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CONTENTS

ABSTRACT

Liquid crystals have many potential uses for optical waveguides. Optical waveguide technology and liquid-crystal physics were reviewed, and those characteristics were examined which appear attractive for fabricating optical waveguide devices such as modulators and switches using liquid crystals. Proper use of these anisotropic fluids may solve many of the difficult switching and modulating problems retarding waveguide technology. However working integrated optical systems require the realization of the following: minimized scattering losses that result from lack of alignment, electrode fabrication compatible with optical waveguides, and liquid-crystal materials that will not degrade under the anticipated optical and electromagnetic fields. These requirements may be realized in the near future with some further work. Thus liquid crystals would be the quickest and most efficient route to microoptical waveguide systems for data processing and communications.

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PROSPECTUS FOR THE DEVELOPMENT OF LIQUID-CRYSTAL WAVEGUIDES

INTRODUCTION

The propagation of light in otpical waveguides is of current interest because these systems can perform many data-processing and communication functions. Integrated optical technology may be envisioned to combine a system that is capable of modulating, switching, and detecting with optical microcircuitry. A microoptical system is desirable since it is rigid, free from environmental effects, and capable of handling greater volumes of information than traditional electronic systems.

Many areas of optical microcircuit research are maturing, and several devices have been successfully demonstrated [1]. Passive optical microcircuits having thin-film lenses, prisms, etc. have been constructed and have demonstrated that most passive optical processing functions can be performed in integrated optical circuits. Active devices have also been demonstrated; however these devices require further work before they can be successfully incorporated into a data system that is competitive with existing bulk data-processing systems. Acoustooptic Bragg switches, mode converters, electrooptic mode converters, switches, modulators and magnetooptic mode converters are some of the active devices that have been demonstrated [1]. The acoustooptic and magnetooptic devices that have been constructed use solid-state waveguides, and the electrooptic devices have employed a liquid waveguide medium (nitrobenzene) [2]. There are reasonable expectations that electrooptic signal processing can be practically performed in certain solid-state waveguides.

This report considers the use of liquid crystals in integrated optical circuits. Because the orientational pattern of a given liquid-crystal state is strongly influenced by electric, magnetic, and acoustic fields [3], liquid crystals offer attractive alternatives to the fabrication of active integrated circuits. The average molecular orientation determines the refractive index affecting a given polarization. By suitable molecular reorientation, the effective index of refraction may be varied as desired. The presence or absence of an applied electric field therefore defines two allowed waveguide states by specifying two different index states. If the liquid crystal is the waveguide medium, then light propagating along this medium is subject to two possible index states. If the liquid crystal is used as a boundary medium for the waveguide, the two orientations of the liquid crystal will determine the waveguide boundary conditions. For both cases the two liquid-crystal orientations make possible many active liquid-crystal devices. This report will consider the different configurations that may be used to form liquid-crystal microoptic devices.

Several problems affect realization of these active devices. The attainment of sufficient molecular alignment is the most severe difficulty to be encountered. This problem has been studied by several authors [4,5], and alignment higher than 99% has already been reported [4]. Another problem is electrode fabrication [2]. Since metallic electrodes that come into contact with the guided wave can strongly attenuate the signal, designs of suitable electrode systems must be developed. This problem is important to all of integrated optics, not only to liquid-crystal devices. Considerable work is in progress on suitable electrode fabrication for liquid-crystal display devices and will aid in electrode fabrication for liquid-crystal waveguides. Finally speed limitations [5,6] on the reorientation of liquid-crystal molecules will probably confine beam modulation to 1 kHz. However switching times can be as short as tens of microseconds (the rise time for switching molecular orientation can be 10 μsec). These devices therefore may be used where speed is not important but switching efficiency is of prime concern.

This report provides a comprehensive analysis of the potential of liquid-crystal waveguide systems. Research that will determine the practicability of such systems has been initiated at NRL.

The next section presents some of the pertinent properties of liquid crystals and optical waveguides and discusses the remarkable possibilities in the combination of liquid crystals and optical waveguides. It also discusses the current status of technology for the modulation of light in waveguides. The third section presents specific liquid-crystal applications. Liquid crystals are considered as the waveguide boundary, as the waveguide itself, and for potential uses in liquid-core fibers. Evaluation and prospects for success are presented in the summary.

BACKGROUND

Waveguides

The optical waveguide can be thought of as a slab of dielectric which confines light by multiple total internal reflections [7,8]. We thus consider three media (Fig. 1): a thin film (n_1), a substrate (n_0), and an unspecified medium (n_2). The plane wavefront is totally reflected alternately between the interfaces S_1 and S_2. For this to happen the index of refraction n_1 of the guiding dielectric must be greater than the indices n_0 and n_2 of the surrounding media and the angle of incidence θ must be greater than the larger of the two critical angles $\theta_{c_{0,2}}$, where

$$\theta_{c_{0,2}} = \sin^{-1}\left(\frac{n_{0,2}}{n_1}\right) . \tag{1}$$

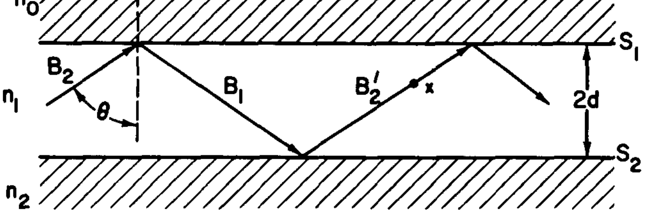

Fig. 1—Optical waveguiding formed by a high-index dielectric layer between two lower index cladding layers. The waveguide boundaries are S_1 and S_2 and the refractive indices are n_1, n_2, and n_0, with $n_1 > n_0$, n_2. A possible light path is indicated by the rays B_2, B_1, and B_2', all of which are incident at the same angle θ (total internal reflection) with the boundaries.

For a given thickness $2d$ and indices n_0, n_1, and n_2 light will propagate with an angle of incidence θ only if, after two successive reflections, the wavefront is again in phase with any portion of the original wavefront that was not involved in these two reflections. If this were not the case, after many reflections wavefronts with a range of phases between 0 and 2π would add to zero amplitude or, equivalently, the wave would not propagate. This requirement implies that at an arbitrary point x the phase of one wavefront obtained from another by two successive reflections must equal the phase of the other wavefront at x without reflections, or differ by a multiple of 2π. This requirement permits propagation for only discrete values of θ. Each value of θ is associated with a mode of propagation and each mode has a characteristic velocity of propagation. As θ increases, the velocity of propagation to the right also increases. One can associate a different effective index of refraction, which is a function of d, n_1, n_2 and n_0, for each waveguide mode (Fig. 2). The details of the mathematics which describe optical waveguides may be found in Ref. 7 and 8.

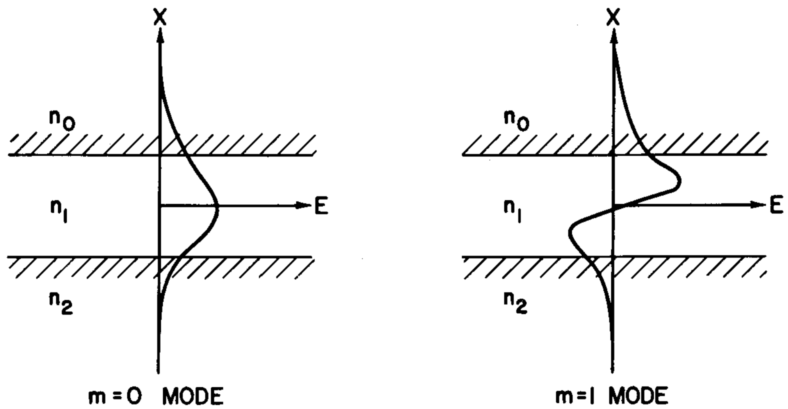

Fig. 2—Electric-field distribution in a waveguide for the lowest order *TE* mode ($m = 0$) and the next higher order mode ($m = 1$). In general $m + 1$ determines the number of electric-field extrema in the waveguide. Depending on the size of the waveguide and the indices, a significant portion of the wave may be outside the waveguide in the boundary layers. This field, which decays exponentially in the x direction, is called the evanescent field.

We now consider those properties of waveguides which lead to low-loss propagation, to techniques of input and output coupling, and to optical switching and modulation. There is considerable discussion in the literature [9] concerning various topological shapes of optical waveguides and their characteristics. Waveguides may be flat slabs, rectangular, cylindrical, or any other shape. Metal-clad dielectrics may not be used in optical waveguides due to the high losses. When light is reflected off a metal surface, the energy losses depend on the metal, the wavelength of the light, surface condition, polarization, and angle of incidence, and the losses are typically about 1 or 2% per reflection. Hence metal-clad waveguides, because of the number of reflections per centimeter, are extremely lossy in the optical region. In the dielectric-clad waveguide, losses are due to absorption in the dielectrics and scattering losses. If the cladding has no absorption at the optical wavelength being propagated, then no energy is absorbed from the evanescent wave (extending into the cladding) and the waveguide suffers only from scattering losses.

The boundary between the waveguide and the surrounding media must be clean, smooth, and free from scratches inside to minimize surface scatter. Deviations of the waveguide wall by a few percent can cause a power loss of 0.5 dB/cm if the wall imperfection can be described by an exponential correlation function [10]. Besides the lack of a flat, smooth surface, inhomogeneities in the waveguide or cladding media can also lead to significant waveguide losses. This is particularly important in the case of liquid crystals, since the molecular alignment is affected by the walls and the lack of perfect molecular alignment can lead to large losses; these losses could be the dominant waveguide loss mechanism.

