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Realization of optical modulators for fiber optic sensors.

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REALIZATION OF OPTICAL MODULATORS FOR FIBER OPTIC SENSORS

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Abstract: *The principles of realization of solid-state optical modulators for building fiber-optic sensors are considered in the article. The electro-optical effect used by many optical modulators is described. Detailed volume modulators based on electro-optical and acousto-optic effects are presented. Integral-optical modulators with phase and interferometric intensity modulation, as well as pure-fiber optical modulators with phase modulation are described with description. Modulator models in the form of equivalent circuits with lumped parameters and methods for obtaining the frequency characteristics of optical modulators. The implementation of a fiber-optic frequency converter is presented, in which an acoustic wave from a sensor element perturbs two channeled modes in a fiber.*

Keywords: *optical modulator, fiber optic sensor, electro-optical effect, acousto-optical effect, phase modulation, interferometric modulation, equivalent circuit, frequency response.*

Introduction

Optical modulators are a key component of optical fiber systems, performing a variety of functions, including amplitude, phase, frequency, and polarization modulation. Most are implemented as solid-state devices in which light is modulated by varying the optical properties of the device material by an electrical control signal. The control signal is linked to the material properties by an electrooptic, acoustooptic, or magnetooptic mechanism (Fig.1). While many optical modulators are still under investigation in research laboratories, high-performance devices are becoming increasingly available for fiber-sensor applications [1,2].

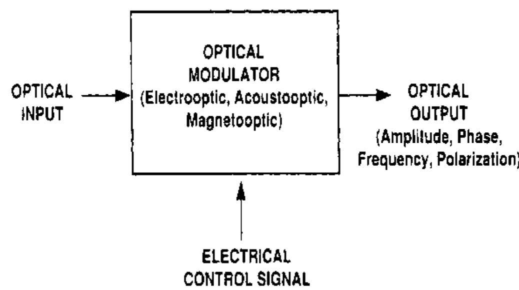

Figure 1. ***Solid-state optical modulator, in which the optical signal is modulated by applying an electrical control signal.***

Three basic types of solid-state optical modulators are bulk, integrated optical, and all-fiber devices.

1. Electrooptic effect

Many optical modulators are based on the linear electrooptic effect [1], in which the refractive indices of crystals are linked to an applied electric field. The effect is characterized in the context of optical beam propagation through a crystal, as described by the index ellipsoid formalism

$$\left(\frac{1}{n^2}\right)_1 x^2 + \left(\frac{1}{n^2}\right)_2 y^2 + \left(\frac{1}{n^2}\right)_3 z^2 + 2\left(\frac{1}{n^2}\right)_4 yz + 2\left(\frac{1}{n^2}\right)_5 xz + 2\left(\frac{1}{n^2}\right)_6 xy = 1 \qquad (1)$$

where x, y and z are directions relative to the crystal axes (Fig. 2). For an arbitrary propagation direction s, optical beams maintain constant linear polarization through a crystal for only those polarization directions allowed by the crystal symmetry. These are determined by a plane thatboth contains the origin of the ellipsoid and is normal to the propagation direction. In general, the intersection of this plane with the index ellipsoid forms an ellipse, and light that is linearly polarized in a direction parallel to either its major or minor axis propagates without a change in polarization. The refractive indices of these two allowed waves are the lengths of the respective axes. A beam can be decomposed into a superposition of its two allowed linear polarization states, and any difference in the refractive indices of the two waves causes the polarization to vary continuously as the beam propagates through the crystal. If the intersection is a circle, any direction of linear polarization is allowed.

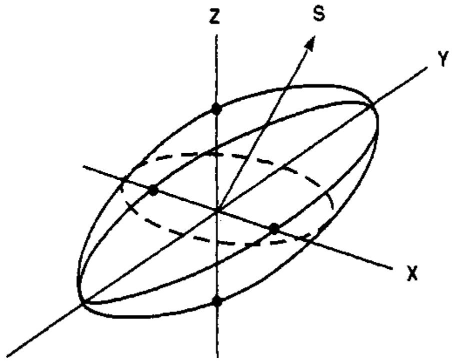

Figure 2. ***As light propagates through a crystal, the two allowed states of linear polarization associated with a propagation direction s are parallel to the axes of the ellipse formed by the intersection of an ellipsoid and a plane perpendicular to s.***

2. Bulk modulators

Bulk modulators are used extensively in optical systems, including fiber optic sensors. These devices are widely available and their characteristics are well established. In this section, bulk modulators based on the electrooptic and acoustooptic effects are discussed since the majority of the devices used in fiber-sensor applications are based on one of these two mechanisms.

