a student will take several departmental courses during a semester, study the material, and be tested on it (and graded if he goes to Harvard). Yale's no-exam system and Harvard's integrated teaching of organ systems and pass/fail set-up have been labeled, perhaps too quickly, as overly progressive by a faculty that is upset with the falling academic performance of its students.

At both Yale and Harvard, 1968 marked a change from 2 years of basic science to 1½ years. The faculty teaching this material largely considered the reform to be a slap in the face. Harvard's basic science faculty counterattacked first, by focusing on the grading system in heated faculty meetings. They succeeded in abolishing pass/fail and then followed through by dismantling the core curriculum in small committee meetings.

Their counterparts at Yale, who did not have the use of an examination, brought their complaints to the Medical School Council and finally convinced the council that students should be evaluated in each course. The Yale student, for the first time in 40 years, will be obligated to choose among exams, written reports, or oral presentations as modes of evaluation in every course he takes.

The next step will be a return to 2 years of basic science, almost definite at Harvard and being lobbied for strongly at Yale. This change flies in the face of the national trend—subsidized with large financial incentives from the federal government—toward 3-year schools and abbreviated basic science curricula. The government incentives are predicated on helping to solve our health care problems by turning out more doctors more quickly.

"The financial pressures are very severe," admits Robert W. Berliner, the new dean of the Yale School of Medicine. "But somebody has to stand up and say, 'This is a lot of nonsense. This is not the way we should be going.'"

While the merits of examinations are obvious, Harvard's decisions to abolish most of its organ system teaching and to return to grades for preclinical work are probably too hasty. These decisions result largely from disgruntled faculty members displaying the political power of their hurt feelings.

Harvard and Yale are becoming more conservative in their educational policies, repudiating a 5-year experiment and a 40-year tradition, respectively. But if the focus of education at these schools continues to shift to the right, the pendulum will undoubtedly reach its limit and begin swinging the other way.—SAMUEL Z. GOLDHABER

RESEARCH NEWS

Thin Film Optics: Still in the Exploratory Stage

The prospect of optical communications systems with the capability of carrying vast amounts of information on a single light beam has tantalized communications engineers, both civilian and military, ever since the advent of the laser in 1960. But now, 13 years later, large-scale optical communications systems are still some time off, although in the last 2 years developments in optical fibers to carry light beams have greatly enhanced the practicability of long-distance optical communications. Cheap and reliable systems to generate light, to process the light to make optical signals, and to detect these signals have not yet been developed.

Present optical systems are composed of bulky assortments of lasers, mirrors, and other devices that are difficult to move or keep aligned. An increasing amount of interest and funding, therefore, is being directed toward thin film optical devices, in which optical functions will be accomplished by thin layers of materials deposited on a common backing or substrate. Such materials for use in optics have the potential for reducing the size of the devices and their cost and for eliminating mechanical alignment problems. The ultimate goal is an integrated optical system consisting of a single small substrate chip that supports a complete thin film optical circuit—a system which many researchers view as being analogous to integrated circuit electronics.

Among the components of a thin film optical system are light sources that generate an optical carrier wave, waveguides that carry the wave through the optical circuit to the transmission medium, and modulators that impress the signal to be transmitted (such as a telephone conversation or a television program) onto the optical carrier. Devices that transfer the modulated optical wave to the transmission medium —either an optical fiber or the air—and optical detectors that receive the transmitted wave are also receiving attention. The complete optical communications system would consist of these devices put together to form transmitting stations, repeater stations (to amplify the signal at intervals along the transmission path), and receiving stations.

The basic element of a thin film optical circuit is the waveguide, whose function is analogous to that of a wire in an electrical circuit. The waveguide is formed by depositing a thin film of material with a thickness comparable to the wavelength of the guided light onto a substrate; in order to delineate the waveguide pattern, excess material can be removed by means of photolithographic or related techniques that have been developed for integrated circuits. To perform as an optical waveguide, a thin film must have an index of refraction greater than that of the surrounding medium, that is, the substrate below and either air or some material above. Light that travels along the waveguide is thus reflected by the top and bottom surfaces of the thin film in a zigzag path and does not escape the film, provided that the light path does not make too large an angle with the waveguide surface. When the height and width of a waveguide are less than the wavelength of the light, there is a unique angle at which the light can reflect from the surface (single mode transmission). Larger waveguides permit light to reflect at several angles (multimode transmission). For many high-frequency applications, it is often useful to have single mode transmission.