One technique [11] of a high degree of molecular alignment involves uniform rubbing of the liquid-crystal boundaries and is referred to as the homogeneous alignment technique. This presumably scratches the surface and provides a preferred direction in which the molecules align. The homogeneous alignment technique may not be compatible with low-loss waveguide fabrication. The other reported alignment technique [12], referred to as the homeotropic alignment technique, involves the deposition of a thin film of polar atoms (surfactant) on the surface. Again a preferred alignment direction is established and a high degree alignment is possible, usually at right angles to the alignment achieved by rubbing. This method seems more applicable to waveguide techniques and requirements.

To couple light into and out of a waveguide, it is necessary to change the boundary conditions. This may be done in several ways. In the prism coupler a prism is brought within a few optical wavelengths of a waveguide surface and *frustrates* [13] total internal reflection at the surface. Frustrated total internal reflection or evanescent-field coupling occurs because the boundary conditions of a waveguide are modified by the presence of the prism. A second type of coupler, the *grating coupler* [14], consists of a periodic structure in contact with the waveguide boundary. This structure permits momentum matching between a guided optical wave and a wave propagating in the cladding medium and thus provides coupling between the two waves. Both types of couplers may be fabricated using liquid crystals.

To construct active devices, the index of the waveguide media, or the determining boundary conditions, must be actively controlled by some external parameter. Once this is achieved, the construction of systems that will act as modulators, deflectors, and switches is possible.

Modulation may be achieved by electrooptic, acoustooptic, and magnetooptic phenomena. The electrooptic modulators make use of induced birefringence to cause phase changes in the optical waveguide modes. For example, in a waveguide of electrooptic material, or in a waveguide on an electrooptic substrate, the propagation factors for TE and TM modes vary differently with an applied electric field. If a TE wave is passed through a modulator, a phase shift may be induced, which causes a TE wave to be coupled to an orthogonally polarized TM mode. Viewed through an appropriate analyzer, the output is an amplitude-modulated signal. Magnetooptic modulators make use of induced optical activity instead of induced birefringence and require current-modulated signals instead of voltage-modulated signals. A device of this type has been demonstrated [15].

Deflectors can operate either via the electrooptic or acoustooptic effect. In the case of electrooptic deflectors not used in optical waveguides, these devices are usually digital deflectors. The digital devices use the principle that the electrooptic effect rotates the plane of polarization of linearly polarized light in a suitable medium, so that a polarizing prism such as a Rochon, Wollaston, or Thompson prism deflects the beam into one of two channels. The same effect is accomplished in optical waveguides using coupled waveguides. No exact analog of the digital deflector has been demonstrated in optical waveguides.

The acoustooptic deflector [16] has the advantage of continuous deflection by electronic tuning of the acoustic frequency. The acoustic wave produces periodic index and surface variations [17], which in turn deflect a portion of the optical radiation by Bragg diffraction. This process is particularly adaptable to a dielectric film, which forms a surface layer on a substrate, producing a waveguide. In this case the acoustic wave is a surface wave, and the optical radiation is also on the surface of the substrate. The interaction can therefore be achieved with much less acoustic power than in the bulk case, and efficiency is improved. Waveguide devices of this sort have been analyzed [16], and a particular configuration is shown in Fig. 3. This device had a maximum observed deflection efficiency of 66% with an electrical input of 2.5 W, or an acoustic power of 0.18 W. Liquid crystals have all the properties that are needed for switching, deflecting, and modulating and appear to be able to combine the advantages of the acoustooptic and electrooptic devices in one compact package.

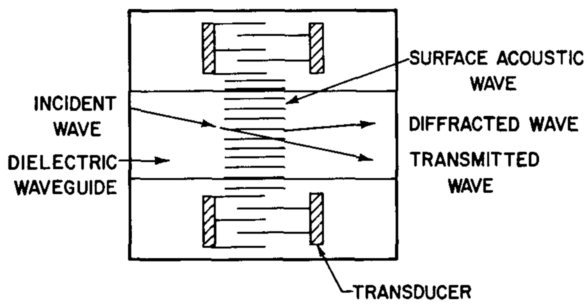

Fig. 3—Acoustooptic deflector. An optical guided wave incident at the Bragg angle is efficiently scattered by a surface acoustic wave. Because the acoustic and optic wave have their energy localized in the waveguide structure, high-efficiency scattering results.

Liquid Crystals

When some organic substances are melted, instead of becoming a clear liquid, they pass through a turbid fluid state which is termed the mesomorphic or liquid-crystal state [18]. The liquid-crystal state has more order in the arrangement of its molecules than the isotropic liquid state, but less than the solid state.

In general a molecule of a compound which forms liquid crystals is elongated, contains a benzene ring, is fairly rigid along a large part of the long axis, is highly polarizable, and contains a permanent dipole [19].

Three major phases of the mesomorphic or liquid-crystal state have been observed: smectic, cholesteric, and nematic. For each major phase there exist subphases or textures (such as homeotropic, smectic C, and focal conic). Cholesteric phases are noted for their high optical activity, whereas the smectic and nematic phases are generally not optically active.

Nematic liquid crystals are composed of long cylindrical molecules which align in a parallel manner. Each molecule can rotate freely only about its long axis but can also have some freedom of movement from side to side or up and down (Fig. 4a). The smectic liquid crystals have layers which slide over one another. Inside each layer the molecules may align in an ordered manner (Fig. 4b) or be randomly distributed. Cholesteric liquid crystals are thought to consist of layers with the alignments in the layers displaced with respect to one another, forming a helical pattern (Fig. 4c) and thus causing the high optical activity.

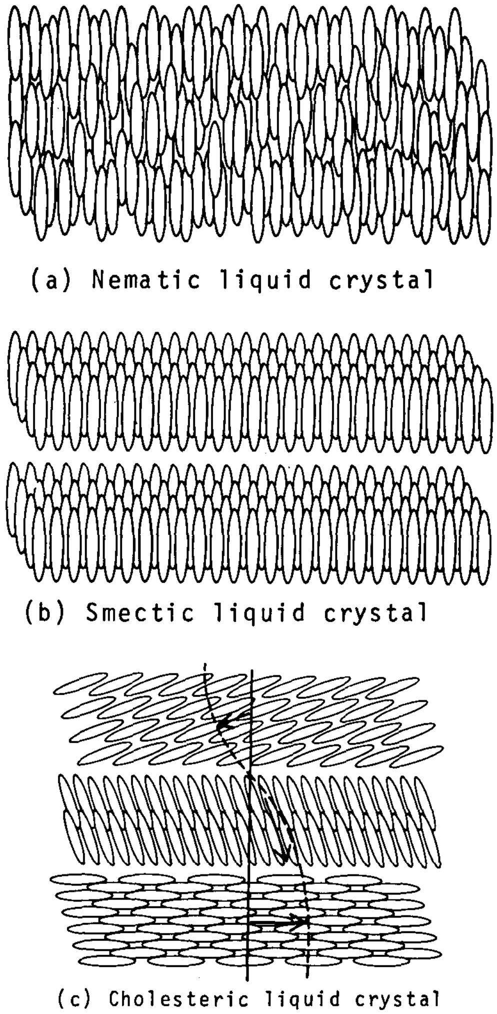

Fig. 4—Proposed models of the nematic, smectic, and cholesteric phases. The nematic liquid crystal is not layered, the smectic liquid crystal is layered with the alignment the same in each layer, and the cholesteric liquid crystal is layered with the internal alignment changing from layer to layer.

Numerous optical effects have been observed using liquid crystals [20], and many of these can lead to practical applications. Table 1 lists some interesting electrooptic effects, some representative materials exhibiting the effects, and their possible applications. All of the properties listed can be used to advantage in optical waveguide systems.

Table 1
Observed Electrooptic Effects in Liquid-Crystal Materials and Some Current Uses in Display Systems [19]

Electrooptic Effect	Representative Liquid Crystal	Mesophase	Operating Temp. (°C)	Applications
Dynamic scattering	Anisylidene-p-n-butylaniline	Nematic	23	Alphanumeric, analog, or matrix displays; dimmable windows or mirrors; page composers; beam splitters; and nonimpact printers.
Tunable diffraction	40% cholesteryl chloride, 26% cholesteryl nonanoate, and 34% cholesteryl olyel carbonate	Cholesteric	23	Alphanumeric or matrix color displays, tunable monochrometers, laser beam deflectors, and light modulators.
Guest-host interaction	99% p-ethoxybenzilidene-p′-aminobenzonitrile and 1% indophenol blue	Nematic with guest dye molecules	110	Tunable optical filters, light modulators, and two-color displays
Optical storage	10% cholesteryl erucate and 90% anisylidene-p-n-butylaniline	Mixed cholesteric and nematic, mostly nematic	23	Displays with memory, light modulators, and data storage planes (optical memory)
Cholesteric-to-nematic transformation	30% primary active amyl p-(4-cyanobenzylideneamino) cinnamate and 70% para substituted benzylidene anilines	Mixed nematic and cholesteric, mostly cholesteric	23	Displays and light modulators
Induced alignment	p-n-octoxybenzylidene-p-aminobenzonitrile	Nematic	85	Displays, intensity modulators, and phase modulators

In general these optic phenomena result from placing an external field in the proximity of the material. Induced alignment has been used for displays. In this mode the electric field aligns the molecules sufficiently so that the material acts as a polarizer. The magnitude of the field affects the efficiency of polarization, and produces quite an effective display when light is viewed after it has first passed through another polarizer (Fig. 5).

