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Integrated Optics: An Introduction

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This paper outlines a proposal for a miniature form of laser beam circuitry. Index of refraction changes of the order of 10^{-2} *or* 10^{-3} *in a substrate such as glass allow guided laser beams of width near* 10 *microns. Photolithographic techniques may permit simultaneous construction of complex circuit patterns. This paper also indicates possible miniature forms for a laser, modulator, and hybrids. If realized, this new art would facilitate isolating the laser circuit assembly from thermal, mechanical, and acoustic ambient changes through small overall size; economy should ultimately result.*

I. INTRODUCTION

Laboratory work and experimental repeater work at laser wavelengths (0.4 to 10 + μm) has been carried out by interconnecting the oscillators, modulators, detectors, and so on, using a form of extremely short-range radio. A freely propagating beam has been reflected around corners, occasionally refocused with lenses to avoid energy loss resulting from beam spreading, and often sheltered by tubular enclosures from refractive distortions resulting from thermal gradients in the ambient air. Typical separations between components range from a few centimeters to a foot; aggregations of apparatus in a single-channel experimental laser repeater are measured in square feet. The resulting apparatus is sensitive to ambient temperature gradients, to absolute temperature changes, to airborne acoustical effects, and to mechanical vibrations of the separately mounted parts. All of these effects are understood and are susceptible to appropriate engineering design; but one naturally looks for alternatives.

Looking ahead, one sees the possibility of guiding laser beams on miniature transmission lines, analogous to the hollow rectangular waveguide or coaxial cable used extensively in lower frequency repeaters. Accompanying papers report contributions leading toward the new form of laser circuitry.[1–3] This paper gives a general view of the proposal and indicates specific component possibilities.

II. LASER BEAM GUIDANCE

We visualize a dielectric waveguide wherein a region having an index of refraction n_2 is surrounded by a region of index n_1, as in Fig. 1a. Then a two-dimensional analysis shows that the energy in the lowest-order guided wave is confined almost entirely to the n_2 region if

$$n_1 = n_2(1 - \Delta), \tag{1}$$

where

$$\Delta \cong \frac{3}{4}\left(\frac{\lambda}{a}\right)^2 \tag{2}$$

λ = free space wavelength
a = half-width of n_2 region, $(\lambda/an_2) \ll 1$.

Table I, calculated from equations (1) and (2) for $\lambda = 0.6328\ \mu$m, shows that only a very small change in index Δn_2 is needed to provide the desired guidance. Some higher order modes are above cutoff using these parameters; more exact theory can be used to calculate the smaller guide width which restricts the guidance to a single mode at

Fig. 1 — Waveguide cross sections: (a) rectangular shape, index $n_2 > n_1$, (b) round shape.

TABLE I—VALUES OF Δ FOR VARIOUS OPTICAL BEAM WIDTHS

Optical Beam Width $2a$	Δ
1 mm	10^{-6}
0.1 mm	10^{-4}
0.01 mm	10^{-2}

the expense of having a larger field component at the n_2 to n_1 interface where dimensional irregularities may occur.[1-4] Values of Δ larger than tabulated for a particular guide width $2a$ do not appreciably change the field distribution for the lowest order mode in the n_2 region but would allow more propagating modes.

It is not important that there be a sharp step in index as in the n_2 to n_1 transition of Fig. 1a. Alternatively, the index can taper smoothly from a maximum at the waveguide's center to a lower value at radius r according to*

$$n = n_2[1 - c(r/a)^p] \tag{3}$$

with

$$c = 0.16\left(\frac{\lambda}{a}\right)^2$$

$$2a = \text{laser beam width, provided } a \gg \lambda. \tag{4}$$

The exponent p can have any even positive value; the lowest order mode field always has an approximately cosinusoidal shape in the region $0 < r < a$ with about 1/10 peak value at $r \cong a$ and with approximately exponentially decaying magnitude for $r > a$.

The square law index variation, given by $p = 2$ in equation (3), has the well-known property that phase constant differences for the various propagating modes are independent of frequency.[6,7] The square law medium is free of delay distortion resulting from mode conversion and is unique in that property.[5,8]

We can anticipate guiding beams around relatively sharp bends as summarized in Table II. The Δ's associated with these beam widths may be obtained from equation (2) or Table I. By using a guide which confines the beam to a 5 to 10_μm width (implies a Δ of 0.04 to 0.01) the bend radius can be in the 1.8 to 14.5 mm (70 to 570 mils) region, which could facilitate very small circuitry.

