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Military Applications of Fiber Optics and Integrated Optics

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Invited Paper

***Abstract*—A general discussion of military applications of integrated optics and fiber optics is presented. Specific applications discussed are: 1) a multiterminal multiplexed data highway for aircraft and shipboard use; 2) optical fibers as tethers; 3) a 10.6-μm heterodyne detector; and 4) integrated optical phased arrays.**

I. Introduction

THE VIRTUES and potential of fiber optics and integrated optics are well known and have been discussed in other papers in this section. This area of optical technology is receiving a lot of attention at the present time from industry and the military. From the military point of view there are a fairly large number of application areas where this technology can possibly offer unique solutions to critical problems. In the remainder of this paper a few possible application areas will be discussed ranging from near-term to long-range possibilities.

Fiber optics is receiving a lot of attention at present due primarily to its potential for the telecommunications industry. Fibers with extremely low losses have been reported and the prospect of ultrahigh bandwidth optical transmission lines with multikilometer repeater spacing is a very real possibility. However, the large-scale use of fibers for telecommunications is probably at least ten years away. The military, on the other hand, has very real problems that can be solved with fibers of shorter length and more modest bandwidth. For example, optical information transfer (OIT) on board aircraft involves fiber lengths of less than 30 m, and bandwidths less than 100 MHz. Since higher losses can be tolerated, these applications can proceed without a large amount of fiber development.

The realization of the full military potential of OIT, and in particular fiber optic systems, will be aided by the development of integrated microoptical circuits [1]. In general, this technology will eliminate many problems inherent in bulk optical devices. The optical processing of information with integrated microoptical circuits will minimize the number of optics–electronics interfaces in OIT systems.

The potential advantages of OIT systems are well understood qualitatively. Generally, the use of fiber optics instead of conventional transmission lines in military hardware should cause the following impact.

1) Reduce, by up to a factor of 5, transmission-line system size and weight for conventional information bandwidths. This will make redundant control systems attractive which will increase reliability and battlefield survivability. As the individual fibers in a fiber bundle break, optical systems are expected to experience a gradual degradation in contrast to the catastrophic failure caused by shorts with conventional technology.

2) Eliminate the problems caused by electromagnetic crosstalk and interference which will allow close spacing of transmission lines and operation near radar transmitters.

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3) Increase electromagnetic security by eliminating RF emission and making inductive taps impossible.

4) Decrease interface problems, such as ground loops, making modular avionics more attractive.

5) Ultimately lead to ultra broad-band communication bandwidths (1–10 GHz).

It seems probable that integrated optical circuits (IOC) will be used in conjunction with fiber optics transmission systems to overcome some of the difficulties associated with using light to transmit information and may also find an independent role in various forms of optical processing.

The interest in fiber optics and IOC evidenced by the commercial telecommunications industry is clearly motivated by a well-defined eventual requirement for ultra broad-band (1–10-GHz) communication systems. When a high degree of multiplexing becomes common, such a broad-band capability (evidenced by single-mode or SELFOC fibers) will also prove advantageous for future military systems. Over the intermediate term, however, the introduction of this technology will involve applications requiring lower bandwidths where the first four listed advantages are important and bundles of conventional multimode fibers can be used.

II. Areas of Application

An important area that is being worked on now is optical data transmission for aircraft. The first generation of this concept is a collection of point-to-point fiber optic links. More advanced concepts involve optical data highways with several random access terminals. Optical links such as these would carry information between computers, sensors, and systems on board an aircraft. They are attractive because potentially they are small, lightweight, free of EMI, free of impedence matching problems, secure, and could lead to modular avionics.

There is another general area where optical fibers can play a key role. This is the problem of tethers for towed arrays, remotely piloted vehicles, wire guided missiles, etc. The need here is for a lightweight data link over a very long path length. Development of this area will require the lowest loss fibers and/or small repeaters.

