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The Progress of Integrated Optics in Japan

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(Invited Paper)

***Abstract*—Recent progress in the field of integrated optics in Japan is reviewed. The research effort on planar guides, active integrated optics, and microoptics is outlined and pertinent references are given.**

I. INTRODUCTION

IN JAPAN, research in integrated optics appears to be accelerated by the rapid development of reliable optical components for optical communications and the expectation of wider application of optoelectronics in the future.

This paper is restricted to a summary of research activities in integrated optics in Japan. It is limited only to research but the scarcity of information given here is augmented by many references.

II. OPTICAL PLANAR GUIDES

A. Geometries and Materials

Optical planar waveguides and the question of maximum-gain conditions in a semiconductor junction laser were investigated, taking the different plasma frequencies inside and outside of the active layers into account [1].

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The transverse-mode confinement in asymmetric thin-film dielectric guides with inhomogeneous refractive-index distributions was discussed [2], [3]. To build active devices with the help of optical dielectric waveguides, a tunable parametric oscillator was proposed. Phase matching was accomplished with the help of the mode-dependent dsipersion characteristic of the slab guide [4].

More recently, scattering caused by random imperfections in dielectric-slab waveguides was discussed in detail [5], and the modes of metal-clad dielectric guides [6] and anisotropic and gyrotropic guides [7] were investigated. A method of parameter measurements using two guided modes was applied to thin-film glass guides prepared by an RF sputtering process [8].

Ion-exchange and ion-migration methods were applied with excellent success to form guiding cores in glass plates [9], [10]. Thallium ions were diffused from the surface of the glass through a mask. Losses of these two-dimensional multimode guides were reported to be less than 0.01 dB/cm at a wavelength of 0.63 μm. Direct connection between these guides or between the guides and optical fibers was achieved with losses of less than 10 percent. Axial changes in the depth of the guiding core beneath the surface were achieved by using a spatially varying electric field to produce ion migration [11]. Diffusion of lead ions was also used to form glass guides, and focusing properties were demonstrated [12]. Many other materials for thin-film guides were discussed, for example, tantalum pentaoxide [13], coloring of RF sputtered glass films [14], and ion implantation of thallium into fused quartz which was reported to have low loss [15].

Single-crystal thin-film $LiNbO_3$ for light guides was formed by epitaxial growth methods [16], and by RF sputtering [17], [84]. Optical waveguides made of $GaAs_{1-x}P_x$ prepared by plasma oxidation [18], and waveguides made of As–S–Ge glass [19], were reported. Organic films were also considered as waveguides [20]–[23].

Narrow dielectric strips on top of the cladding on a thin film were used to form a two-dimensional guide called "optical strip line" [24]. GaAs thin film was also used for that purpose [31]. In these structures, bends of a few millimeters of curvature were possible without causing high losses. It is reported that this technique can be used to form a two-dimensional guide on the surface of a bulk crystal. Formation of this kind of guide by a planar metal cladding was also demonstrated [26].

A thin-film lenslike light guide with parabolic distribution of the film thickness was formed by RF sputtering of the glass [25]. Focusing lengths of a few millimeters to a few centimeters were reported which were strongly dependent on the transverse mode. The distribution of the thickness could be controlled with the help of a back-sputtering process. One-dimensional Fourier transforms could be observed in this guide and one-dimensional image processing was also considered.

B. Measurement of Guide Parameters

Surface irregularities of 70 Å with a correlation length of 1 μm were measured in RF-sputtered glass films by the observation of the scattering patterns of the guided waves [27], and also by using a probe needle [28] and an electron microscope [29]. The film thickness and the refractive index of the core were measured with accuracies of 0.3 and 0.1 percent, respectively, using two propagating modes [8]. The anisotropic properties of the guide were also determined by this method. In a guide formed by the diffusion of ions, these techniques were applied to determine the depth of the diffusion. The diffusion constants D, thus determined, were 1×10^{-15} and 2×10^{-16} [m²/s] for Ag ions in silica and Vycor, respectively, at 470°C, and 1×10^{-15} for Tl ion in Vycor at the same temperature.