The behavior of electrooptic modulators in electrical systems can usually be analyzed by simple equivalent-circuit models. In the lumped-element schematic shown in Fig. 3, the modulator is modeled as a parallel-plate capacitor with capacitance C given by

$$c = \frac{\varepsilon LW}{d} \qquad (2)$$

where ε is the permittivity of the modulator crystal. The typical modulator has a small series resistance *R*m. In addition, this model comprises source and termination resistances that are both equal to *R*s. The voltage across the capacitor corresponds to the modulator voltage, which is assumed to be uniform across the electrode. The effects of finite electrical transit time are ignored.

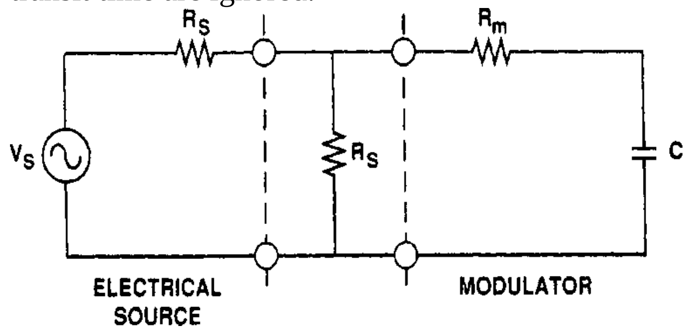

Figure 3. ***Lumped-element equivalent-circuit model of an electrooptic modulator system. The capacitor voltage corresponds to the modulator electrode voltage.***

The lumped-element model in Fig. 3 yields a modulation bandwidth that extends from dc to the 3-dB bandwidth f_{3dB}, where

$$f_{3dB} = \frac{1}{2\pi R_s C} = \frac{1}{2\pi \varepsilon R_s}\frac{1}{(L/d)W} \qquad (3)$$

which is valid for $R_m \ll R_s$. Both V_π and f_{3dB} are inversely proportional to L /d, which results in a design trade-off between wide bandwidth and low V_π. As an example, a typical $LiNbO_3$ modulator with parameters $\varepsilon = 32\varepsilon_0$, *R*s = 50 Ω, $n^3/r = 3 \times 10^{-10}$ m/V, L = 2 cm, W = d = 2 mm, and $\lambda = 1.3$ μm will have a capacitance C of approximately 6 pF, yielding a bandwidth f_{3dB} of 500 MHz and a figure of merit V_π of 425 V.

3. Electrooptic intensity modulation

A bulk electrooptic intensity modulator [1,2] can easily be realized by taking advantage of the polarization dependence of the phase modulator. A simple implementation of an intensity modulator in $LiNbO_3$ consists of a polarization-dependent phase modulator inserted between crossed polarizers (Fig. 4). By changing the phase modulator voltage *V*(t) the polarization of the beam incident on the output polarizer is varied, which in turn leads to intensity modulation. In this structure the optical beam is decomposed into ordinary and extraordinary waves, linearly polarized along the *x* and *z* axes of the $LiNbO_3$ crystal, respectively. The input polarizer is oriented 45° with respect to these axes, so the field, which is propagating in the y direction, can be written as

$$\overline{E}(y) = \frac{E_0}{\sqrt{2}}\{exp[i\phi_x(y)]\overline{x} + exp[i\phi_z(y)]\overline{z}\} \quad (4)$$

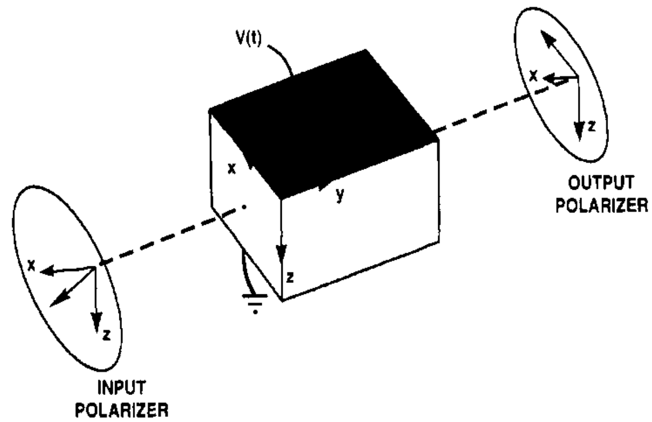

Figure 4. ***Bulk electrooptic intensity modulator consisting of an input polarizer oriented 45° with respect to the modulator axes, a polarization-dependent electrooptic phase modulator, and an output polarizer oriented 90° with respect to the input polarizer.***

Acoustooptic devices are used most often in fiber-sensor applications as optical frequency shifters, and only to a lesser extent as intensity modulators. In acoustooptic modulators [1,2], an optical beam propagating through a crystal interacts with a traveling-wave index perturbation generated by an acoustic wave. The perturbation results from a photoelastic effect whereby a mechanical strain produces a linear variation in refractive index; this resembles a traveling-wave diffraction grating, which under certain conditions can efficiently deflect an optical beam (Fig. 5). Devices have been realized in which a surface acoustic wave (SAW) interacts with an optical wave confined in a slab waveguide [1]. However, although these offer higher efficiency than bulk devices, they are more difficult to implement.