The later generations of both these applications will involve integrated microoptical circuits. This technology is farther off than fiber optics but it is progressing steadily and offers a lot of potential. There are also areas where integrated optics alone are important. Efficient two-dimensional acoustooptical scanners for optical data recorders are possible and acoustooptical deflection can be used in an integrated optical circuit along with a linear array of detectors to form a microwave frequency analyzer. Two-dimensional optical signal processing is also possible in IOC form. Other applications are in the IR and in particular at 10.6 μm. These applications are tied to the increased use of CO_2 lasers for military applications. Efficient high-frequency modulators can be made in microoptical form which can be used with modest power levels. Optical receivers using heterodyne detection for laser radars and satellite communications links can also be made in microoptical form. The requirements for frequency tunable local oscillators and complex array geometries make bulk optical heterodyne receivers extremely complex and sensitive to environmental effects. IOC is a possible solution to these problems. Another area is coherent phase front control. An IOC array of phase modulators could conceivably be constructed to correct a laser beam for atmospheric distortion effects and provide some beam steering although the limited power-handling capability of IOC would be a serious constraint.

There are many more areas for IOC application that can be considered such as display, up-conversion, and lightweight atmospheric optical data links. With careful consideration of the state of the art of what can be done in the near future these applications seem further off.

Fiber optics communication systems will be limited to the visible and near IR portion of the spectrum since in that region diode light sources are available, detectors do not have to be cooled, and the most likely fiber materials have their maximum transparency. IOC experimental procedures are usually easier in the visible or near IR, however dimensional tolerances can be relaxed as one proceeds into the IR.

In the remainder of this paper four possible application areas with military relevance are considered in detail—optical data bus, 10.6-μm optical heterodyne detector, tether, and optical phased array antenna. These four applications address real problems and include a rather broad cross section of fiber optics and integrated optics technology.

III. Optical Data Bus

Fiber optics technology offers much promise for data communication systems. Indeed all of the efforts of Bell Labs in this technology are directed towards this application. The military will, however, have special requirements. In general, bandwidths will be smaller than those of the telecommunications industry and lengths will be shorter with more input–output terminals required along a transmission line. The principal military application of fiber optic bundles will involve multiplexed transmission lines of moderate length interconnecting avionics subsystems on aircraft or ships. For military application the emphasis will eventually be on multiterminal systems. Severe volume, weight, and mutual interference problems are now encountered when conventional transmission lines are jammed together on mobile platforms.

For moderately large information capacities, optical transmission lines in avionics systems will offer advantages involving volume, weight, and complete invulnerability to electromagnetic interference and interface problems, compared to conventional RF transmission lines. Fiber optics bundles need be no more than 1 mm in diameter even for large information capacity. For tens of megahertz bandwidths, conventional transmission lines often need diameters to ten times this size. The elimination of ground loops should make modular electronic systems more attractive. The potential advantages of optical transmission systems such as insensitivity to high temperatures, reliability (through redundancy), and lack of fire hazard may also prove important in select cases.

Integrated optical circuits can play a role in such systems by providing sources and modulators for systems which use conventional multimode fibers and additionally by providing couplers (active and passive) and remote optical switches for systems which use single-mode fibers. With the advent of spectral multiplexing techniques, integrated optical circuits can provide wavelength selective couplers and components for single-mode systems. With transmission lines which use a large number of modes IOC will not be able to provide signal processing after the data have passed through the transmission line since efficient coupling from a multimode fiber to an IOC, which contains at most a small number of modes, is not possible.

The first generation of multiplexed optical data transmission systems probably will be configured to be adequate for aircraft avionics and the sensor subsystems of small ships. A main transmission line length of 30–60 m with eight or more major input and output terminals (with multiple access) and a 10–100-Mb/s information capacity should cover both applications. 100 Mb/s is enough to simultaneously transmit one to two TV images. Bandwidth requirements often depend on whether TV imagery is carried on the bus. Hierarchical access to the bus will be required to hold coupling losses down. For these lengths and bandwidths use of a multimode fiber optics bundle with low-cost GaAs light-emitting diodes ($P \sim 1$ mW) and silicon p-i-n photodiode detectors is the most straightforward approach. Nonreciprocal coupling (all the input gets on whereas only a fraction of the throughput is coupled off) to the bus is required to limit terminal loss if a conventional data bus layout is used (see Fig. 1). Such input–output coupling to the main data bus could most easily be provided by nonreciprocal "T" connectors.