Waveguides have been made by various processes from many different materials, including liquids, polymers, glasses, semiconductors, and insulators. Organosilicon polymer films on glass substrates have, for example, been made by P. K. Tien, G. Smolinsky, and R. J. Martin of Bell Telephone Laboratories, Holmdel, New Jersey, by depositing organosilicon monomers through an argon plasma, which initiated the polymerization, onto the glass substrate. These films exhibited waveguide propagation with an optical attenuation or loss of signal of less than 0.04 decibel per centimeter. A loss of 1 db/cm (20 percent per centimeter) or less is considered by most researchers as a useful indicator at which waveguide materials become practical. P. F. Heidrich and E. G. Lean of IBM's Thomas J. Watson Research Center, Yorktown Heights, New York, have made glass waveguides on quartz substrates which had signal losses of about 0.04 db/cm. The films were deposited by a sputtering process in which atoms from a target material were knocked loose by incoming ions under the action of an electric field and subsequently were deposited on the substrate.

If double film layers of two different materials are used, it is possible to substantially change the propagation of light waves in thin films. R. Shubert and J. H. Harris of the University of Washington, Seattle, have demonstrated that lenses, diffraction gratings, and other optical components can be fabricated by controlling the thickness or shape of the second layer.

Some scientists believe that the best waveguide materials will be those that can be used for both modulator devices and waveguides. Materials that are electro-optically active, such as gallium arsenide and its related alloys, lithium niobate, zinc oxide, and zinc selenide, are therefore the subjects of much current research and have been made into waveguides with losses less than or close to 1 db/cm. Similarly, piezoelectric materials, such as lithium niobate and zinc oxide, and magneto-optically active materials, such as the iron garnets, are also being studied.

In order to efficiently propagate through a waveguide, the light must be coherent, hence the requirement for the laser as a source. Although the discovery of the laser gave birth to the dreams of optical communications, lasers are, in many respects, the least developed component in an optical thin film circuit. But constructing a thin film laser in an optical circuit that will operate continuously for long periods at room temperature presents problems.

One solution to the thin film part of the problem depends on a principle called distributed feedback, first demonstrated experimentally by H. Kogelnik and C. V. Shank, of Bell Telephone Laboratories. A common procedure is to make a corrugation pattern on the top surface of the waveguide. This pattern can be formed when holographic techniques are used to make a mask along with, for example, an ion beam to etch the corrugations in the waveguide through the mask. The resulting periodic variation in the thickness of the waveguide, like the mirrors at the ends of a normal laser, permits the intensity of the coherent light to build up.

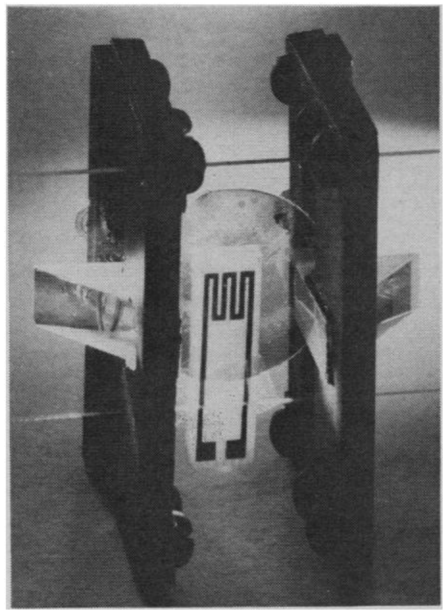

Fig. 1. Magneto-optic modulator, consisting of an yttrium gallium scandium iron garnet film on a gadolinium gallium garnet substrate and a serpentine-shaped electrical circuit. Current through the circuit creates a magnetic field, giving rise to the modulation. The laser beam enters and leaves the modulator through the prisms at each end.

