the quality of films made of negative photoresists. The properties of optical waveguides prepared by graft copolymerization on substrates made of monomeric materials have been examined.[14] Thin-film light guides have been obtained by polymerizing aromatic organic compounds in a high-frequency discharge.[15]

Waveguides with losses of 0.2 dB/cm ($\lambda=0.7$ μm)[18] have been prepared by vacuum evaporation of a special glass CAS ($n=1.46$) onto a quartz substrate. Light-guide films have been prepared by sputtering a tantalum cathode in an O_2–N_2 mixture; they had a refractive index that was variable in the range 1.85–2.16 with a variation of thickness of ~20 Å: the losses of light radiation energy do not exceed 1 dB/cm.[17,18] Optical waveguides made of Nb_2O_5 films ($n=2.1$–2.27) have been made by reactive d.c. sputtering; the minimal losses were 0.5 dB/cm.[19] Recent studies have shown that neodymium pentaphosphate has a high optical amplification of stimulated radiation, whereby it seems possible to build thin-film lasers; thin films of this material can be easily obtained by hf sputtering (losses ~1 dB/cm at $\lambda=0.63$ μm, and 1.2 dB/cm at $\lambda=1.06$ μm).[20] Development of the technology of preparing waveguides doped with neodymium is continuing.[21,22]

Waveguides have been obtained by migration of silver ions in lithium niobate in a melt of $AgNO_3$ by out-diffusion of $LiNbO_3$ in $LiTaO_3$.[24] Optical waveguides in quartz[25–27] and ZnTe[28] have been obtained by ion implantation. Typical energies and ion densities ranged from 0.3 to 3 MeV and from 10^{14} to 5×10^{16} cm^{-2}, respectively, with minimal losses of 0.3 dB/cm. Thin-film waveguides in GaAs have been made by neutron irradiation.[29]

A review is given in[30] of the methods and technology of preparing optical waveguides based on amorphous and single-crystal semiconductor materials, and the most recent advances in development of the molecular-beam epitaxy method are discussed. The development of the technology of growing single-crystal thin films of $LiNbO_3$ is important, since this material is cheaper than GaAs, while the quality of electro-optic modulators based on it is higher. The light losses amounted to 1 dB/cm for a $LiNbO_3$ film on an $LiTaO_3$ substrate prepared by the epitaxy method.[31,32] A new "capillary" technology has been proposed for growing films of lithium niobate on $LiTaO_3$ substrates.[33] A method has been developed for preparing waveguides made of Ge/GaAs.[34]

The excitation of different types of waveguides has its contrasts and features, and it requires further analysis of the input systems. For example, conditions are formulated in[35] in universal form for the most efficient excitation of diffuse waveguides by tunneling and diffraction methods, and the efficiency of grating input devices is analyzed.[36,37] The coupling element used for input of radiation into a thin-film waveguide can at the same time be a convenient instrument for determining the parameters of the film with high accuracy.[38] The parameters of heteroepitaxial structures in the system

GaAs–AlAs have been measured by using coupling prisms[39] and diffraction gratings.[40]

One of the most important problems to be faced in preparing integrated-optics systems is to ensure efficient coupling of the light flux between two thin-film waveguides. For two different waveguides having a substantial phase mismatch, efficient coupling can be had by using a diffraction grating having the appropriate period, placed in the space between the two thin-film light guides, and used for phase matching. Experiments have established that the maximum efficiency of coupling of this device is 27%.[41]

A third method of input of radiation into a film (through a tapered edge of the waveguide) is continuing to be studied[42–44] and it is already being applied in actual integrated-optics devices, e.g., in semiconductor lasers that have a passive and an active waveguide of this type coupled inside the resonator.[45]

The potentialities of integrated-optics systems will be substantially expanded if efficient and simple devices will be developed for coupling between glass-fiber and film light guides. Some inventions have already been made along this line,[46,47] and matching of a thin-film waveguide with a fiber light guide has been obtained by tunneling,[48] diffraction,[49] and through a tapered edge.[44]

In addition to the listed elements for matching laser radiation with optical waveguides, there is another input device, the holographic device, in which a hologram plays the role of the matching element. One can feed radiation through such a device into film[50,51] and fiber light guides.[52] Yet the technical realization of such a device is complex, though it has some advantages.