A desire for the use of low-cost light sources [1-mW light-emitting diodes (LED's)] and silicon p-i-n diodes sets a maximum transfer loss of ~25 dB for a 100-Mb/s information capacity. Most of this loss will be associated with splitting off from the main line at the major terminals. This loss must be carefully divided up between components. Throughput loss caused by packing fraction problems occurring at each "T" coupler is the major problem with the conventional data bus layout. Alternatively, the "star" layout approach to multi-terminal communication systems, developed by Dr. Frank Thiel of the Corning Glass Works, can be used where each terminal has a separate input and output bundle which connects to a central "scrambler."

The principal components which need development are the following.

1) Multimode fiber bundles; 60-m lengths will be required with reasonable packing fraction losses and transmission losses <50 dB/km, so that the loss over 60 m will be less than 3 dB. The low numerical apertures (~0.2) required for the higher bandwidths will require large bundles and special input optics to keep LED input losses reasonable. Higher numerical apertures (NA) should be used with lower bandwidths and/or shorter links. An NA ≥0.4, 80-dB/km fiber would also be very useful. End finishing and repair techniques will have to be worked out for the bundles and high-temperature (300°C) fiber sheathing will need development since the present sheathing melts at temperatures of about 105°C.

2) Optical "T" connectors need development. The approach with the lowest loss is to essentially use bundle fractionation along with a number of scramblers to ensure that all the information is carried on each fiber before the next terminal is reached. This approach is nonreciprocal in the sense that all the information is coupled onto the rod, whereas only a fraction is coupled off.

If a light pipe integrator (clad glass rod) is used as the scrambler packing, fraction losses will be limiting. Present low-loss multimode optical fibers lead to high packing fraction losses (5 dB) unless the cladding is removed.

An optical "T" connector currently being worked on at NRL [2] is shown in Fig. 2. Here a fiber bundle is terminated and contacted with a solid glass cylinder. Light from any single fiber in the bundle illuminates the entire exit face of the cylinder. Hence this element acts to integrate or "scamble" the incoming signal over the entire aperture. The technique shown in Fig. 2 uses two cylinders with the input–output

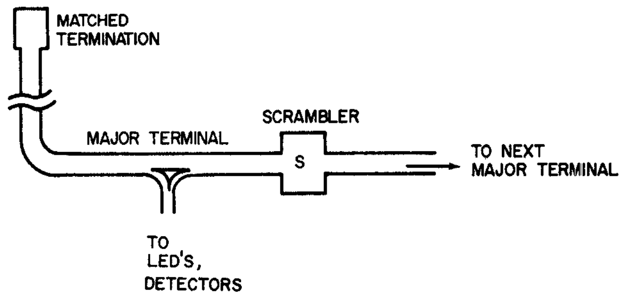

Fig. 1. Optical data bus with fractionation at each major terminal, and scramblers.

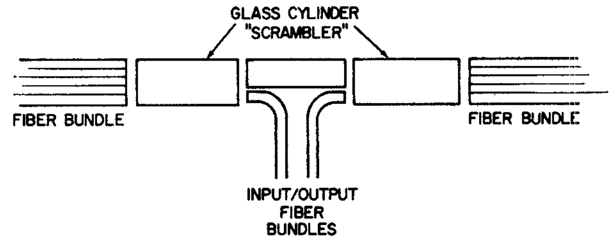

Fig. 2. A schematic diagram of a scrambler–coupler technique being developed at NRL for use with an optical data highway.

coupling to the bundle between them. The central portion is a third glass cylinder with a flat ground on one side. This area serves to allow a small fiber bundle to couple to the scrambler for input–output functions. This "T" coupler is nonreciprocal, self-contained, and needs only suffer one packing fraction loss on throughput.

3) High radiance LED's and silicon photodiode p-i-n structures which meet environmental specification will have to be put together. For modulation frequencies of 50 MHz and above some LED development is necessary. Otherwise, satisfactory components are commercially available.

Growth versions of the multiplexed data bus will be appropriate for large ships. Here 300-m lengths will be needed with up to 100 terminals. 300-Mb/s information capacity should suffice. Transmission losses and terminal bypass losses will now dominate input–output losses so that lower loss fiber bundles, higher power sources, and more sensitive detectors will be needed. Spectral multiplexing should be used to reduce bandwidth requirements. Repeaters will be needed and laser sources and avalanche diodes should be considered with low numerical aperture bundles.