Using this principle, a number of workers have observed lasing action in rhodamine 6G thin film dye lasers. Dye lasers have the disadvantages of having to obtain their energy from another laser and having a short lifetime before failure; but they are of interest because they are tunable in the visible wavelength region and thus could perhaps function at several wavelengths. The successful action of a gallium arsenide laser having the corrugated structure has been demonstrated (at 77°K) by M. Nakamura, A. Yariv, and other workers in a cooperative research effort at the California Institute of Technology, Pasadena, California, and the Hughes Research Laboratories, Malibu, California. Like the dye laser, this gallium arsenide laser also received its energy from another laser. Experiments are also planned to apply the same principle to gallium arsenide junction lasers.

P-n junction lasers seem appropriate for thin film applications not only because they are potentially adaptable to this form, but also because they can be electrically rather than optically excited—a property that permits them to be modulated directly by varying the exciting current, rather than by relying on external modulating devices. Gallium arsenide is especially appealing because the wavelength of light emitted (0.84 micrometer) is propagated efficiently in systems having optical fibers as the transmission medium. So far, p-n junction lasers made only from gallium arsenide do not work at room temperature because of heating problems associated with the relatively high electrical excitation currents required. A more complicated laser made from gallium arsenide and aluminum gallium arsenide (a heterojunction laser) was initially conceived independently in several laboratories in the U.S.S.R. and in the United States. Drawing from the early work of M. B. Panish, I. Hayashi, and their co-workers, researchers at the Bell Telephone Laboratories at Murray Hill, New Jersey, have built long-lifetime (several thousand hours) lasers capable of continuous operation at room temperature. In this structure, layers of aluminum gallium arsenide surround the active gallium arsenide layer and confine the excess current carriers to the gallium arsenide layer, so that the excitation current required for lasing is reduced. This multilayer structure may, however, be hard to adapt to the distributed feedback mode of operation.

Yttrium alunminum garnet (YAG) containing neodymium impurities (neodymium-doped), like gallium arsenide, is of interest as a laser material because its wavelength (1.06 μm) is also suitable for systems with optical fiber transmission lines, but, like the dye lasers, would have to be optically excited. Japanese workers have made thin film neodymium YAG lasers without using the distributed feedback principle, so that coupling such a laser to a thin film circuit remains to be accomplished. Some communications systems may not use optical fibers at all, but may rely on propagation through the atmosphere. For these systems, thin film infrared junction lasers comparable to the 10.6-μm carbon dioxide gas laser will be of interest. H. Holloway and others of the Ford Motor Company at Dearborn, Michigan, have, for example, demonstrated lasing (at 77°K) in thin films of lead telluride. Further work is planned to apply the distributed feedback principle in this material.

At some point the signal to be transmitted must be impressed onto the optical carrier wave; that is, the optical wave must be modulated. A digital system, for example, might operate by turning the light on or off in the waveguide. Modulation schemes are based on changing the index of refraction of the waveguide material. Depending upon the particular effect and the experimental arrangement, the wave amplitude, phase, or frequency can be modulated.

Electro-optic modulation methods are among those most likely to be used, some scientists believe, because of the potential for low power required for operation and the possibility of high modulation speeds, exceeding 1 gigahertz. When a d-c electric field is applied to an electro-optically active material, the material becomes birefringent; that is, the index of refraction of the material depends on the relative orientation of the optic axis induced by the electric field and the polarization vector of the incident light wave. This effect can be used to modulate the amplitude or phase of a light wave. One amplitude modulation scheme that has been demonstrated by G. P. GiaRusso and co-workers at the University of Washington in Seattle and J. M. Hammer and co-workers at the RCA Laboratories, Princeton, New Jersey, consists of an electronic diffraction grating that is activated by applying a voltage to closely spaced copper fingers on a waveguide. When the voltage is applied, the grating diffracts the light, resulting in an amplitude change of the undiffracted transmitted light. Electro-optical modulation schemes have been demonstrated in a variety of materials, including gallium arsenide, zinc oxide, zinc selenide, lithium niobate, and nitrobenzene.