Methods are being developed for direct input of laser radiation into a light guide, and transfer of the emission of a small-size laser to a thin-film waveguide by tunneling has been achieved.[53–55]

Much attention is being paid to problems of developing and studying channel waveguides, since this seems to be just the way of developing to build frequency mixers, directional couplers, and other control elements for laser radiation and information transfer in actual integrated-optics systems. Channel waveguides obtained on semiconductor substrates by diffusion[56] and selective etching[57] methods have been studied. Different variants of the design of waveguides are being studied in a promising material such as GaAs, and the typical radiation losses amount in the channel structures to 0.8 cm^{-1} at $\lambda = 1.06$ μm and 1.2 cm^{-1} at $\lambda = 0.9$ μm,[58] while the losses in planar waveguides based on GaAs having an impurity concentration of 10^{13}–10^{16} cm^{-3} near the intrinsic absorption edge are 2–18 dB/cm.[59]

The elements of integrated-optics systems are being intensively developed and studied experimentally. The possible practical realizations of the main types of optical directional power couplers have been studied in[60]. Controllable directional couplers based on channel waveguides have been built for switching light fluxes in optical waveguides, and the switching therein is carried out by using the electro-optical effect in the coupler material. Most employed waveguides are based on either lithium niobate,[61,62] in which the switching effect is attained at voltages ~6 V, or on GaAs. The switching frequency in the latter is above 100 MHz, the power consumption is 180 μW/MHz, and the losses are ~3 dB/cm.[63] Other elements of integrated systems are also being studied in addition to the directional couplers: planar lenses, prisms, diffraction gratings, thin-film beam splitters and reflectors of waveguide modes,[64] integrated-optics polarizers,[65] a thin-film interferometer that can be used for building a calorimeter and a refractometer,[66] waveguide thin-film photodetectors[67] (a photodetector was prepared on a silicon substrate in[68] inside an optical channel waveguide and had a sensitivity of 0.33 μA/μW at $\lambda = 0.63$ μm with a resolution of 10^{-9} sec). Diffraction gratings that have been produced in a thin-film waveguide have been studied in detail, and they fulfill various functions: mode transformation with efficiency ~90%,[69] emission and reflection of waveguide modes with a reflection coefficient of about unity, or matching of miniature lasers with thin-film waveguides.[70] The effect of the polarization of the light wave on their emission has been studied.[71]

Studies are continuing on the different types of dielectric waveguides and their properties. In[72] is presented a technique of preparation and a methodology and results of experimental study of focusing optical waveguides for integrated-optics systems prepared by diffusion into glass and semiconductor substrates. Resonance optical effects have been studied in two-layer thin-film structures.[73] Interesting results of theoretical and experimental studies of the phenomenon of image production in homogeneous planar optical waveguides are given in[74,75] where they showed that self-imaging is a property of highly-multimode parallel thin-film waveguides. A large number of papers has been devoted to studying the characteristics of diffusion waveguides as one of the most promising types; they permit one to produce optical waveguides and elements of integrated systems in a broad class of monocrystalline and amorphous materials.[76–78] Along this line, an important problem is to establish the parameters of waveguides that have a defined refractive-index profile.[79–83]

The thin-film modulators for laser-radiation based on the electro-optical effect are highly varied. Amplitude modulation of light arising from diffraction by electro-optically produced gratings has been achieved in waveguides of $LiNb_xTa_{1-x}O_3$ on $LiTaO_3$ substrates. Radiation from a cw semiconductor laser was modulated, and modulations were attained of ~80%[84] and 60% with a voltage on the electrodes of 8 V.[85] They got 80% modulation of the radiation at 80 V in waveguides based on epitaxial ZnO layers, with a speed of the element of 3 ns and control power of 4 μW/MHz.[86]