An alternate approach is to use single-mode or SELFOC fibers. Spectral multiplexing might be useful but would not be required, since with these fibers the transmission line will not limit the bandwidth. Laser sources will be required. Diode lasers can operate CW at room temperature, but the lifetime is still limited. Efficient coupling into a bundle of single-mode or SELFOC fibers from a single source is not straightforward. Use of a single fiber instead of a bundle loses the advantages of redundancy and the advantage of fractionation. However, single-mode operation (or operation with a limited number of modes) is more advantageous to IOC device techniques and coupling to the main bus could be performed by using IOC. If single-mode operation is used, coupling will have to be achieved by the use of active switches which change the coupling with time. A bidirectional repeater will require the development of an optical circulator which will require magnetic optical devices. With single-mode operation optical switches at the terminals can be made in IOC form (see Fig. 3).

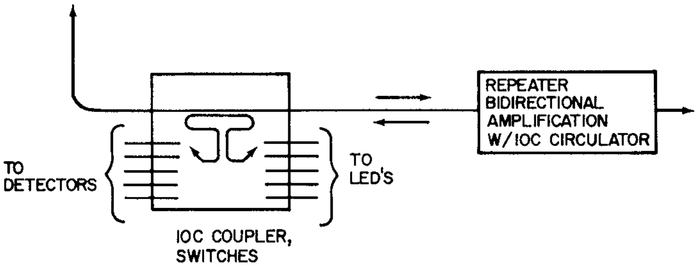

Fig. 3. Single-mode fiber optical data bus using IOC terminals and IOC bidirectional repeaters.

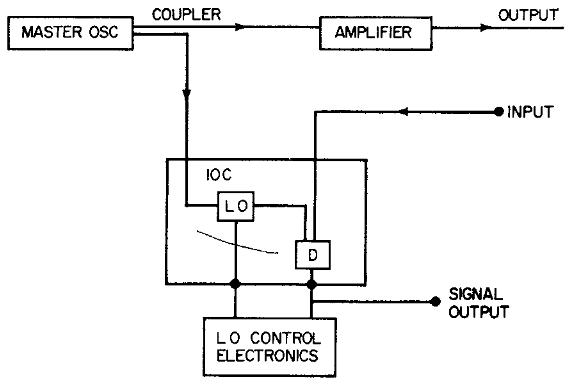

Fig. 4. Block diagram of an optical heterodyne detector where the LO signal is obtained by Doppler shifting a portion of the master oscillator power (see text).

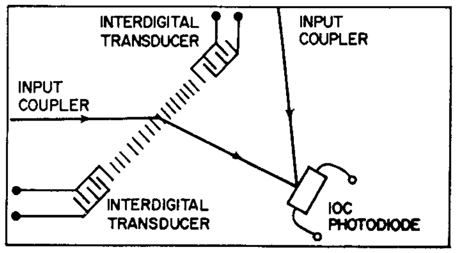

Fig. 5. Basic optical heterodyne unit with Bragg scatterer for LO generation and IOC photodiode.

IV. 10.6-μm Optical Heterodyne Detector

In the infrared, the heterodyne detection of laser radiation offers significant advantages over direct detection. When a heterodyne receiver is operated with enough local oscillator power, dark current noise and receiver thermal noise can be suppressed even for very wide bandwidth operation. The signal-to-noise ratio (SNR) can thereby be increased to the signal photon noise limit. Indeed the narrow spectral acceptance of the heterodyne system ($\Delta\lambda/\lambda < 10^{-3}$) is the only way to achieve this result near 10 μm due to the large thermal backgrounds which are usually present at these wavelengths.

Both the large thermal backgrounds and the absence of high-speed detectors for $\lambda = 10.6$ μm with internal current gain make heterodyne detection particularly attractive for CO_2 laser systems. Heterodyne techniques would also be advantageous for laser systems operating in the 3–5-μm window (DF or CO) since thermal backgrounds are still troublesome and no high-efficiency photocathodes exist for those wavelengths.