Much attention is also being focused on acousto-optic modulation, which may require less power than electro-optic modulation, but which is probably limited to slower modulation speeds, perhaps less than 100 megahertz. In the original experiment, by L. Kuhn and others at the IBM research center in Yorktown Heights, an acoustic surface wave was generated on a quartz substrate, resulting in a periodic variation in the index of refraction of a sputtered glass waveguide, and this variation was used to deflect the optical wave. Lithium niobate also has been used as a substrate. Work is currently progressing on piezoelectric materials, such as lithium niobate and zinc oxide, which can also serve as waveguides, so that the acoustic wave and the optical wave will be propagated in the same material.

Magneto-optic modulation depends on the Faraday effect whereby the plane of polarization of a light wave is rotated in a magnetic field. Researchers disagree as to how fast magneto-optical modulators may operate, but modulation speeds of a few hundred megahertz have been demonstrated in single crystal garnet films (Fig. 1).

Because of the small dimensions of waveguides, a moderate laser power results in very high electric fields in the waveguide, leading to the possibility of nonlinear optical effects, such as harmonic generation and frequency conversion. Nonlinear effects depend on higher than linear powers of the electric field, and are therefore observable at high fields. Second harmonic generation, which converts a light wave with one frequency to a light wave with twice the original frequency, has, for example, been demonstrated in several materials.

Advanced Concepts to Come

Eventually, devices to perform such functions as switching, mixing, and multiplexing will be an important part of thin film optical circuits. A step in this direction was taken by S. Somekh and several others working together in the collaborative effort at California Institute of Technology and Hughes Research Laboratories, when they switched a guided wave between parallel gallium arsenide waveguides. The not-yet-demonstrated ability to control the coupling by applied electric fields could lead to optical multiplexing. Several investigators have also speculated upon, but have not demonstrated, devices that would operate on principles distantly related to that of the distributed feedback laser. One such device, mentioned by some researchers, is a high-speed modulator (greater than 10 gigahertz) that could couple a microwave signal to the optical carrier wave.

At the receiving end of the optical system, the light wave must be detected so that the information can be recovered. Detectors appropriate for thin film optics are likely to be semiconductor detectors in which the incident light on a semiconductor p-n junction or a metal-semiconductor junction generates a voltage. At least two such schemes have been reported. In the first, D. B. Ostrowsky and co-workers at Thomsen/SCF in France reported on a silicon photodiode detector that had been integrated with a sputtered glass waveguide on a silicon dioxide substrate. More recently, H. Stoll and co-workers at the California Institute of Technology and Hughes Research Laboratories have constructed a metal-semiconductor junction of aluminum and gallium arsenide by bombarding the gallium arsenide with protons to make it absorbing and then evaporating aluminum on the proton-bombarded material. Integrating with a gallium arsenide waveguide is straightforward, since the waveguide can be formed first, and then the desired area for the detector is delineated by the proton bombardment. Work is also progressing on junction detectors consisting of lead salt alloys.

Today, most researchers agree, thin film optics is still in the stage where workers are interested in demonstrating that the various functions needed for optical circuitry can be performed by many kinds of materials. Still to come is the day when a fewer number of materials will be used in economically feasible systems and when performance will be optimized. In the meantime, the number of materials being considered suggests that the first thin film optical circuits will be made with several materials—a hybrid circuit. Some laboratories have already demonstrated that light from one waveguide can be coupled to another waveguide made from a different material by means of tapered junction regions between the devices in series. Other approaches to coupling between parts of thin film circuits are also being investigated.

Optical communications with its potential for large information-carrying capacity, high speeds, low cost, and security from interference is clearly the communication system of the future. Thin film optics with its potential for miniaturization, low cost, and ruggedness is eliciting enthusiasm among workers in the optical materials field, and should have a large impact on optical communications. In the present exploratory stage of development of thin film optics, however, nobody can yet foresee exactly what that impact will be.—ARTHUR L. ROBINSON

Additional Reading

1. D. Marcuse, Ed., *Integrated Optics* (IEEE Press, Institute of Electrical and Electronic Engineers, New York, 1973).