Acoustooptic devices are often made of materials such as $LiNbO_3$ and quartz, since the waves can be launched efficiently in these crystals over a frequency range from tens of megahertz to several gigahertz. The acoustic velocity v_a in $LiNbO_3$ is approximately 6 X 10^3 m/s, and thus a 1-GHz acoustic wave has a wavelength Λ_a of about 6 μm, which is comparable to optical wavelengths. The amplitude of the associated index perturbation is proportional to the square root of the acoustic intensity.

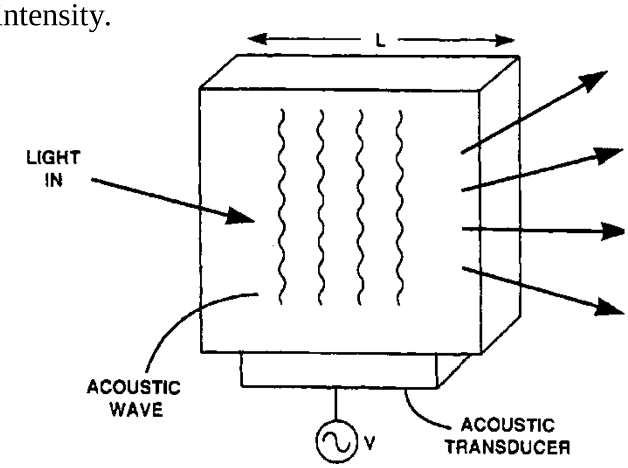

Figure 5. ***Bulk acoustooptic modulator operating in the Raman-Nath regime, in which the acoustic wave perturbs the optical beam resulting in multiple diffracted beams.***

An acoustooptic modulator operates in one of two modes [2]. For short interaction lengths, where $L \ll \Lambda_a^2/\lambda$, the device operates in the so-called Raman-Nath regime, creating multiple diffracted beams (Fig. 5) whose packaging. Rather complicated monolithic channel waveguide circuits can be structured, and thus the variety of available devices is much larger than for bulk components. As an example, a multifunction integrated-optical chip for fiber gyroscopes is illustrated schematically in Fig. 6. The chip contains a *Y*-branch power splitter, a phase modulator, and an optical frequency shifter.

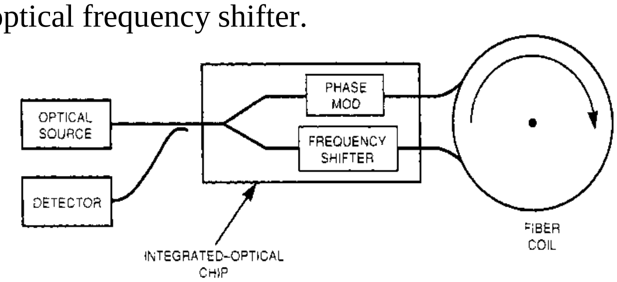

Figure 6. ***Fiber-gyroscope multifunction integrated optical chip.***

Modulation of an optical signal directly within an optical fiber is a particularly attractive concept for fiber-sensor applications, since it would eliminate the need for fiber coupling, which in turn would substantially reduce optical insertion loss as well as simplify packaging. All-fiber devices are a challenge to implement because the most common fiber material is glass, which is noncrystalline, precluding a direct link between an applied electric field and the refractive index. Thus mechanical means such as squeezing the fiber are required to obtain an index change. Performance of all-fiber modulators is as yet weak and relatively slow compared with discrete devices, but they are of considerable interest and are being developed actively. In this section, all-fiber phase modulators and frequency shifters are described.

4. Phase Modulation

Phase modulation in all-fiber devices is achieved by either stretching or squeezing the fiber by some external means, which is expressed mathematically as

$$\phi(t) = \frac{2\pi}{\lambda}[L\Delta n(t) + n\Delta L(t)] \quad (5)$$

where *Δn(t)* and *ΔL(t)* are variations of the refractive index and the device length, respectively. Compared with bulk and integrated-optical devices, in which the effect of length variation is negligible, even a small fractional change of length of the long fibers in all-fiber modulators can lead to significant phase modulation.

The most widely used all-fiber phase modulator consists of optical fiber wrapped around a piezoelectric ring, commonly made of poled lead zirconate titanate (PZT) (Fig. 7) [1,2]. Voltage applied across the ring changes the ring circumference and fiber length. The modulator sensitivity depends on the electrode configuration, the modulation frequency, and the ring diameter. Sensitivities of ~ 50 mrad/V-turn are typically achieved for modulation at 0.63 μm with a ring diameter of 2 cm.