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* A somewhat more accurate expression is given as equation (59) in Ref. 5. This permits a series of terms in $(r/a)^p$ to represent the index variation.

TABLE II—ESTIMATED BENDING RADIUS

Laser Beam Width $2a$ in mm	Estimated Acceptable Bending Radius in m* ($\lambda = 0.633\ \mu$m)
1	14,500
0.1	14.5
0.01	0.0145
0.005	0.0018

* This estimate is obtained using equation (33) of Ref. 9, and includes an allowance of 0.25 dB maximum loss resulting from a bend of any angle.

III. FABRICATION OF SMALL WAVEGUIDES

Tiny laser guides can be fabricated in the form of glass fibers. Previous work on fiber-optics for image transmission or incoherent light sensing has provided a considerable body of experience on which to build, not all of which is applicable. So-called "clad" fibers have two discrete regions of index as in Fig. 1a. The n_1 region (which carries little light) must be as thin as possible in image-transmitting fibers to minimize the "dead" region in the output image. For modulated laser beam transmission the cladding must be much thicker and the "core" (n_2 of Fig. 1a) much smaller to yield well-isolated single mode transmission.

Whereas glass fibers may be used to connect repeater components and certainly are convenient as flexible connections, we can use another form of dielectric waveguide for miniature laser circuitry. Fig. 2

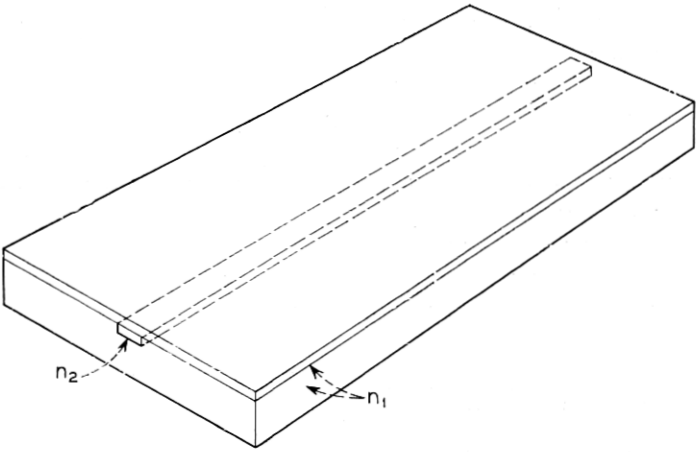

Fig. 2 — Planar waveguide formed using photolithographic techniques.

shows a channel of index n_2 surrounded by a region of index n_1, which would serve as a dielectric waveguide of the type discussed in connection with Fig. 1. This might be created in glass using a series of steps as follows. A mask could be used to expose selectively a light-sensitive photo-resist previously placed on a sheet of glass, followed by washing and selective deposition (if needed) of a more durable material for masking purposes. Then a diffusion, bombardment, or ionic replacement process could be used to change the index of refraction of the glass, thereby creating the n_2 channel imbedded in the n_1 substrate. Finally the top layer of n_1 material could be sputtered on the entire top surface.

Using photolithographic techniques which are currently evolving for low frequency integrated circuit applications, channel widths in the 2 to 5 μm range may be achievable and dimensions on the order of 10 μm are readily held. Complicated masking patterns may in time be made, leading to the possibility of simultaneously making complicated laser circuits using combinations of elements such as those described in the following paragraphs.*

This description is intended to be a broad indication of possible feasibility rather than a blueprint. However, relevant contributions are appearing. G. M. C. Fisher and A. D. Pearson have reported processes which reduce or increase the index of refraction of glass by as much as 0.7 per cent.[10] F. K. Reinhart, D. F. Nelson, and J. McKenna have reported the existence of an index increase in gallium phosphide junctions which is effective as a light guide at zero bias.[11-13] Optical waveguides formed by proton irradiation have been reported.[14] Further contributions may be anticipated.[15]

Some relevant work on two-dimensional light guides has been reported.[16-20] In this work one transverse dimension of the guided wave was in the 10 to 100 μm region; but the other transverse dimension was orders of magnitude larger. We seek waveguides tightly guided in both transverse dimensions in order to make possible the components proposed in Section IV.