Heterodyne detection for optical communication systems, optical radar systems, and laser-line and raster scanners can significantly reduce transmitter power requirements; however, at this time this detection technique is complicated and expensive. The primary reason is that a laser local oscillator must be provided and careful alignment maintained.

Master oscillator fluctuations and Doppler shifts due to moving targets and receivers will change the frequency of the received radiation. Unless the local oscillator tracks these shifts the detector must be operated with a very wide bandwidth with bandwidth reduction accomplished after the IF channel. Since Doppler shifts for space targets get as high as 1.5 GHz at 10.6 μm (150 MHz for airplane targets) detector frequency response and electrical crosstalk problems are serious, and large LO power and expensive electronics are necessary with a fixed-frequency LO approach.

A far more elegant solution is to frequency shift radiation from the transmitter master oscillator for the local oscillator and make it frequency track the received signal. Indeed this would in many cases be the only way to use heterodyne detection in the mid-IR, since Doppler shifts get larger at shorter wavelengths. Even at 10.6 μm severe problems have been encountered in developing frequency shifters of sufficiently high bandwidth using bulk electrooptical and acoustooptical interactions [3], [4]. Interactions which are confined to an optical waveguide may offer the best approach to constructing a practical frequency shifter since higher efficiency can be obtained due to the absence of diffraction effects. The alternative of using $Pb_{1-x}Sn_xTe$ diode lasers for tunable LO power does work but problems in obtaining sufficient output power in a single mode remain [5].

Integrated optics offers potential for the heterodyne detector. With IOC the detector diode, local oscillator source, and frequency shifter are an integral unit. This unit is small, lightweight, and free of environmental effects such as vibrations. Frequency shifting of the LO should be very efficient with IOC. Packaged in this manner the heterodyne detector could be stacked into arrays for IR image detection. Present technology concepts for matrix heterodyne receivers, to be used with pulsed imaging laser radars, have serious image disection problems which could be helped by the introduction of 10.6-μm optical waveguides. Photodiodes have not yet been fabricated to be compatible with optical waveguides. There are potential materials compatibility problems and fabrication technique problems, but there are no reasons to assume these are unsolvable. Further there has been no demonstration of an IOC local oscillator at 10.6 μm. The easiest approach to this problem is an external source frequency shifted by an appropriate technique.

A basic heterodyne detector is shown in Fig. 4. A master oscillator–amplifier combination provides the output signal for the system. A part of the master oscillator signal is tapped off to provide an LO source. The LO–detector (D) combination is an IOC. The LO is obtained by Doppler shifting the master oscillator input. The Doppler-shifted frequency is controlled by the electronics package which monitors the intermediate frequency at the detector.

The general problem areas associated with the IOC portion of this detector are: 1) low-loss 10-μm planar waveguides; 2) photodiodes compatible with IOC; 3) 10-μm planar waveguide output couplers; and 4) acoustooptic capability in 10-μm waveguide.

The basic optical heterodyne unit is shown in Fig. 5. "End-fire" tapered couplers are used to couple 10.6-μm radiation into the IOC. They must efficiently (>90 percent) accept the collimated input radiation when incident in a given field of view. The local oscillator signal is generated by using the Doppler-shifted light from Bragg scattering. The scattering is due to an acoustic surface wave generated by interdigital transducers. LO and signal are incident in a photodiode fabricated on the IOC. The bandwidth of this device should be 1 GHz. Some applications will require the development of a 2-D array of these basic elements.

V. Tether

Tethers are used to tow acoustic detector arrays behind surface ships and submarines. The basic idea is to have the listening device as far away from the noise of the towing ship as possible. Distances in excess of 6000 yd are sometimes used. The cables that are used for this application must be strong enough to overcome the tremendous drag on itself and the detectors. Hence they are typically 1-in diameter cables and when rolled up on the stern of a surface ship are very conspicuous and heavy. Besides providing the towing function for the detectors the cable must provide electrical conductors for power signal transmission. Since the loss per unit length of coaxial cable is a function of its diameter, this accounts for the large diameter of the tether. Further, to extend the length of the cable the diameter of the coaxial line must increase to maintain the signal. This requires the diameter of the entire cable to increase and therefore increase the drag. Hence it must be made stronger. The effect is not linear and represents a major problem. In short, the major problem areas are weight and size of the cable necessary for sufficient data rate handling capability.