A key feature of the modulator frequency response is acoustic resonance, which is determined by the ring geometry and the mode of operation. In the so-called hoop mode, which operates by changing the ring circumference (Fig. 7), the resonance frequency varies inversely with the ring diameter. A typical frequency constant is 100 kHz-cm, so a 2-cm ring has a resonance frequency of ~ 50 kHz. At resonance the modulator sensitivity is significantly enhanced. On the other hand, in applications that require a flat frequency response, such as serrodyne frequency shifting, this effect may be undersirable because the resonance limits the modulation bandwidth to tens of kilohertz. Also, increasing the resonance frequency by decreasing the ring diameter can lead to unacceptable fiber-bending losses.

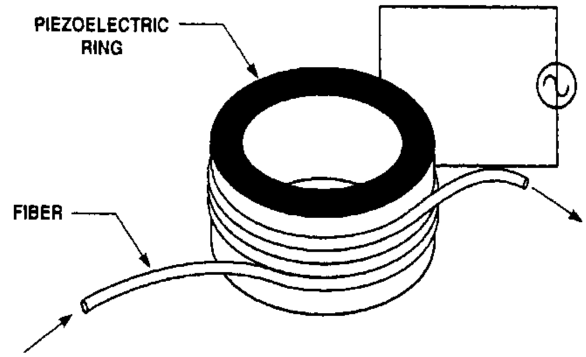

Figure 7. ***Fiber optic phase modulator consisting of a fiber coiled around a piezoelectric ring. Application of voltage changes the ring diameter and the fiber length.***

Several other schemes based on the piezoelectric effect have been developed to achieve a higher frequency response, such as coating the fiber with a polymer and squeezing it by applying an electric field [1], which changes both the refractive index and length of the fiber. One implementation of this design involves depositing a metal electrode on a bare fiber, coating the fiber with a polyvinylidene fluoride (PVF_2) polymer, and depositing an outer electrode. The polymer jacket becomes piezoelectric after it is poled in an applied field. For an 18-cm-long sample operating at a wavelength of 0.63 μm, the sensitivity is ~ 30 mrad/V-m for frequencies up to 10 kHz, where there is both axial and radial strain, and ~ 10 mrad/V-m for frequencies from 10 kHz to 2.5 MHz, where there is only radial strain. A π-radian peak-to-peak phase modulation at 1 MHz would require a 30-V peak-to-peak signal applied to a 10-m-long modulator. Higher sensitivities are envisioned using different polymers and more efficient poling orientations.

All-fiber frequency shifters, which resemble the TE/TM frequency shifters considered in [2], are based on traveling-wave coupling using a fiber that supports two guided modes with a difference in propagation constant of $\Delta\beta$ [1]. An acoustic wave of frequency ω_a launched into the fiber perturbs the index profile resulting in mode coupling, which causes a frequency shift of $\pm\omega_a$. The phase-matched interaction required for efficient power transfer is obtained by setting

$$\Delta\beta = \frac{2\pi}{\Lambda_a}, \quad (6)$$

where Λ_a is the acoustic wavelength. This technique has been demonstrated with fiber supporting two spatial modes and also with high-birefringence fiber that supports two polarization modes.

Conclusion

In the latter implementation illustrated in Fig. 8, an acoustic transducer converts input electrical power into a Rayleigh wave that propagates along a block of fused quartz and generates traveling-wave index distortion and polarization mode coupling in a high-birefringence fiber pressed against the block. For the coupling to occur, the stress exerted by the wave must be in a direction other than the principal axis of the fiber; and to obtain phase matching, the angle between the fiber and the acoustic wave must be 27°.

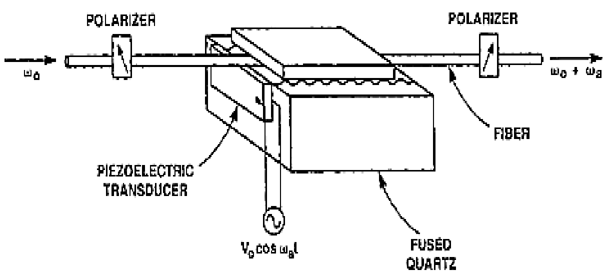

Figure 8. ***Fiber optic frequency shifter in which an acoustic wave from a transducer perturbs the two guided modes of a high-birefringence fiber, causing mode coupling.***

An experimental device of this type designed for a center frequency of 4.5 MHz with a tuning range of 290 kHz had a fiber beat length $2\pi/\Delta\beta$ of 1.7 mm at a 0.63-μm wavelength and achieved 95% conversion efficiency in a pulsed mode with 25-W peak input electrical power. The sideband suppression was 40 dB and the carrier suppression was 25 dB.

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