IV. INTEGRATED-CIRCUIT LASER

The transmission line of Fig. 2 becomes a resonator when mirrors are placed at the ends, or when a series of partially reflecting trans-

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* Complicated masking patterns are feasible now where the area involved is small; depth-of-focus problems may require advances in masking to produce the large area patterns we need.

verse lines are spaced at an odd quarter-wave multiple apart to reinforce reflections at the resonator's peak frequency (Fig. 3). The partial reflectors are analogous to layered dielectric mirrors and are large enough in the transverse plane to intercept most of the guided-wave energy; they may be increased index regions placed in the sheet as noted in Section III, empty grooves, or minute grooves coated with metal.

By adding a small concentration of neodymium ions and by providing a pump, the resonant cavity becomes a laser. Fig 4 shows, in cross section, two possible ways the pump might be applied. In Fig 4a the active material (such as neodymium) can be applied only in the vicinity of the n_2 waveguide channel (by sputtering on the surface, beneath the SnO_2 film, for example) or might be distributed throughout the substrate. The spherical reflector confines the pump energy near the waveguide where the laser field is a maximum. The electroluminescent material (for example, doped zinc sulphide) is selected to provide radiation at a pumping line for the active lasing materials.

In Fig. 4b, ac (kilohertz rate) excitation of the electroluminescent pumping material is implied; the electroluminescent material is distributed throughout the glass substrate. Relatively low power laser sources might be produced in similar structures, the order of 0.1 watt being adequate for many communication applications.

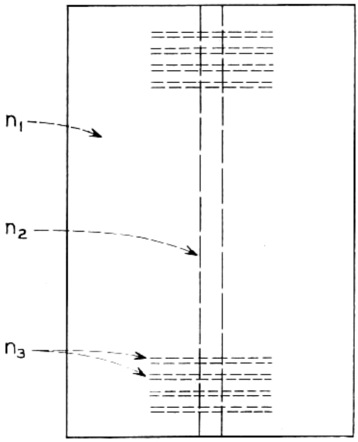

Fig. 3 — Resonator using planar waveguide.

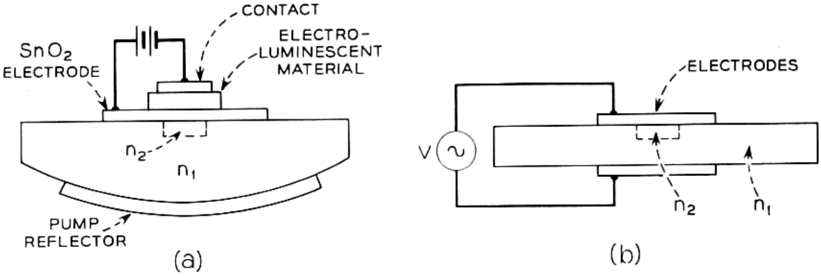

Fig. 4 — Cross sections of possible lasers in planar waveguide: (a) external pump (b) pump ions imbedded in laser circuit.

V. MODULATOR

Figure 5 shows a possible phase modulator for a guided laser beam. The electrooptic material might be the substrate or might be applied as a thin surface layer adjacent to the guiding index region n_2. Using photolithographic techniques, it should be possible to use spacing between the metallic electrodes of about 25 μm which would yield large modulating fields with only a few volts of modulator drive.

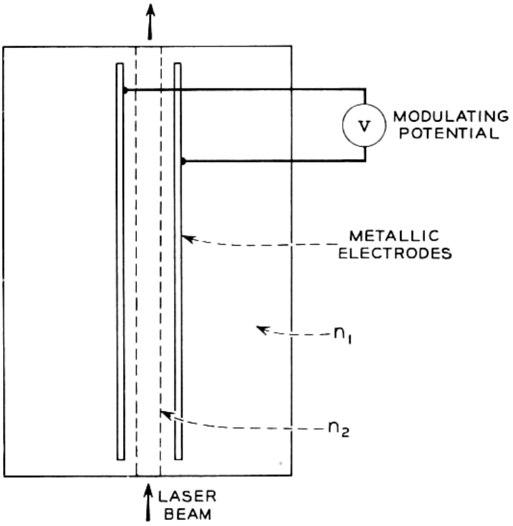

Fig. 5 — Phase modulator.

VI. HYBRID

Figure 6 shows the directional coupler form of hybrid. The exponentially decaying fields, propagating in the n_1 region of Fig. 2, overlap for the two parallel guides of Fig. 6, providing continuous distributed coupling. Reference 1 gives approximate expressions for calculating the guide spacing and needed coupling length.