Tethers are also used for guided ordnance delivery. A tether is the only possible guidance approach for a long-range torpedo. Midcourse guidance must be provided until the target is within range of the sensitivity limited acoustic sensors carried by the torpedo.

Above-the-water missiles also use a tether as a guidance command link. A wire guided approach has proven far more reliable than the free-space IR optical links. Tethered links are, of course, not susceptible to jamming. For ordnance applications the data rates are small ~10 kb/s (unless images are transmitted back to the launcher), but the required lengths are several miles. Any new technology which reduces the size and weight of tethers could open up new realms of performance for such ordnance.

OIT is a possible solution to the tether problems. Glass fiber waveguides are not only lighter than coaxial cables, but smaller in diameter. The fiber bundle itself can be less than 1 mm in diameter. This means that the tether can have a smaller diameter for less drag and a smaller weight per unit length. The reduction in overall diameter of an armored cable should be at least a factor of 2. The total volume of reeled cable would be smaller and less conspicuous. The introduction of this technology for tether application must await the development of manufacturing techniques to make truly long, low-loss fiber bundles.

This application of OIT is basically a very long point-to-point communication problem. For acoustic arrays the information capacity requirement is 10 Mb/s at maximum. Signals for N sensors must be processed and converted to optical signals. At the other end the signals must be detected and demultiplexed into N channels of information. This communication link requires a low-loss very long multimode optical fiber bundle with low numerical aperture to avoid geometrical dispersion effects which limit bandwidth for long lengths. A numerical aperture of ~0.1 would be compatible with laser diode sources and would allow for a bit rate of 10 Mb/s for lengths up to 3000 m. Laser sources would be needed for efficient input coupling (diode lasers operating CW at room temperature exist at present on a laboratory basis). Assuming a transmission loss of 25 dB/km (20 dB/km has already been observed in short lengths of fiber with NA = 0.1), a length of 3000 m represents an overall loss of 75 dB. Use of avalanche diode detection would place a minimum requirement on the diode laser of ~200-mW output power for a 10-Mb/s capacity. This should be feasible with development; however, for first-generation systems a bandwidth of 500 kHz will ease the source requirements to the 10-mW region.

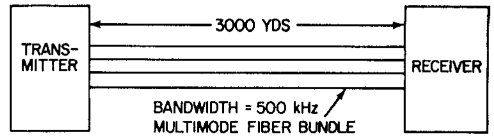

Fig. 6. First-generation tether demonstration.

If losses are increased, spectral multiplexing will be required to reduce the bandwidth and retain the information capacity. An alternative to spectral multiplexing is the use of a repeater or repeaters along the line to maintain the signal. The repeater could use IOC components to avoid a large package and the extra drag and weight. Also the spectral multiplexing would be accomplished either by separate laser sources into different parts of the fiber bundle immediately followed by a "scrambler" or an IOC with several sources, a spatial mixer, and IOC–fiber coupler. Similar concepts would apply at the receiver end of the line. The components and details of a first-generation approach to this problem are given below.

The first-generation system is shown in Fig. 6. It is a point-to-point optical fiber communication link with 500-kHz bandwidth ($S/N = 8$). There is a total length of 3000 yd. The transmitter consists of a single laser diode end coupled to the fiber bundle. The receiver is a single avalanche diode. The goals required for this demonstration are: 1) continuous low-loss fiber bundle (<25 dB/km) of 3000-m length and numerical aperture of <0.2; and 2) minimize the input and output coupling losses by design of an appropriate mechanical coupler. A laser diode with 10 mW of output power could suffice.

VI. Optical Phase Front Control

Electromagnetic phase front control has been extensively used in the microwave region to provide electronically controlled beam steering and beam forming. Indeed the phased array antenna has provided a beam-steering agility which would be impossible by mechanical means. The application of such techniques at optical frequencies could alleviate many pointing and deflection problems associated with the use of laser beams.