The cholesteric phase exhibits reflected colors which are caused by a molecular diffraction grating tunable as a function of temperature [18]. This color reflection is believed to be caused by Bragg-like reflection from a helical structure that causes the high optical activity observed. Since the Bragg angle is a function of the pitch of the helix, changes of color may be induced by changes of pitch. The pitch is determined by intermolecular distances which are affected by temperature, pressure, and applied electric field.

Currently the dynamic scattering mode has elicited the greatest excitement in the display field. This mode is thought to arise from the interaction of ions with the liquid-crystal molecules. These molecules (which are negatively anisotropic) align at right angles

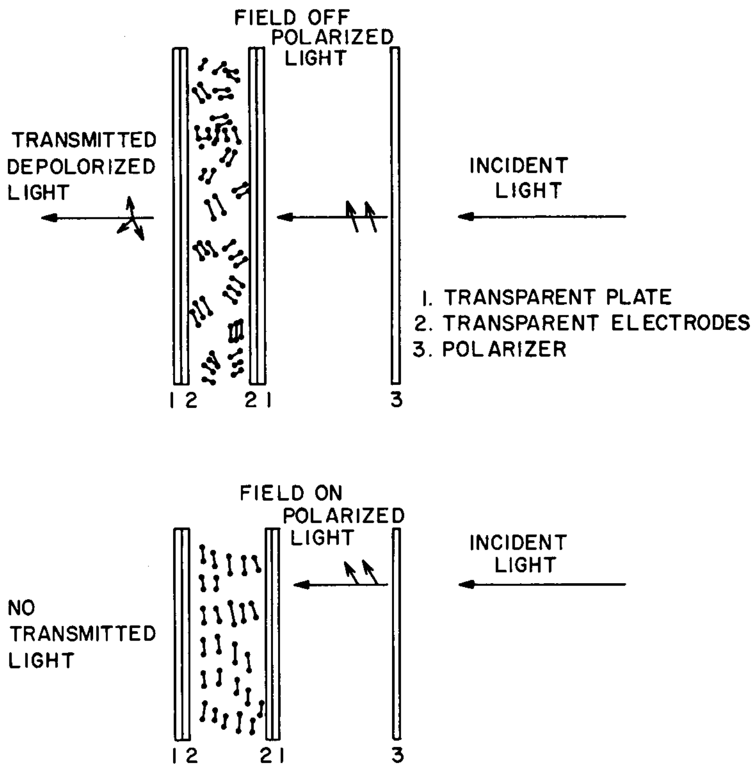

Fig. 5—System that uses field-induced polarization as a means of information display

to the applied field. The ions move along the field, hitting the liquid-crystal molecules. This interaction causes local turbulence which results in light scattering (Fig. 6). Though induced alignment provides the greatest obvious applications to waveguides, the dynamic scattering mode may offer unique advantages for certain types of optical switches.

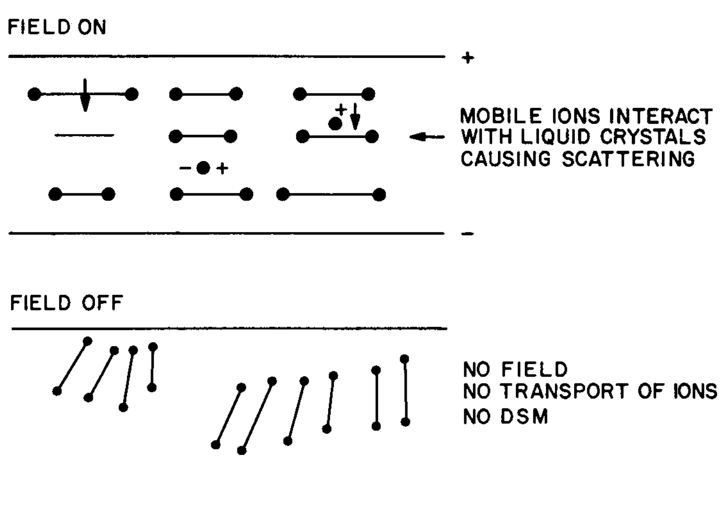

Fig. 6—Proposed model for the dynamic scattering mode (DSM)

LIQUID-CRYSTAL WAVEGUIDE APPLICATIONS

Table 2 presents several properties of liquid crystals that make them attractive as integral components in optical waveguides. The last column in the table is a synopsis of the specific role each effect could have in an optical waveguide system. Each liquid-crystal structure has applications as more than one active device. Though some devices have been fabricated using other materials (such as nitrobenzene as an electrooptic modulator), liquid crystals provide a class of material potentially capable of performing all desired optical processing functions. Table 2 describes the pertinent liquid-crystal structure, field effects upon the structure, and the resulting waveguide device.

Induced Alignment

The alignment of the nematic mesophase without any applied external field depends strongly on the nature of the surface bounding the phase. It has been previously determined that appropriate rubbing of cleaned glass windows results in *homogeneous* material. Modifications of this technique have included streaming of ions over the glass homogeneously [4] and also firm stroking with paper [11]. The probable mechanism of alignment is homogeneous grooving of the glass. This grooving may introduce scattering losses into the waveguide device, but the extent of the losses has not been ascertained. This grooving problem should not however prevent use of liquid crystals in waveguide systems. If scattering losses are high, a sufficiently small region may still be used to good advantage.

An alternative method of alignment in zero field is the use of a monolayer of surfactant. For positive dielectric materials the alignment is called homeotropic. Literature values for both types of alignment indicates that losses of 3 to 5 dB/cm are attainable.

The orientational changes produced by large electric fields (Fig. 5) lead to substantial index variations for a given polarization of light. By changing the index of refraction, several active functions may be performed:

- *Phase modulation* results if a TE and TM mode are propagated along the waveguide. By changing the index of the propagating wave material, one mode may be retarded relative to other modes, resulting in a net phase change.

- *"Active" lenses and prisms* may be fabricated by applying electric fields that result in spatial index changes of a desired form (Fig. 7).

- *Mode suppression* is accomplished by changing the index of either the waveguide or the boundary so that the propagating wave is beyond cutoff. This has implications in output coupling systems. A suitable index change may also result in the propagation of one mode and the suppression of another; this is *mode switching*. Another way of achieving *mode suppression* is by using a nematic system exhibiting the dynamic-scattering mode. When sufficient voltage is applied, dynamic scattering occurs, causing mode suppression.

Guest-Host Interaction

By dissolving a pleochroic dye into a nematic system that undergoes induced alignment, a different electrooptical effect may be realized. Absorbance occurs only in a specific direction in the dye (Fig. 8); therefore the amount of absorbance may be modulated

Table 2
Properties and Uses of Liquid Crystals in Waveguides

Mesophase Structure	Effect of the Field on the Liquid Crystal	Field Structure	Optical Properties		Uses as a Field-Controlled Waveguide Device
			Applied Field Off	Applied Field On	
Nematic	Regular alignment using E_2 and H_y	$E_x = 0$ parallel to Hy and E_x large parallel to walls	Transparent, birefringent, and small-angle scattering	Index change and Pockel effect	Phase modulation, mode coupling, active lens, active prism, mode switching, mode suppression, output coupling, and spatial switching
Nematic and dye	Guest-host interaction	$E_z = 0$ randomly aligned to walls and E_z large aligned to field	Linear dichroism	Transparent with isotropy along the z axis	Frequency selection, amplitude modulation, mode selection, and output coupling
Nematic and 5% cholesteric	Stored texture	Address molecules parallel to walls	Transparent and birefringent	Intense diffuse wide-angle scattering	Waveguide switch
Nematic and smectic	Domain formation	$E_z = 0$ parallel to walls and E_z large produces liquid rotation	Transparent and birefringent uniaxial positive	Parallel array of cylindrical lenses and index change	Mode suppression, mode switching, and amplitude modulation
Cholesteric	Dilation of helix undisturbed cholesteric	$E_z = 0$ domain parallel to walls and E_z-large domain parallel to field	Birefringent and uniaxial negative Bragg or Raman-Nath diffraction	Decreased birefringence and decreased diffraction angles	Phase modulation, frequency modulation, mode coupling, mode switching, frequency selection, phase matching (i.e., frequency coupling), and output coupling
Cholesteric (subphase is Grand Jean plane texture)	Surface deformation	Helix reorientation and mass transport along field gradients	Bragg diffraction (dispersive reflection)	Altered reflection from deformed areas	Same as the item above plus acoustically coupled modulation
Cholesteric and Dye	Surface deformation	Same as the item above	Same as the item above	Same as the item above	Same as the item above pluse mode gain (internal-feed back laser), frequency modulation, amplitude modulation, and light interrogation to determine the state of information transfer

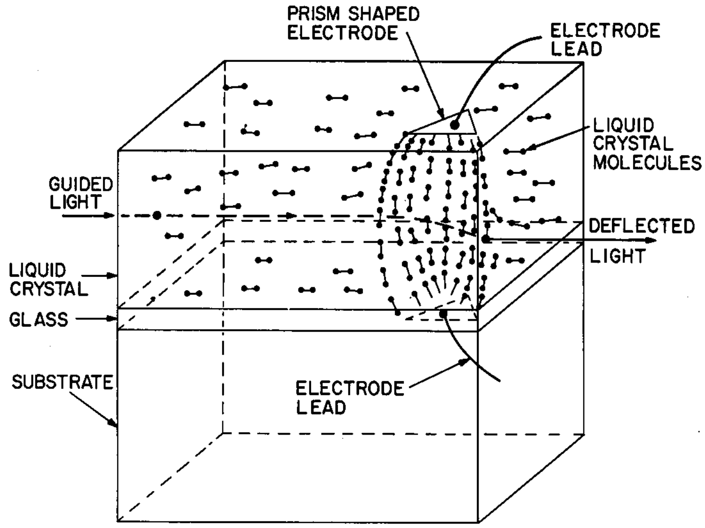

Fig. 7—Liquid-crystal waveguide functioning as an active prism. It could similarly function as an active lens.

by the applied electric field [21]. If two dyes with different preferred absorbing axes are dissolved in the system, color switching is obtainable by controlling the applied field. This can be used as a method of *frequency selection.* This system may also be used for amplitude modulation of propagating modes in the nematic-phase-plus-dye waveguide by selective absorption. TE-TM mode discrimination may be obtained through the polarization-selective absorption available in the system. If the pleochroic dye is chosen to be suitably fluorescent, *random access* to the waveguide system may be achieved. By applying a field, the dye will either fluoresce or not. The fluorescence (frequency-shifted radiation) will not propagate in the waveguide but will couple out, thus providing information on the optical states in the system.