Figure 7 shows the partially reflecting mirror form of hybrid; the reflecting line may be a narrow groove coated with a metal film, an empty groove, or a high index dielectric region created by a masking and diffusion or ionic replacement process. A single empty groove, an odd quarter of a wavelength thick, in the direction of propagation would give a coupling loss of about 9 dB.

VII. FREQUENCY-SELECTIVE FILTERS

Using techniques familiar at lower frequencies, hybrids and resonant circuits can be combined to form filters, a needed component in frequency-division multiplex systems. Figure 8 shows such an arrangement, where band pass cavities C_1 and C_2 are used to separate f_a from f_b and f_c; hybrids divide and recombine the energy to form a constant

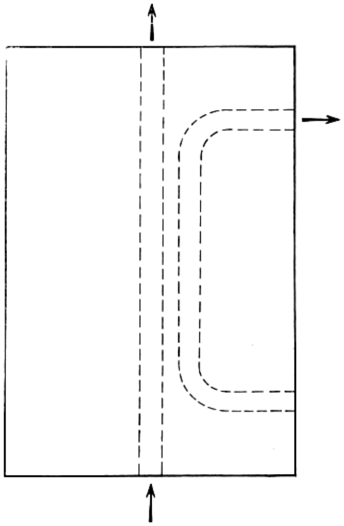

Fig. 6 — Directional coupler type hybrid.

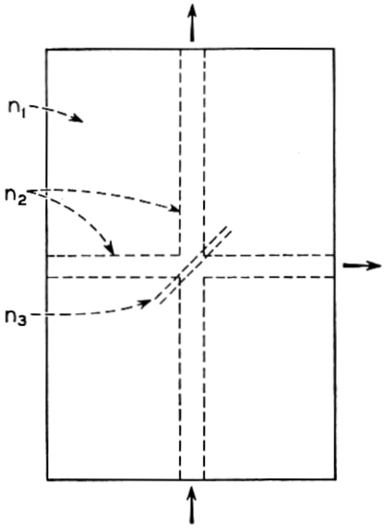

Fig. 7 — Junction type hybrid.

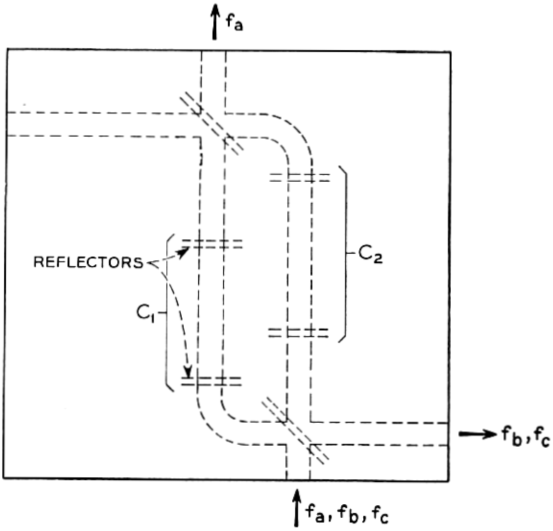

Fig. 8 — Channel dropping filter.

resistance filter. Alternatively, a multiple-line grating could be used in place of the resonant cavities as the reflecting element to reflect f_a only, and the output positions of f_a and f_b, f_c would interchange.

In filters of this kind the intrinsic loss of the substrate is of course important. Good quality glasses have bulk losses as low as 1 dB per m, which corresponds to an intrinsic Q of about 30 million; this would allow filters with band widths of a few hundred megacycles in the visible region; therefore, intrinsic substrate loss should not be too limiting.

VIII. CONCLUSIONS

This paper outlines a prospect for laser circuitry and devices which, if realized, would have many attractive features. Photolithographic processes would simplify reproducing complicated circuits, once the original was developed. Small size would facilitate isolating the completed circuit assembly from thermal, mechanical, and acoustic ambient changes. For communication purposes, low laser power levels are adequate so that the heat to be dissipated hopefully will not be large. In the very small laser beam cross sections, nonlinear effects needed for modulation and frequency changing should be achievable with only a few volts of drive.

Finally, a word of caution is needed. Work is just beginning in the directions indicated, and we have identified goals rather than accomplishments. We recognize these are difficult goals; but we believe they are worth the serious effort required to achieve them.

IX. ACKNOWLEDGEMENT

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