The usual phased array antenna consists of an $N \times N$ array of radiating apertures, each $1/2\ \lambda$ apart and whose phases and amplitudes are electronically controlled. The minimum beamwidth from such an antenna is approximately π/N rad which can be scanned over π rad. IOC with batch processing could provide the high density of phase-controlled apertures required at optical frequencies; but no matter how the phased array was configured beam steering would be limited to $N \times N$ resolutions elements. There is a strong tradeoff between beam size and maximum deflection angle. Even for a large number of phase-controlled apertures (10^4) a milliradian beam could only be deflected over 5°.

For high-resolution scanning applications, with larger numbers of resolution elements, one would like to design a nearly continuous antenna. The continuous antenna must have a capability of varying the phase across the beam in any desired fashion.

Using IOC technology, an optical antenna that will act as a nearly continuous antenna (the number of elements approaching infinity) is shown in Fig. 7. An input laser is coupled into a waveguide which has electrooptic capabilities. On this waveguide are placed 10 or more electrodes of precisely determined shapes. These shapes are designed to modulate the beam in a precise fashion. In particular, the modulation defined by each electrode is described by a function that is approximately orthogonal to the other nine. By varying the voltage across each of the electrodes, a quasi-continuous phase shift may be impressed on the beam. The IOC will thus act as a nearly continuous antenna, i.e., one which has an extremely large number of antenna elements. Complete phase front control will be limited in this case by the closeness by which the 10 functions chosen approach a complete set. High-resolution beam steering, however, can be accomplished with two modulators.

Acoustooptic scattering of light in IOC is an alternate means available for beam scanning. Through Bragg scattering, the optical beam in the IOC may be directed into the Bragg angle which is (acoustic) frequency dependent. Thus, with careful design, continual scanning could be available through this technique. However, there are several disadvantages of this technique. 1) There are problems in launching acoustic-surface waves with varying frequencies in IOC. Very high frequencies are needed for appreciable deflection of visible radiation (this problem is eased for 10.6 μm). Good broadband interdigital transducers are not readily available. 2) The angle between the incident light wave and the acoustic wave must be varied as the acoustic frequency is changed for efficient Bragg scattering. 3) The electronics associated with acoustic-wave generation is quite bulky and conversion of acoustic power to surface waves is generally inefficient. 4) Electrooptic switching offers much faster switching capabilities. 5) Electrooptically controlled antenna offer better resolution, more freedom for tailoring the output beam to the desired pattern, and more compact packaging.

The technology necessary to construct the required IOC is or will shortly be available. Waveguides (planar) for use in IOC presently have losses of about 1 dB/cm. This magnitude of loss is acceptable for the antenna array. Fabrication of waveguide by ion implantation, ion exchange, sputtering, and liquid epitaxy has been demonstrated. Passive thin-film optical elements such as lenses, prisms, etc., have been fabricated and will find use in the present system (especially beam splitters). Construction of waveguides with 1-μm resolution has been demonstrated, and this will enable the construction of the electrode shapes needed to define the modulation function. However, good endfire couplers have yet to be demonstrated and thin-film lasers and amplifiers have only been developed in the visible. Electrooptic modulators have been developed and demonstrated but these do not have the required degree of sophistication. These shortcomings, however, are well within the scope of present technology.

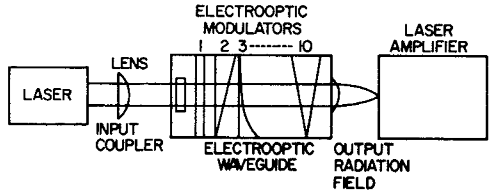

Fig. 7. Schematic diagram of first-generation linear phased array.

The main use for optical antenna arrays is the control of the radiation field they produce. Two important areas that will use precise beam control are the following.

A. Display or Scanning Applications

Since the beam position is controlled by the element-to-element phase shift, the beam maximum can be scanned by electrooptically shifting the phase of the wavefront. This allows scanning without changing the mechanical orientation of the antenna, a practical consideration especially important in applications where vibrations are present. The antenna in this case can be rigidly mounted, thus avoiding misalignment problems. Another important characteristic of this system is that the number of resolution spots attainable from this type of system, i.e., continuous-type antenna, is quite high because the field may be extremely well defined and controlled. TV quality displays require more than 10^5 resolution elements so that the continuous antenna approach is the only one possible.