Storage Effects

If 10% of a positive anisotropic* cholesteric phase is dissolved in approximately 90% of a negative anisotropic system, an electrooptic memory is obtained [22,23]. A low-frequency electric field produces a highly scattering region (lower limits) which remains scattering indefinitely after the field is switched off. The scattering state is erased by the application of a high-frequency electric field. This effect may be used as an *Optical switch* in waveguide systems.

Domain Formation

Both smectic and nematic phases can produce domains under suitable conditions. With the electric field off, the system is transparent, birefringent, and uniaxial positive. By applying an electric field parallel to the walls, a parallel array of domains is produced. These domains act as cylindrical lenses. If an appropriate acoustic wave is coupled into the system, the parallel nature of the lenses is replaced by a periodic structure [24]. This can be used for *mode coupling.*

***Positive anisotropy occurs when the long axis of the molecule is parallel to the dipole moment.**

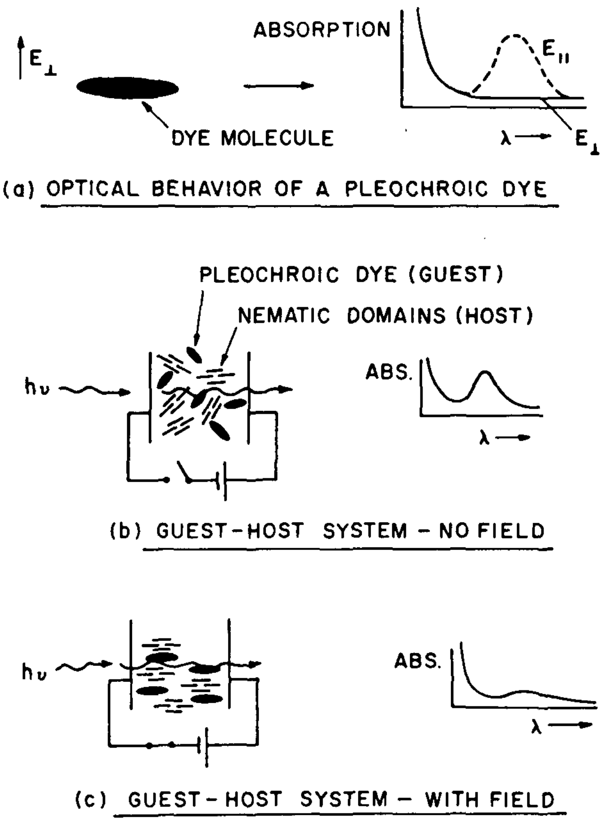

Fig. 8—Absorbance of a pleochroic dye as a function of its alignment in host nematic domains

One problem in the effective use of this effect is the scattering caused by the discontinuities at the domain boundaries. It may be possible to circumvent this difficulty by using a suitably small region, thus minimizing the losses.

Cholesteric Mesophase

The cholesteric phase exhibits both high optical activity and selective reflection of colors. The apparent reflective color changes as well as the wavelength of maximum optical activity vary as a function of temperature, electric field, and dissolved vapor. In the past, cholesteric-liquid-crystal systems have been used in skin-cancer detection, skin thermography, and vapor detection in infrared spectrometric analysis.

The nature of the propagation of light in thin films along the waveguide axis is not known. Along the helical axis the cholesteric phase exhibits optical activity, but the degree of optical activity, if any, is not known along different axes, although elliptical polarization is expected. If optical activity occurs along these other axes, then the waveguide devices listed in Table 2 for the cholesteric phase structure should be realizable. The principles of their operation involve changes in the refractive index and have been outlined in the previous sections.

Liquid-Crystal Fiber Core

One can envision several uses in the application of liquid crystals to optical-fiber technology. A particular possibility is liquid-core fibers (Fig. 9). The liquid-crystal molecules may be aligned in one of two orthogonal directions in the fiber core, either perpendicular to the core axis (Fig. 9a) or parallel to the core axis (Fig. 9b). An optical wave propagating along this fiber will interact with one of the two refractive indices. By applying a large electric field to the fiber, the refractive index may be switched. If an electric field of smaller strength is applied, the molecules are only partially reoriented. Both total and partial switching are useful and lead to different devices.

If one partially reorients the molecules, the molecules at the core center will be oriented more easily than those at the wall. As mentioned previously, the wall tends to align the molecules and in the present application will tend to hinder the reorientation by

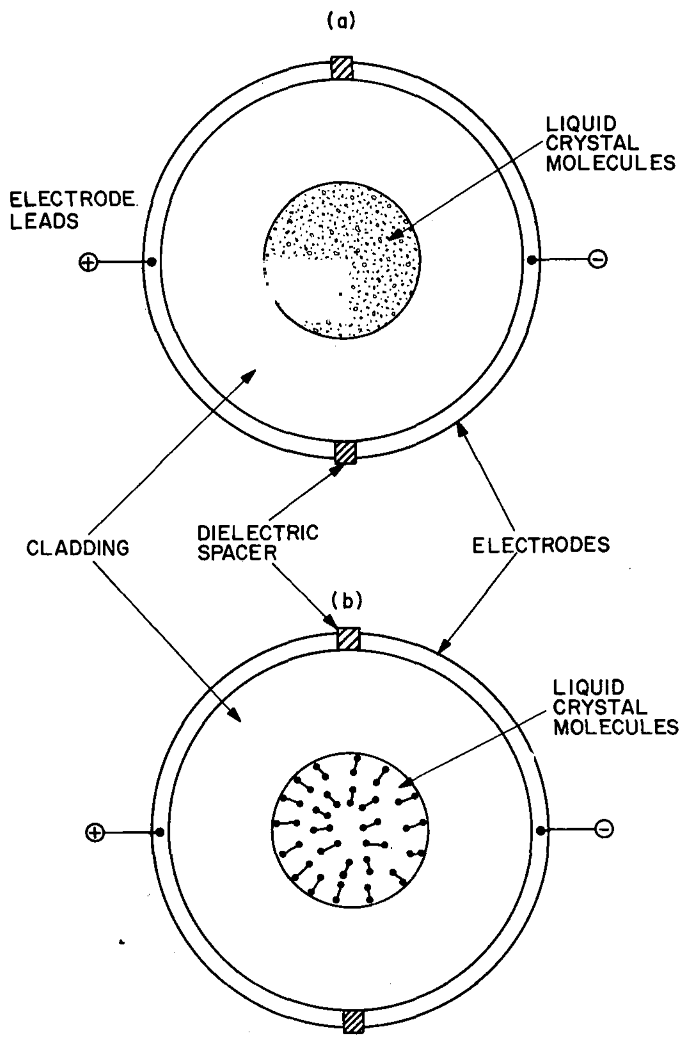

Fig. 9—Liquid-crystal fiber core. In (a) the molecules align parallel to the core axis due to surface effects, and in (b) the molecules align perpendicular to the core axis due to the electric field.

the electric field. This will lead to a varying index change across the liquid core fiber and will act as a lens capable of focusing the propagating wave.

When the field is large enough to cause complete reorientation, then amplitude modulation results. By decreasing the index, the propagating wave may now be made to be below cutoff. This will result in the guided wave being coupled out of the fiber *(fiber output coupler).* If the transmitted signal is of interest, the electric field may be used to *modulate* the amplitude. Finally, if a cholesteric liquid crystal is used, its optical rotatory powers may be used to adjust the phase between two modes propagating along the fiber. This will result in a *dispersion compensator.*

SUMMARY

This report has explored the potential of liquid-crystal materials in optical waveguide systems. The combination of these two technologies has a possible synergistic effect. It has been shown that many of the difficult switching and modulating problems currently affecting the progress of waveguide technology may be solved by the proper use of anisotropic fluids. Before working integrated optical systems can be fabricated, several fundamental problems must be solved:

- Scattering losses from lack of sufficient alignment must be minimized.
- Electrode fabrication compatible with optical waveguides must be realized.
- Liquid-crystal materials must be obtained that will not degrade under the optical and electromagnetic fields present in these contemplated devices.

These problems are solvable in the near future. Thus liquid crystals are likely to be the quickest and most efficient route to optical waveguide systems.

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13. ABSTRACT

Liquid crystals have many potential uses for optical waveguides. Optical waveguide technology and liquid-crystal physics were reviewed, and those characteristics were examined which appear attractive for fabricating optical waveguide devices such as modulators and switches using liquid crystals. Proper use of these anisotropic fluids may solve many of the difficult switching and modulating problems retarding waveguide technology. However working integrated optical systems require the realization of the following: minimized scattering losses that result from lack of alignment, electrode fabrication compatible with optical waveguides, and liquid-crystal materials that will not degrade under the anticipated optical and electromagnetic fields. These requirements may be realized in the near future with some further work. Thus liquid crystals would be the quickest and most efficient route to microoptical waveguide systems for data processing and communications.