C. Couplers and Filters

A directional coupler in a multilayer thin-film waveguide was demonstrated [30] and planar coupling was studied [31], [33]. Branching of a dielectric guide to a multilayer dielectric waveguide was also achieved [32].

Grating couplers were studied by an equivalent-circuit consideration [34] and the coupling efficiency was investigated with photoresist gratings [35]. Optical coupling from the tapered end of a thin-film guide to an optical fiber was demonstrated [36], [37].

A TE_0-mode filter was formed by sputtering a metal film on a thin glass-film guide [38]. Mode-dependent filter actions of metal-clad guides are described in detail in [6] and [39]. A TE-mode filter in a multilayer dielectric guide was studied [40].

Nonreciprocal devices in optical circuits are discussed theoretically in [41].

III. ACTIVE INTEGRATED OPTICS

A. Integrated Lasers

Semiconductor injection lasers consist of the integration of the mirrors, the pumping mechanism, the active waveguides, and the modulation mechanism. Laser lifetimes were extensively studied and room-temperature CW operation up to several thousands of hours were confirmed with double-heterojunction (DH) injection lasers [42]. Oscillations in a single axial and transverse mode of GaAs DH lasers were experimentally achieved by several authors and analyzed theoretically [43]–[47], [59]. Laser operation in the visible spectrum by optical pumping was reported [51], and heating effects were studied [52]. Recent developments in this field in Japan were already reported in [48].

The problem of efficient connection between injection lasers and external circuits is not yet fully solved. To realize a monolythic integrated optical circuit, basic research on distributed feedback (DFB) lasers was done. A DH structure with a grating was made by growing an epitaxial layer of AlGaAs on a corrugated surface of a thin GaAs layer. Preliminary reports indicate that the current and voltage characteristics of these lasers are the same as those of normal DH structures [49]. Experiments on DFB dye lasers were performed [50]. A laser was also proposed consisting of a ring resonator that is connected to the external circuits with a directional coupler.

Amplification at 1.06-μm wavelength using an Nd: glass film was reported with a gain of several tens of percent [53].

B. Modulation

If the integrated optic lasers were of the injection type, direct modulation through the pump current might be effective. Modulation in the millimeter-wave region was already reported [54]. However, there is a limit to the maximum modulation frequency because of the finite carrier lifetime [55]. This effect limits the upper modulation frequency to several gigahertz in GaAs lasers. A resonancelike phenomenon has been observed at certain modulation frequencies where the efficiency becomes high and a sinusoidal modulation of the pump current produces optical pulses [56]. External modulation by means of gain modulation of a laser amplifier was proposed. 200-Mbit pulse modulation of DH–GaAlAs lasers has been reported for PCM modulation [57], and analytical simulations have been studied [58].

With regard to external modulators, the phase modulation in an $LiNbO_3$ thin film was reported [60]. The change of coupling in a directional coupler was proposed as a mechanism for intensity modulation [61]. Waveguide action in an $LiNbO_3$ crystal due to an applied voltage [62], modulation phenomena at the surface of such a crystal [63], and modulation due to UV light excitation [64] were investigated.

Mode concersion between TE and TM modes was achieved in a thin film of amorphous tellurium dioxide [65].

C. Parametric Guides

A tunable parametric oscillator consisting of a GaAs film was proposed operating on the principle of changing the refractive index of the cladding [4]. Phase-matched second-harmonic generation was obtained in quartz covered with a glass film at a wavelength of 0.53 μm with an output power of 70 mW [66], [67]. Another crystal of CuCl was theoretically studied [68]. Second- and third-harmonic generation in a monooriented ZnS film was also achieved at the phase-matched condition [69].

D. Deflectors

Effective thin-film acoustooptical light deflectors have been considered. A deflection efficiency of 90 percent at 130 MHz due to monolithically integrated ZnO film was obtained [70], [71]. Similar results were reported with an As_2S_3 film on an $LiNbO_3$ substrate at 200-MHz modulation [72].

IV. MICROOPTICS

Compact integration of miniaturized conventional optical elements is attractive for practical use [74].

