APPLICATIONS OF ELECTRO-OPTIC GRATINGS IN INTEGRATED OPTICAL SIGNAL PROCESSING DEVICES*

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SUMMARY

The electro-optic grating is an easily fabricated component which allows a rapid and efficient interaction with an optical wave in a planar electro-optic waveguide. The operation of such gratings and their use as intensity modulators, spatial light modulators, and components in correlators and in a variety of computational units is described.

INTRODUCTION

The electro-optic effect has been the most important interaction mechanism used in the design of the active integrated optical devices employing channel waveguides.[1] In these devices, the designer is able to take advantage of the lateral confinement of the light which allows long interaction lengths and consequently low voltages. In the present paper we will, in contrast, be concerned with the use of the electro-optic effect in planar integrated optical structures. In this planar geometry, the guided light is confined to a several micrometer-thick waveguide at the surface of a suitable electro-optic substrate. Lateral diffraction is not inhibited, but the confinement close to the surface allows the use of moderate voltages to obtain a strong interaction with the guided light. In particular we will show how the interaction of a relatively broad guided beam with an electro-optically induced thick phase (Bragg) grating[2] can be used to advantage in a variety of integrated optical devices. We begin by describing the properties of the gratings and then discuss a number of modulators, correlators and computational units which incorporate these gratings.

THE ELECTRO-OPTIC GRATING

The basic geometry of the I.O. grating electrodes is shown in figure 1. The electrodes are defined by standard photolithographic techniques upon the surface** of a planar electro-optic optical waveguide such as Ti-indiffused[4] $LiNbO_3$. It is conventional to make the electrode line-wide equal the spacing between adjacent fingers, so the required photolighographic resolution is $\Lambda/4$.

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** Often a sputtered glass buffer layer is employed[3] to isolate the guided wave from perturbation due to the metallization pattern.

The application of a voltage across the electrodes results in a periodic electric field which, via the electro-optic effect, gives rise to a periodic modulation of the index of refraction of the waveguide material and thus to the mode index of the guided wave. The guided wave sees this periodic perturbation as a thick phase grating and will be diffracted as indicated in figure 1 when incident upon the grating at the Bragg angle, defined by

$$\sin\theta_B = \frac{\lambda}{2\Lambda} \qquad (1)$$

where λ is the optical wavelength in the medium.

The diffraction efficiency[5] is

$$\eta = \sin^2 \frac{\pi \Delta n d}{\lambda_o \cos\theta_B} \qquad (2)$$

where Δn is the amplitude of the periodic index modulation. The magnitude of Δn is determined by the product of the applied field strength E, and the appropriate electro-optic coefficient r_{ij} according to[6]

$$\Delta n = \frac{1}{2} n^3 r_{ij} E \qquad (3)$$

where n is the average index of refraction. Inclusion of geometric effects[7] results in an index modulation

$$\Delta n = \frac{1}{2} n^3 r_{ij} \frac{2}{\pi} \left(\frac{V}{\Lambda/4}\right) \qquad (4)$$

or a diffraction efficiency of

$$\eta(V) = \sin^2 \left(\frac{4n^3 r_{ij} d}{\lambda_o \cos\theta_B} V\right) \qquad (5)$$

Ignoring buffer layer effects, eq. (5) indicates that for Λ = 8 μm, a He-Ne laser and d = 2 mm, we get 100% diffraction efficiency for V = 3.1 volts. Since high diffraction efficiencies are readily achieved and the electrode capacitances are quite low, it is evident that the electro-optic Bragg effect can be utilized to make a high performance modulator. This device was originally suggested by Hammer and Phillips,[2] and has more recently been employed by Holman[8] to make a high performance planar modulation with a 69% optical throughput.

THE INTEGRATED OPTICAL SPATIAL LIGHT MODULATOR

The basic grating structure can be extended as shown in figure 2 by introducing electrodes which allow segments of the grating to be individually addressed. In this manner, one can impose a transverse amplitude modulation upon the diffracted beam. The undiffracted beam will of course have a complementary modulation. The grating structure is now operating as an electrically addressable integrated optical spatial light modulator (IOSLM) and can, in principle, be used to modulate an arbitrarily wide guided wave. The modulator can be used in an analog or a binary mode, although there will obviously be a finite number of addressable segments. The largest such IOSLM we have fabricated thus far[9] is composed of 32 segments 200 μm wide and spans a 6.4 mm-wide guided wave.