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Magnetooptic devices						
Data processing						
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Information processing						

CONTENTS

ABSTRACT

Liquid crystals have many potential uses for optical waveguides. Optical waveguide technology and liquid-crystal physics were reviewed, and those characteristics were examined which appear attractive for fabricating optical waveguide devices such as modulators and switches using liquid crystals. Proper use of these anisotropic fluids may solve many of the difficult switching and modulating problems retarding waveguide technology. However working integrated optical systems require the realization of the following: minimized scattering losses that result from lack of alignment, electrode fabrication compatible with optical waveguides, and liquid-crystal materials that will not degrade under the anticipated optical and electromagnetic fields. These requirements may be realized in the near future with some further work. Thus liquid crystals would be the quickest and most efficient route to microoptical waveguide systems for data processing and communications.

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PROSPECTUS FOR THE DEVELOPMENT OF LIQUID-CRYSTAL WAVEGUIDES

INTRODUCTION

The propagation of light in otpical waveguides is of current interest because these systems can perform many data-processing and communication functions. Integrated optical technology may be envisioned to combine a system that is capable of modulating, switching, and detecting with optical microcircuitry. A microoptical system is desirable since it is rigid, free from environmental effects, and capable of handling greater volumes of information than traditional electronic systems.

Many areas of optical microcircuit research are maturing, and several devices have been successfully demonstrated [1]. Passive optical microcircuits having thin-film lenses, prisms, etc. have been constructed and have demonstrated that most passive optical processing functions can be performed in integrated optical circuits. Active devices have also been demonstrated; however these devices require further work before they can be successfully incorporated into a data system that is competitive with existing bulk data-processing systems. Acoustooptic Bragg switches, mode converters, electrooptic mode converters, switches, modulators and magnetooptic mode converters are some of the active devices that have been demonstrated [1]. The acoustooptic and magnetooptic devices that have been constructed use solid-state waveguides, and the electrooptic devices have employed a liquid waveguide medium (nitrobenzene) [2]. There are reasonable expectations that electrooptic signal processing can be practically performed in certain solid-state waveguides.

This report considers the use of liquid crystals in integrated optical circuits. Because the orientational pattern of a given liquid-crystal state is strongly influenced by electric, magnetic, and acoustic fields [3], liquid crystals offer attractive alternatives to the fabrication of active integrated circuits. The average molecular orientation determines the refractive index affecting a given polarization. By suitable molecular reorientation, the effective index of refraction may be varied as desired. The presence or absence of an applied electric field therefore defines two allowed waveguide states by specifying two different index states. If the liquid crystal is the waveguide medium, then light propagating along this medium is subject to two possible index states. If the liquid crystal is used as a boundary medium for the waveguide, the two orientations of the liquid crystal will determine the waveguide boundary conditions. For both cases the two liquid-crystal orientations make possible many active liquid-crystal devices. This report will consider the different configurations that may be used to form liquid-crystal microoptic devices.

Several problems affect realization of these active devices. The attainment of sufficient molecular alignment is the most severe difficulty to be encountered. This problem has been studied by several authors [4,5], and alignment higher than 99% has already been reported [4]. Another problem is electrode fabrication [2]. Since metallic electrodes that come into contact with the guided wave can strongly attenuate the signal, designs of suitable electrode systems must be developed. This problem is important to all of integrated optics, not only to liquid-crystal devices. Considerable work is in progress on suitable electrode fabrication for liquid-crystal display devices and will aid in electrode fabrication for liquid-crystal waveguides. Finally speed limitations [5,6] on the reorientation of liquid-crystal molecules will probably confine beam modulation to 1 kHz. However switching times can be as short as tens of microseconds (the rise time for switching molecular orientation can be 10 μsec). These devices therefore may be used where speed is not important but switching efficiency is of prime concern.

This report provides a comprehensive analysis of the potential of liquid-crystal waveguide systems. Research that will determine the practicability of such systems has been initiated at NRL.

The next section presents some of the pertinent properties of liquid crystals and optical waveguides and discusses the remarkable possibilities in the combination of liquid crystals and optical waveguides. It also discusses the current status of technology for the modulation of light in waveguides. The third section presents specific liquid-crystal applications. Liquid crystals are considered as the waveguide boundary, as the waveguide itself, and for potential uses in liquid-core fibers. Evaluation and prospects for success are presented in the summary.

BACKGROUND

Waveguides

The optical waveguide can be thought of as a slab of dielectric which confines light by multiple total internal reflections [7,8]. We thus consider three media (Fig. 1): a thin film (n_1), a substrate (n_0), and an unspecified medium (n_2). The plane wavefront is totally reflected alternately between the interfaces S_1 and S_2. For this to happen the index of refraction n_1 of the guiding dielectric must be greater than the indices n_0 and n_2 of the surrounding media and the angle of incidence θ must be greater than the larger of the two critical angles $\theta_{c_{0,2}}$, where

$$\theta_{c_{0,2}} = \sin^{-1}\left(\frac{n_{0,2}}{n_1}\right) . \quad (1)$$

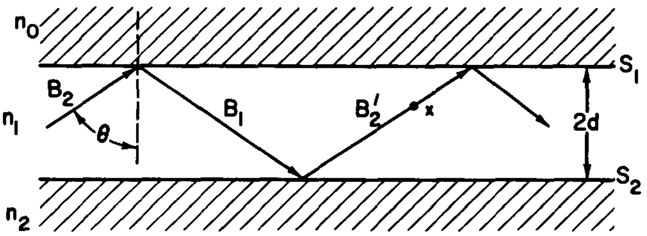

Fig. 1—Optical waveguiding formed by a high-index dielectric layer between two lower index cladding layers. The waveguide boundaries are S_1 and S_2 and the refractive indices are n_1, n_2, and n_0, with $n_1 > n_0$, n_2. A possible light path is indicated by the rays B_2, B_1, and B_2', all of which are incident at the same angle θ (total internal reflection) with the boundaries.

For a given thickness $2d$ and indices n_0, n_1, and n_2 light will propagate with an angle of incidence θ only if, after two successive reflections, the wavefront is again in phase with any portion of the original wavefront that was not involved in these two reflections. If this were not the case, after many reflections wavefronts with a range of phases between 0 and 2π would add to zero amplitude or, equivalently, the wave would not propagate. This requirement implies that at an arbitrary point x the phase of one wavefront obtained from another by two successive reflections must equal the phase of the other wavefront at x without reflections, or differ by a multiple of 2π. This requirement permits propagation for only discrete values of θ. Each value of θ is associated with a mode of propagation and each mode has a characteristic velocity of propagation. As θ increases, the velocity of propagation to the right also increases. One can associate a different effective index of refraction, which is a function of d, n_1, n_2 and n_0, for each waveguide mode (Fig. 2). The details of the mathematics which describe optical waveguides may be found in Ref. 7 and 8.

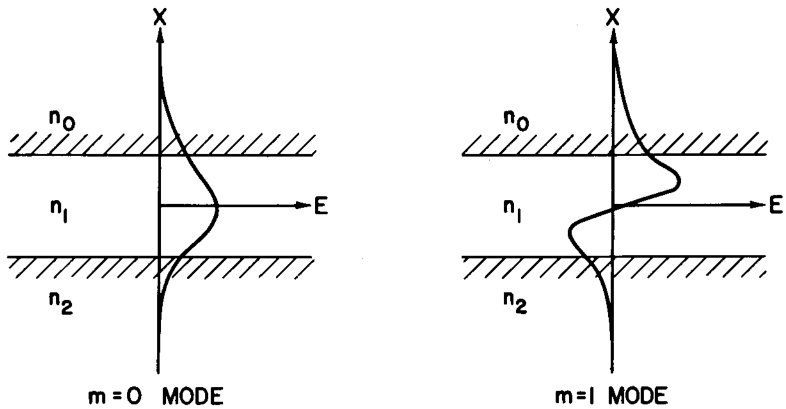

Fig. 2—Electric-field distribution in a waveguide for the lowest order *TE* mode (m = 0) and the next higher order mode (m = 1). In general m + 1 determines the number of electric-field extrema in the waveguide. Depending on the size of the waveguide and the indices, a significant portion of the wave may be outside the waveguide in the boundary layers. This field, which decays exponentially in the x direction, is called the evanescent field.

We now consider those properties of waveguides which lead to low-loss propagation, to techniques of input and output coupling, and to optical switching and modulation. There is considerable discussion in the literature [9] concerning various topological shapes of optical waveguides and their characteristics. Waveguides may be flat slabs, rectangular, cylindrical, or any other shape. Metal-clad dielectrics may not be used in optical waveguides due to the high losses. When light is reflected off a metal surface, the energy losses depend on the metal, the wavelength of the light, surface condition, polarization, and angle of incidence, and the losses are typically about 1 or 2% per reflection. Hence metal-clad waveguides, because of the number of reflections per centimeter, are extremely lossy in the optical region. In the dielectric-clad waveguide, losses are due to absorption in the dielectrics and scattering losses. If the cladding has no absorption at the optical wavelength being propagated, then no energy is absorbed from the evanescent wave (extending into the cladding) and the waveguide suffers only from scattering losses.