B. Beam Control

By varying the phases across the beam in the IOC it is possible to tailor the resulting output beam to any desired form. This is important in beam propagation applications where atmospheric distortion of the propagating beam destroys the beam quality. Atmospheric turbulance limits the beam size to 0.5×10^{-4} rad at sea level regardless of beam aperture if phase front control is not employed. Beam control is an important long-range goal for many military laser systems where the effectiveness of the system is reduced by beam distortion. The phased array optical antenna concept, in conjunction with beam feedback, makes it possible to continually correct for atmospheric disturbance, thereby permitting the transmission of optical beams with the desired optical quality ($\sim 10^{-5}$ rad). Some beam-steering capability will also be available in a beam-control antenna system. Return beams can also yield image resolution finer than the turbulence limit if phase front control is introduced. Approximately 100 phase-controlled antennas (10×10) should be able to obtain the order of magnitude better beam quality than is generally desired ($0.5 \times 10^4 \rightarrow 0.5 \times 10^5$ rad). An IOC approach with discreet modulators is also possible; however, the optimum approach may be to use a continuous antenna with the modulators carefully designed to correct for typical distortions. Power-handling problems in thin films will limit the use of IOC to portions of the transmitter chain where average power is still modest.

VII. Summary

As seen from the above discussion there are a wide variety of military applications for fiber optics and integrated optics technology. The fiber optics application are certainly furthest along in terms of practical development. However, future generations of applications will almost certainly have integrated optical circuits. Only then will the full potential advantages of this technology be realized.

This technological area is not without problems. There are serious materials fabrication problems. Radiation sensitivity of these optical materials is a potentially serious problem area that has not been discussed.

It is probably fair to conclude that the military-related applications of this technology are nearer term than those of the telecommunication industry. Further, the impetus provided by military needs will lead to successful applications of fiber optics and integrated optics in the near future.

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Faraday Optical Isolator/Gyrator Design in Planar Dielectric Waveguide Form

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Invited Paper

***Abstract*—The possibilities of using the magnetic Faraday effect to provide a planar dielectric waveguide isolator or circulator are studied. At least two active elements which couple the TE and TM waveguide modes are required. One of these is magnetooptic. Preliminary design data for a dielectric waveguide isolator in which the mode-converting media forms the substrate and top layer of a single waveguide structure are reported. This design should prove more practical than the optical tandem structures proposed previously.**

I. Introduction

ESSENTIAL to the proper development of integrated optical systems is the availability of the basic components for providing sources, detectors, waveguiding, modulation, switching, etc. Switching and modulation may be achieved by using electrooptic [1], acoustooptic [2] (both bulk and surface wave), and magnetooptic [3] effects to couple the TE and TM modes of waveguide propagation[1] and provide mode conversion. For example, amplitude modulation may be achieved for a TE waveguide mode by applying an ac field to an electrooptic material that forms part of the waveguide structure. There will be induced a variable coupling to the TM mode, and the TE and TM intensities will fluctuate in a complementary way. Most mode-conversion schemes are reciprocal in the sense that the effects produced are not altered by reversing the propagation. The exception to this is the longitudinal magnetooptic or Faraday effect [4] (magnetization parallel to propagation direction). Faraday rotation devices [5] have been found particularly useful in microwave waveguiding: they provide nonreciprocal transmission characteristics that have been exploited to make isolators and circulators invaluable to microwave circuitry.

In this paper we present a study of the problems and possible solutions for the fabrication of an optical planar-waveguide mode converter. It is nonreciprocal in that in the forward direction there is complete mode conversion from TE to TM and TM to TE, but in the reverse direction a TE mode will emerge as a TE mode. The nonreciprocity arises from the Faraday effect. It is well known that a linearly polarized optical beam propagating along the magnetic-field direction in an isotropic material finds its plane of polarization rotated as it proceeds. The effect is largest in ferromagnetic materials. Linearly polarized light behaves similarly in optically active materials, but the magnetic effect is uniquely different in one important respect: the "handedness" of the rotation is oppo-

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[1] The eigenmodes of an isotropic planar dielectric waveguide structure are TE, with the electric vector perpendicular to the plane normal, and TM, with the magnetic vector so oriented.