A miniaturized light modulator was realized with tandem connection of four optoelectric crystals using focusing fiber lenses (SELFOC) to avoid beam divergence. The half-wave voltage was reported to be 17 V, and the bandwidth was from dc to 1.6 GHz [73]. A modulator of the Fabry–Perot type was also realized with the help of the fiber lenses [74]. A combination of one- and two-dimensional fiber lenses was applied to launch a mode from a DH laser into an optical fiber [74]. The theoretical background for the propagation of waves and mode transformations was given in [76]–[81].

The miniaturization of light modulators was achieved using slab plates of crystals. Intensity modulation of a 0.63 μm wave by an $LiTaO_3$ single crystal of 40-μm thickness cladded with a Ce–O_2 film was performed at a half-wave voltage of 13 V [82]. GaAs slab plates were used to modulate light at 10.6-μm wavelength [83].

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Heterostructure Injection Lasers

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(Invited Paper)

***Abstract*—The utilization of the nearly ideal heterojunction that can be achieved between GaAs and $Al_xGa_{1-x}As$ to confine both light and electrical carriers has lead to the evolution of several new classes as injection lasers with very low room-temperature current-density thresholds for lasing ($\lesssim$1000 A/cm²), and structures whose operation can be more readily understood than the earlier homostructure lasers. These are as follows: the single-heterostructure (SH) laser which utilizes one heterojunction to confine light and carriers on one side of the structure; the double-heterostructure (DH) laser in which both carriers and light are confined to the same region; and the separate-confinement-heterostructure (SCH) laser in which the carriers are separately confined to a narrow region within the optical cavity. A state-of-the-art description of these lasers and some of the mode structures encountered in their operation is presented. Recent work is described which permits the growth of low-strain heterostructures with heterojunctions between GaAs and $Al_xGa_{1-x}As_{1-y}P_y$ strain reduction from mismatch and bonding of contacts has resulted in lasers which, while maintaining very low room-temperature current thresholds, also have very long lifetimes (>10^5 h) for continuous operation.**

INTRODUCTION

ONE of the important candidates being considered as the signal generator for optical-communications systems is the heterostructure injection laser. Lasing action by the stimulated recombination of carriers injected across a p-n junction was predicted [1], [2] in 1961 and was achieved [3]–[6] in 1962. These early injection lasers were generally rectangular chips of GaAs containing a p-n junction perpendicular to two polished or cleaved ends of the chip. The structure is illustrated in Fig. 1. The polished or cleaved ends are partial mirrors. Light is

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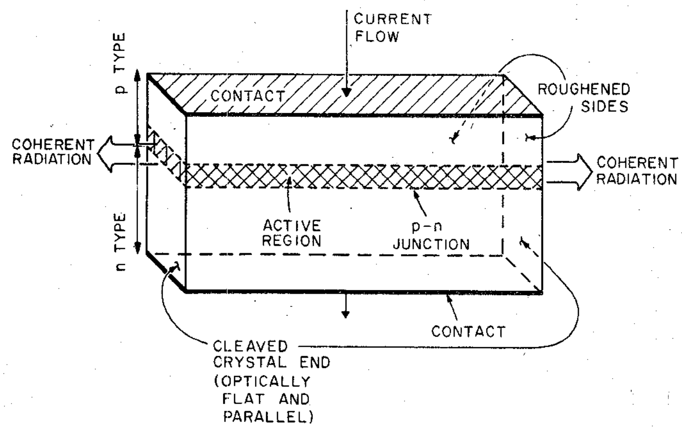

Fig. 1. A homostructure p-n junction laser in the form of a Fabry–Perot cavity. After Panish and Hayashi [21].

generated by the injection of electrons into the p region with subsequent radiative recombination of holes and electrons. This recombination occurs in a volume adjacent to the p-n junction and between the two mirrors. The active region between the mirrors is then an optical cavity. Structures such as that illustrated in Fig. 1 are now generally referred to as homostructure lasers because they are made of a single material such as GaAs, and thus contain no heterojunctions. These types of injection lasers typically have very high room-temperature-threshold current densities (~50 000 A/cm²), because little or no control over the thickness of the recombination region can be achieved as the result of unrestricted diffusion of injected carriers and because that region constitutes a very poor waveguide. The band-edge potential diagram, the refractive index, and the optical-field dis-