The boundary between the waveguide and the surrounding media must be clean, smooth, and free from scratches inside to minimize surface scatter. Deviations of the waveguide wall by a few percent can cause a power loss of 0.5 dB/cm if the wall imperfection can be described by an exponential correlation function [10]. Besides the lack of a flat, smooth surface, inhomogeneities in the waveguide or cladding media can also lead to significant waveguide losses. This is particularly important in the case of liquid crystals, since the molecular alignment is affected by the walls and the lack of perfect molecular alignment can lead to large losses; these losses could be the dominant waveguide loss mechanism.

One technique [11] of a high degree of molecular alignment involves uniform rubbing of the liquid-crystal boundaries and is referred to as the homogeneous alignment technique. This presumably scratches the surface and provides a preferred direction in which the molecules align. The homogeneous alignment technique may not be compatible with low-loss waveguide fabrication. The other reported alignment technique [12], referred to as the homeotropic alignment technique, involves the deposition of a thin film of polar atoms (surfactant) on the surface. Again a preferred alignment direction is established and a high degree alignment is possible, usually at right angles to the alignment achieved by rubbing. This method seems more applicable to waveguide techniques and requirements.

To couple light into and out of a waveguide, it is necessary to change the boundary conditions. This may be done in several ways. In the prism coupler a prism is brought within a few optical wavelengths of a waveguide surface and *frustrates* [13] total internal reflection at the surface. Frustrated total internal reflection or evanescent-field coupling occurs because the boundary conditions of a waveguide are modified by the presence of the prism. A second type of coupler, the *grating coupler* [14], consists of a periodic structure in contact with the waveguide boundary. This structure permits momentum matching between a guided optical wave and a wave propagating in the cladding medium and thus provides coupling between the two waves. Both types of couplers may be fabricated using liquid crystals.

To construct active devices, the index of the waveguide media, or the determining boundary conditions, must be actively controlled by some external parameter. Once this is achieved, the construction of systems that will act as modulators, deflectors, and switches is possible.

Modulation may be achieved by electrooptic, acoustooptic, and magnetooptic phenomena. The electrooptic modulators make use of induced birefringence to cause phase changes in the optical waveguide modes. For example, in a waveguide of electrooptic material, or in a waveguide on an electrooptic substrate, the propagation factors for TE and TM modes vary differently with an applied electric field. If a TE wave is passed through a modulator, a phase shift may be induced, which causes a TE wave to be coupled to an orthogonally polarized TM mode. Viewed through an appropriate analyzer, the output is an amplitude-modulated signal. Magnetooptic modulators make use of induced optical activity instead of induced birefringence and require current-modulated signals instead of voltage-modulated signals. A device of this type has been demonstrated [15].

Deflectors can operate either via the electrooptic or acoustooptic effect. In the case of electrooptic deflectors not used in optical waveguides, these devices are usually digital deflectors. The digital devices use the principle that the electrooptic effect rotates the plane of polarization of linearly polarized light in a suitable medium, so that a polarizing prism such as a Rochon, Wollaston, or Thompson prism deflects the beam into one of two channels. The same effect is accomplished in optical waveguides using coupled waveguides. No exact analog of the digital deflector has been demonstrated in optical waveguides.

The acoustooptic deflector [16] has the advantage of continuous deflection by electronic tuning of the acoustic frequency. The acoustic wave produces periodic index and surface variations [17], which in turn deflect a portion of the optical radiation by Bragg diffraction. This process is particularly adaptable to a dielectric film, which forms a surface layer on a substrate, producing a waveguide. In this case the acoustic wave is a surface wave, and the optical radiation is also on the surface of the substrate. The interaction can therefore be achieved with much less acoustic power than in the bulk case, and efficiency is improved. Waveguide devices of this sort have been analyzed [16], and a particular configuration is shown in Fig. 3. This device had a maximum observed deflection efficiency of 66% with an electrical input of 2.5 W, or an acoustic power of 0.18 W. Liquid crystals have all the properties that are needed for switching, deflecting, and modulating and appear to be able to combine the advantages of the acoustooptic and electrooptic devices in one compact package.

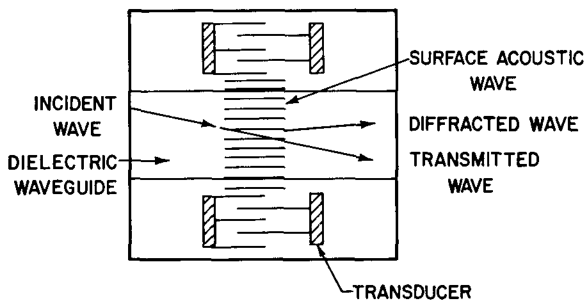

Fig. 3—Acoustooptic deflector. An optical guided wave incident at the Bragg angle is efficiently scattered by a surface acoustic wave. Because the acoustic and optic wave have their energy localized in the waveguide structure, high-efficiency scattering results.

Liquid Crystals

When some organic substances are melted, instead of becoming a clear liquid, they pass through a turbid fluid state which is termed the mesomorphic or liquid-crystal state [18]. The liquid-crystal state has more order in the arrangement of its molecules than the isotropic liquid state, but less than the solid state.

In general a molecule of a compound which forms liquid crystals is elongated, contains a benzene ring, is fairly rigid along a large part of the long axis, is highly polarizable, and contains a permanent dipole [19].

Three major phases of the mesomorphic or liquid-crystal state have been observed: smectic, cholesteric, and nematic. For each major phase there exist subphases or textures (such as homeotropic, smectic C, and focal conic). Cholesteric phases are noted for their high optical activity, whereas the smectic and nematic phases are generally not optically active.

Nematic liquid crystals are composed of long cylindrical molecules which align in a parallel manner. Each molecule can rotate freely only about its long axis but can also have some freedom of movement from side to side or up and down (Fig. 4a). The smectic liquid crystals have layers which slide over one another. Inside each layer the molecules may align in an ordered manner (Fig. 4b) or be randomly distributed. Cholesteric liquid crystals are thought to consist of layers with the alignments in the layers displaced with respect to one another, forming a helical pattern (Fig. 4c) and thus causing the high optical activity.

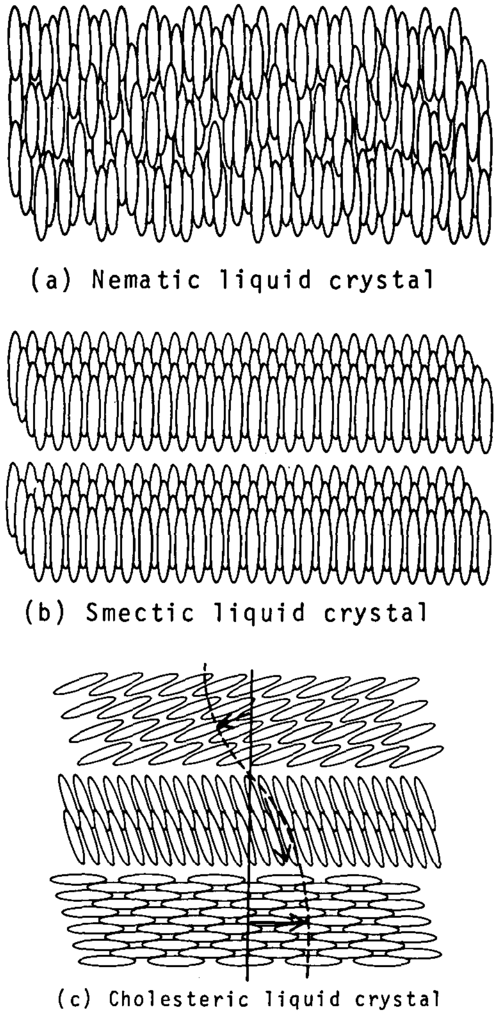

Fig. 4—Proposed models of the nematic, smectic, and cholesteric phases. The nematic liquid crystal is not layered, the smectic liquid crystal is layered with the alignment the same in each layer, and the cholesteric liquid crystal is layered with the internal alignment changing from layer to layer.

Numerous optical effects have been observed using liquid crystals [20], and many of these can lead to practical applications. Table 1 lists some interesting electrooptic effects, some representative materials exhibiting the effects, and their possible applications. All of the properties listed can be used to advantage in optical waveguide systems.

Table 1
Observed Electrooptic Effects in Liquid-Crystal Materials and Some Current Uses in Display Systems [19]

Electrooptic Effect	Representative Liquid Crystal	Mesophase	Operating Temp. (°C)	Applications
Dynamic scattering	Anisylidene-p-n-butylaniline	Nematic	23	Alphanumeric, analog, or matrix displays; dimmable windows or mirrors; page composers; beam splitters; and nonimpact printers.
Tunable diffraction	40% cholesteryl chloride, 26% cholesteryl nonanoate, and 34% cholesteryl olyel carbonate	Cholesteric	23	Alphanumeric or matrix color displays, tunable monochrometers, laser beam deflectors, and light modulators.
Guest-host interaction	99% p-ethoxybenzilidene-p′-aminobenzonitrile and 1% indophenol blue	Nematic with guest dye molecules	110	Tunable optical filters, light modulators, and two-color displays
Optical storage	10% cholesteryl erucate and 90% anisylidene-p-n-butylaniline	Mixed cholesteric and nematic, mostly nematic	23	Displays with memory, light modulators, and data storage planes (optical memory)
Cholesteric-to-nematic transformation	30% primary active amyl p-(4-cyanobenzylideneamino) cinnamate and 70% para substituted benzylidene anilines	Mixed nematic and cholesteric, mostly cholesteric	23	Displays and light modulators
Induced alignment	p-n-octoxybenzylidene-p-aminobenzonitrile	Nematic	85	Displays, intensity modulators, and phase modulators

In general these optic phenomena result from placing an external field in the proximity of the material. Induced alignment has been used for displays. In this mode the electric field aligns the molecules sufficiently so that the material acts as a polarizer. The magnitude of the field affects the efficiency of polarization, and produces quite an effective display when light is viewed after it has first passed through another polarizer (Fig. 5).