Phase modulation has been studied in channel waveguides 4.6 μm wide that were obtained by diffusion of titanium into a $LiNbO_3$ crystal. The coefficient of modulation amounted to 0.3 V/radian with a modulating power of 1.7 μW/MHz · radian^2 at $\lambda = 0.63$ μm[87]; frequency modulation at 150 MHz has been obtained in channel waveguides based on epitaxial GaAs films with a power of 300 μW/MHz.[88] A frequency of 1 GHz was attained in ridge waveguides based on $LiTaO_3$ with a ridge width of 24 μm at a control voltage of 30 V.[89] A phase difference of 150° in heterostructures based on AlGaAs corresponded to a control voltage of 10 V.[90]

A modulator based on a Mach–Zehnder interferometer has been developed in a thin-film design, and the modulator was made in the form of a coupling ridge waveguide in $LiNbO_3$[91] and ZnSe.[92] A typical value of the half-wave voltage for it was 19 V.

Light modulation has been obtained by varying the parameters of the electro-optical substrate of a waveguide. The modulation coefficient amounted to $\sim 8\times 10^{-3}$ radians/V/cm at frequencies of 1 kHz when CdTe and KDP substrates were used.[93] A "push-pull" modulator based on an Nb_2O_5 film deposited on a $LiNbO_3$ substrate has also been built, and they attained a frequency of 1.8 GHz with a control voltage of 17 V.[94]

Modulation of radiation at a frequency of 600 MHz has been attained at voltages of 300 V in a thin $LiTaO_3$ plate 70-μm thick with strip contacts.[95] A modulator based on gallium arsenide has been made for radiation of wavelength 10.6 μm, and the frequency of modulation was 16 GHz.[96]

Modulation by electroabsorption in waveguides based on GaAs has been studied.[97]

Modulation with a depth of 10% at 60-Hz frequency based on the magneto-optic effect has been obtained at a field strength of 6 Oe[98]; optical-mode conversion in a ferrite film has been studied by using a homogeneous magnetic field.[99]

The characteristics of waveguide acousto-optical modulators have been widely studied. They studied in[100] the phase modulation of light at 62-MHz frequency. An experimental study has been made of diffraction of light propagating through a thin-film ZnO waveguide by acoustic surface waves that were being excited at 130-MHz frequency by using interdigital electrodes whose diffraction efficiency was as much as 90% at 100 mW acoustic power.[101] A frequency of 28.7 MHz was attained in devices made of polystyrene films.[102] An element has been built for processing optical information in a thin-film waveguide by volume gratings induced by acoustic surface waves. Here they used As_2S_3 films on $LiNbO_3$ substrates, and obtained a diffraction efficiency of 93% at 3 mW acoustic power.[103]

A new configuration of electrodes has been proposed: when deposited on an optical waveguide, they act analogously to an electro-optical prism, and switching is attained with a control voltage of 15 V.[104]

Light modulation has been obtained in waveguides based on liquid crystals.[105] They report in[106] on light modulation in liquid crystals and in nitrobenzene based on the Kerr effect, and they attained frequencies of 50 kHz and 2 MHz with control voltages of 100 and 60 V, respectively. In[107], they studied amplitude modulation of light arising from loss of total internal reflection at the boundary of a light guide with a coating made of a liquid crystal.

Studies of nonlinear phenomena in thin-film waveguides are continuing. Second-harmonic generation has been carried out experimentally under phase-synchronization conditions in ZnS waveguides deposited on a crystalline substrate made of $LiNbO_3$, with use of the nonlinear properties of both the film and the substrate,[108] and in GaP waveguides on a CaF_2 substrate.[109]

A large number of studies has been devoted to distributed-feedback lasers, but since a review[9] has been published recently on this topic, we shall take up only the most recent advances.

The stationary regime of laser action in an optically-pumped laser has been treated theoretically, and they calculated the amplification coefficient, threshold, and output laser-action amplitude as functions of the coherence of the pumping radiation.[110] Possibilities have been studied of mode selection and obtaining a single-frequency generation regime.[111] Laser action has been obtained in an injection heterolaser with distributed Bragg mirrors at a temperature of 180 °K[112] and at room temperature.[113] Dye lasers have been reported that have a small radiation divergence,[114] and which operate at a repetition frequency up to 100 Hz.[115]

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