The cholesteric phase exhibits reflected colors which are caused by a molecular diffraction grating tunable as a function of temperature [18]. This color reflection is believed to be caused by Bragg-like reflection from a helical structure that causes the high optical activity observed. Since the Bragg angle is a function of the pitch of the helix, changes of color may be induced by changes of pitch. The pitch is determined by intermolecular distances which are affected by temperature, pressure, and applied electric field.

Currently the dynamic scattering mode has elicited the greatest excitement in the display field. This mode is thought to arise from the interaction of ions with the liquid-crystal molecules. These molecules (which are negatively anisotropic) align at right angles

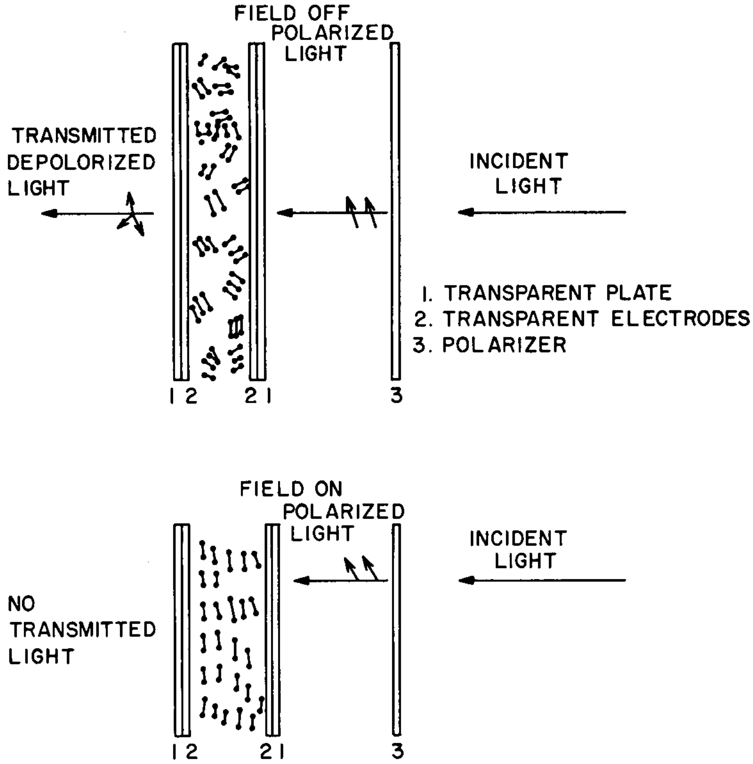

Fig. 5—System that uses field-induced polarization as a means of information display

to the applied field. The ions move along the field, hitting the liquid-crystal molecules. This interaction causes local turbulence which results in light scattering (Fig. 6). Though induced alignment provides the greatest obvious applications to waveguides, the dynamic scattering mode may offer unique advantages for certain types of optical switches.

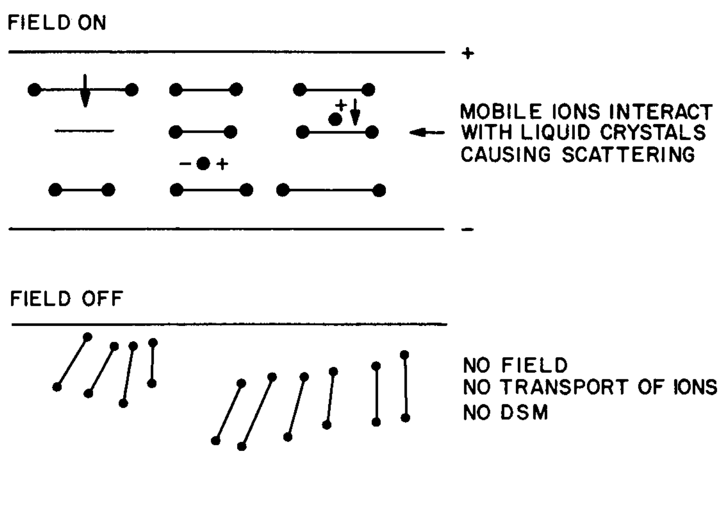

Fig. 6—Proposed model for the dynamic scattering mode (DSM)

LIQUID-CRYSTAL WAVEGUIDE APPLICATIONS

Table 2 presents several properties of liquid crystals that make them attractive as integral components in optical waveguides. The last column in the table is a synopsis of the specific role each effect could have in an optical waveguide system. Each liquid-crystal structure has applications as more than one active device. Though some devices have been fabricated using other materials (such as nitrobenzene as an electrooptic modulator), liquid crystals provide a class of material potentially capable of performing all desired optical processing functions. Table 2 describes the pertinent liquid-crystal structure, field effects upon the structure, and the resulting waveguide device.

Induced Alignment

The alignment of the nematic mesophase without any applied external field depends strongly on the nature of the surface bounding the phase. It has been previously determined that appropriate rubbing of cleaned glass windows results in *homogeneous* material. Modifications of this technique have included streaming of ions over the glass homogeneously [4] and also firm stroking with paper [11]. The probable mechanism of alignment is homogeneous grooving of the glass. This grooving may introduce scattering losses into the waveguide device, but the extent of the losses has not been ascertained. This grooving problem should not however prevent use of liquid crystals in waveguide systems. If scattering losses are high, a sufficiently small region may still be used to good advantage.

An alternative method of alignment in zero field is the use of a monolayer of surfactant. For positive dielectric materials the alignment is called homeotropic. Literature values for both types of alignment indicates that losses of 3 to 5 dB/cm are attainable.

The orientational changes produced by large electric fields (Fig. 5) lead to substantial index variations for a given polarization of light. By changing the index of refraction, several active functions may be performed:

- *Phase modulation* results if a TE and TM mode are propagated along the waveguide. By changing the index of the propagating wave material, one mode may be retarded relative to other modes, resulting in a net phase change.

- *"Active" lenses and prisms* may be fabricated by applying electric fields that result in spatial index changes of a desired form (Fig. 7).

- *Mode suppression* is accomplished by changing the index of either the waveguide or the boundary so that the propagating wave is beyond cutoff. This has implications in output coupling systems. A suitable index change may also result in the propagation of one mode and the suppression of another; this is *mode switching.* Another way of achieving *mode suppression* is by using a nematic system exhibiting the dynamic-scattering mode. When sufficient voltage is applied, dynamic scattering occurs, causing mode suppression.

Guest-Host Interaction

By dissolving a pleochroic dye into a nematic system that undergoes induced alignment, a different electrooptical effect may be realized. Absorbance occurs only in a specific direction in the dye (Fig. 8); therefore the amount of absorbance may be modulated

Table 2
Properties and Uses of Liquid Crystals in Waveguides

Mesophase Structure	Effect of the Field on the Liquid Crystal	Field Structure	Optical Properties		Uses as a Field-Controlled Waveguide Device
			Applied Field Off	Applied Field On	
Nematic	Regular alignment using E_2 and H_y	$E_x = 0$ parallel to Hy and E_x large parallel to walls	Transparent, birefringent, and small-angle scattering	Index change and Pockel effect	Phase modulation, mode coupling, active lens, active prism, mode switching, mode suppression, output coupling, and spatial switching
Nematic and dye	Guest-host interaction	$E_z = 0$ randomly aligned to walls and E_z large aligned to field	Linear dichroism	Transparent with isotropy along the z axis	Frequency selection, amplitude modulation, mode selection, and output coupling
Nematic and 5% cholesteric	Stored texture	Address molecules parallel to walls	Transparent and birefringent	Intense diffuse wide-angle scattering	Waveguide switch
Nematic and smectic	Domain formation	$E_z = 0$ parallel to walls and E_z large produces liquid rotation	Transparent and birefringent uniaxial positive	Parallel array of cylindrical lenses and index change	Mode suppression, mode switching, and amplitude modulation
Cholesteric	Dilation of helix undisturbed cholesteric	$E_z = 0$ domain parallel to walls and E_z-large domain parallel to field	Birefringent and uniaxial negative Bragg or Raman-Nath diffraction	Decreased birefringence and decreased diffraction angles	Phase modulation, frequency modulation, mode coupling, mode switching, frequency selection, phase matching (i.e., frequency coupling), and output coupling
Cholesteric (subphase is Grand Jean plane texture)	Surface deformation	Helix reorientation and mass transport along field gradients	Bragg diffraction (dispersive reflection)	Altered reflection from deformed areas	Same as the item above plus acoustically coupled modulation
Cholesteric and Dye	Surface deformation	Same as the item above	Same as the item above	Same as the item above	Same as the item above pluse mode gain (internal-feed back laser), frequency modulation, amplitude modulation, and light interrogation to determine the state of information transfer

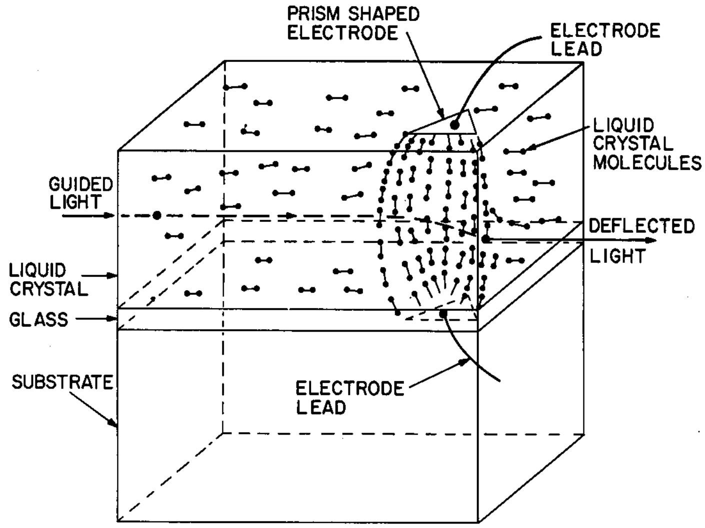

Fig. 7—Liquid-crystal waveguide functioning as an active prism. It could similarly function as an active lens.

by the applied electric field [21]. If two dyes with different preferred absorbing axes are dissolved in the system, color switching is obtainable by controlling the applied field. This can be used as a method of *frequency selection.* This system may also be used for amplitude modulation of propagating modes in the nematic-phase-plus-dye waveguide by selective absorption. TE-TM mode discrimination may be obtained through the polarization-selective absorption available in the system. If the pleochroic dye is chosen to be suitably fluorescent, *random access* to the waveguide system may be achieved. By applying a field, the dye will either fluoresce or not. The fluorescence (frequency-shifted radiation) will not propagate in the waveguide but will couple out, thus providing information on the optical states in the system.

Storage Effects

If 10% of a positive anisotropic* cholesteric phase is dissolved in approximately 90% of a negative anisotropic system, an electrooptic memory is obtained [22,23]. A low-frequency electric field produces a highly scattering region (lower limits) which remains scattering indefinitely after the field is switched off. The scattering state is erased by the application of a high-frequency electric field. This effect may be used as an *Optical switch* in waveguide systems.

Domain Formation

Both smectic and nematic phases can produce domains under suitable conditions. With the electric field off, the system is transparent, birefringent, and uniaxial positive. By applying an electric field parallel to the walls, a parallel array of domains is produced. These domains act as cylindrical lenses. If an appropriate acoustic wave is coupled into the system, the parallel nature of the lenses is replaced by a periodic structure [24]. This can be used for *mode coupling.*

*Positive anisotropy occurs when the long axis of the molecule is parallel to the dipole moment.

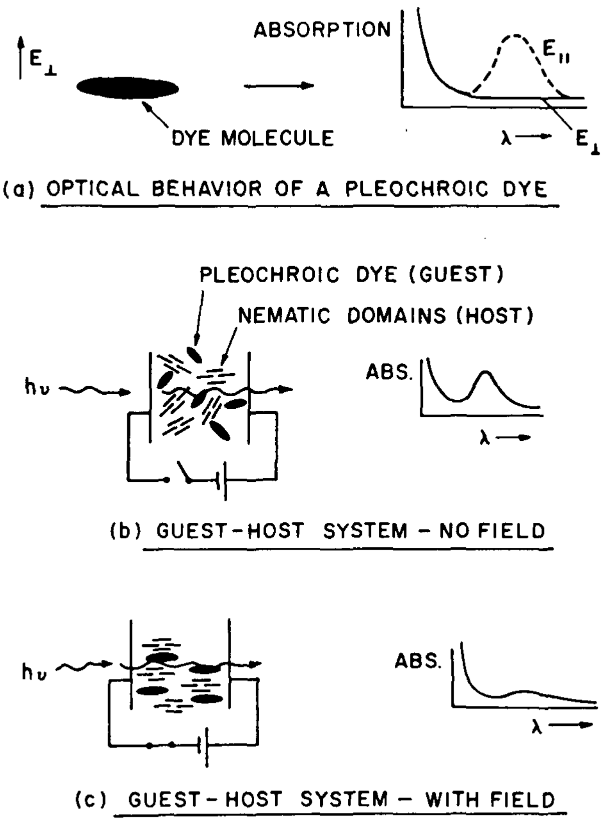

Fig. 8—Absorbance of a pleochroic dye as a function of its alignment in host nematic domains

One problem in the effective use of this effect is the scattering caused by the discontinuities at the domain boundaries. It may be possible to circumvent this difficulty by using a suitably small region, thus minimizing the losses.

Cholesteric Mesophase

The cholesteric phase exhibits both high optical activity and selective reflection of colors. The apparent reflective color changes as well as the wavelength of maximum optical activity vary as a function of temperature, electric field, and dissolved vapor. In the past, cholesteric-liquid-crystal systems have been used in skin-cancer detection, skin thermography, and vapor detection in infrared spectrometric analysis.

The nature of the propagation of light in thin films along the waveguide axis is not known. Along the helical axis the cholesteric phase exhibits optical activity, but the degree of optical activity, if any, is not known along different axes, although elliptical polarization is expected. If optical activity occurs along these other axes, then the waveguide devices listed in Table 2 for the cholesteric phase structure should be realizable. The principles of their operation involve changes in the refractive index and have been outlined in the previous sections.

Liquid-Crystal Fiber Core

One can envision several uses in the application of liquid crystals to optical-fiber technology. A particular possibility is liquid-core fibers (Fig. 9). The liquid-crystal molecules may be aligned in one of two orthogonal directions in the fiber core, either perpendicular to the core axis (Fig. 9a) or parallel to the core axis (Fig. 9b). An optical wave propagating along this fiber will interact with one of the two refractive indices. By applying a large electric field to the fiber, the refractive index may be switched. If an electric field of smaller strength is applied, the molecules are only partially reoriented. Both total and partial switching are useful and lead to different devices.

If one partially reorients the molecules, the molecules at the core center will be oriented more easily than those at the wall. As mentioned previously, the wall tends to align the molecules and in the present application will tend to hinder the reorientation by

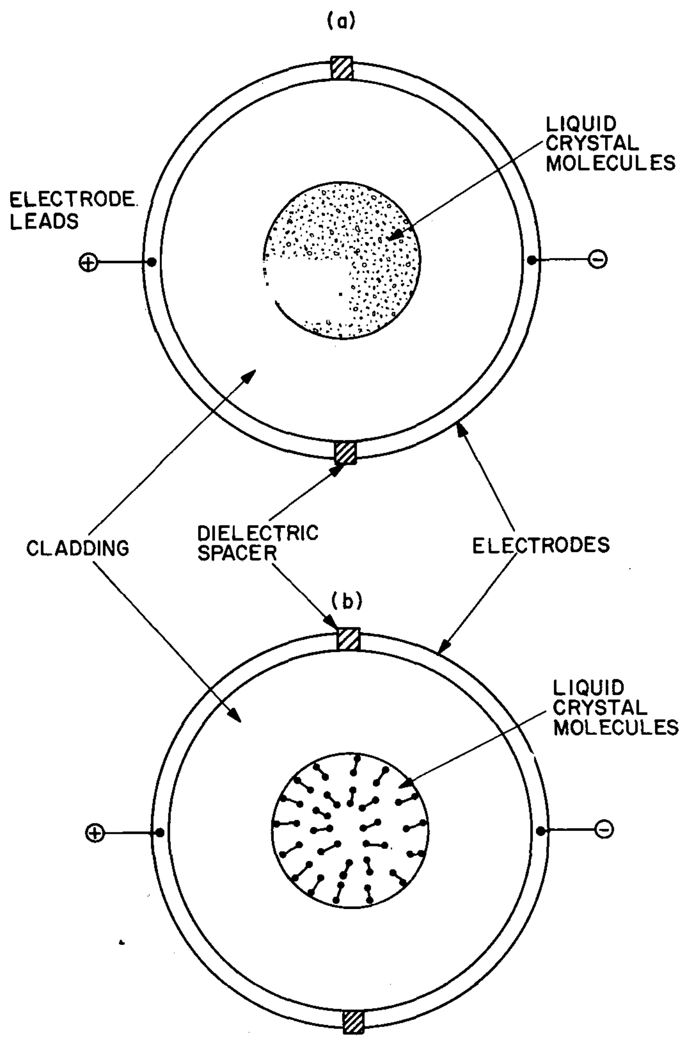

Fig. 9—Liquid-crystal fiber core. In (a) the molecules align parallel to the core axis due to surface effects, and in (b) the molecules align perpendicular to the core axis due to the electric field.

the electric field. This will lead to a varying index change across the liquid core fiber and will act as a lens capable of focusing the propagating wave.

When the field is large enough to cause complete reorientation, then amplitude modulation results. By decreasing the index, the propagating wave may now be made to be below cutoff. This will result in the guided wave being coupled out of the fiber *(fiber output coupler).* If the transmitted signal is of interest, the electric field may be used to *modulate* the amplitude. Finally, if a cholesteric liquid crystal is used, its optical rotatory powers may be used to adjust the phase between two modes propagating along the fiber. This will result in a *dispersion compensator.*

SUMMARY

This report has explored the potential of liquid-crystal materials in optical waveguide systems. The combination of these two technologies has a possible synergistic effect. It has been shown that many of the difficult switching and modulating problems currently affecting the progress of waveguide technology may be solved by the proper use of anisotropic fluids. Before working integrated optical systems can be fabricated, several fundamental problems must be solved:

- Scattering losses from lack of sufficient alignment must be minimized.

- Electrode fabrication compatible with optical waveguides must be realized.

- Liquid-crystal materials must be obtained that will not degrade under the optical and electromagnetic fields present in these contemplated devices.

These problems are solvable in the near future. Thus liquid crystals are likely to be the quickest and most efficient route to optical waveguide systems.

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