It should be possible to reduce the width of each grating segment to 50 μm or less. It would then be possible to use the IOSLM in the signal and filter planes of a planar optical Fourier transform device.[10] However, even with the larger grating segment size, several useful functions can be performed by incorporating a SAW transducer on the same substrate as the IOSLM. If the orientations of the EO and acoustic gratings are chosen so that only doubly diffracted light is detected, then by introducing a single acoustic pulse which is shorter than a single IOSLM element, the transverse modulation produced by the IOSLM is converted to a temporal modulation of the output (doubly diffracted) beam. Parallel-to-serial conversion is thus accomplished. Another application involving the combined IOSLM SAW structure is the correlator, which is shown schematically in figure 3. Such a device has been constructed[9] and operates on a 32 bit word at a data-rate of 17.5 Mbit/sec.

COMPUTATION WITH GRATINGS

Consider once again the simple grating structure shown in figure 1. If voltage V_A is applied to one electrode and voltage V_B to the other, the diffracted light intensity is given by

$$I = I_o \sin^2 [a(V_A - V_B)] \tag{6}$$

where a is a constant. For $I \lesssim 0.1\, I_o$ we have

$$I = I_o\, a^2 (V_A - V_B)^2 \tag{7}$$

Now arrange N such electrode sets in a vertical line so that they can each be addressed by the same broad optical beam. If the N components of the vector $\vec{A}$ are applied to one electrode of each set and the corresponding component of the vector $\vec{B}$ is applied to the opposed electrodes then the total deflected intensity is

$$I = \sum_{i=1} I_i = \sum_{i=1} a^2 (V_{Ai} - V_{Bi})^2 \tag{8}$$

We have therefore calculated the magnitude of the difference of the two vectors.

Vector multiplication can also be performed as is suggested in figure 4. In this structure the diffracted intensity from the i^{th} segment is

$$I_i = I_o\, \eta_{Ai}\, \eta_{Bi} \tag{9}$$

Of course, each η is actually proportional to the square of the voltage difference but it can be shown that by a simple signal processing technique, the desired $A_i B_i$ term can be extracted from I_i. The structure shown in figure 4 is therefore capable of performing the scalar product of two vectors.

It should also be noted that if binary signals are applied to the grating structures then standard logic operations may be performed. The structure used for subtraction can be used to generate the EXCLUSIVE OR operation, or the NOT operation, while the structure used for multiplication can be used for the logical AND. These operations may also be carried out in parallel, and in the case of binary signals, the complications arising from the the $\sin^2$ response are no longer present.

SUMMARY

We have shown a variety of applications of electro-optically induced Bragg gratings in integrated optical signal processing and computation devices. The gratings are easy to fabricate and operate efficiently on relatively low voltages. The design principles are well known and reliable. It is therefore quite likely that a large number of additional devices employing similar grating structures will be developed.

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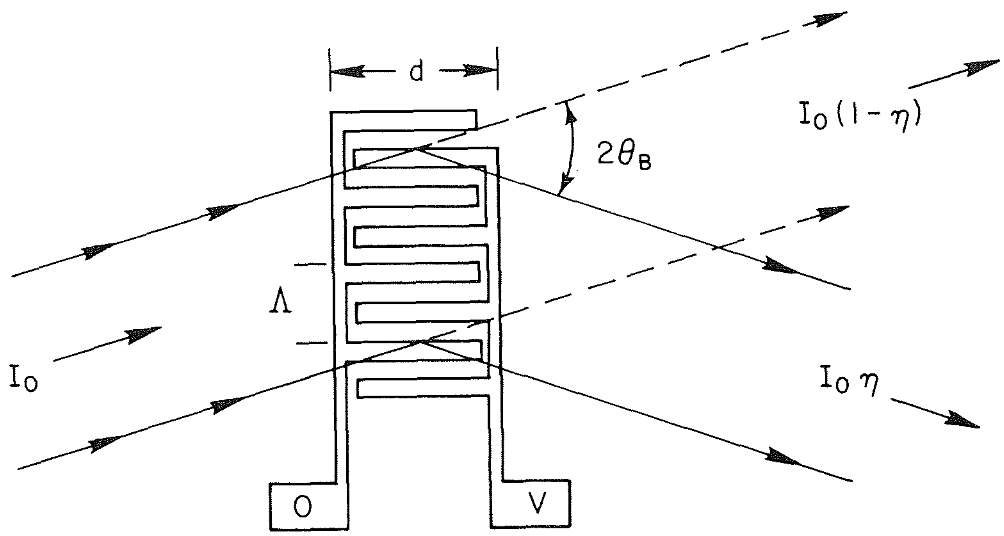

Figure 1.- Basic electrode structure. The grating wavelength Λ and depth d are indicated.

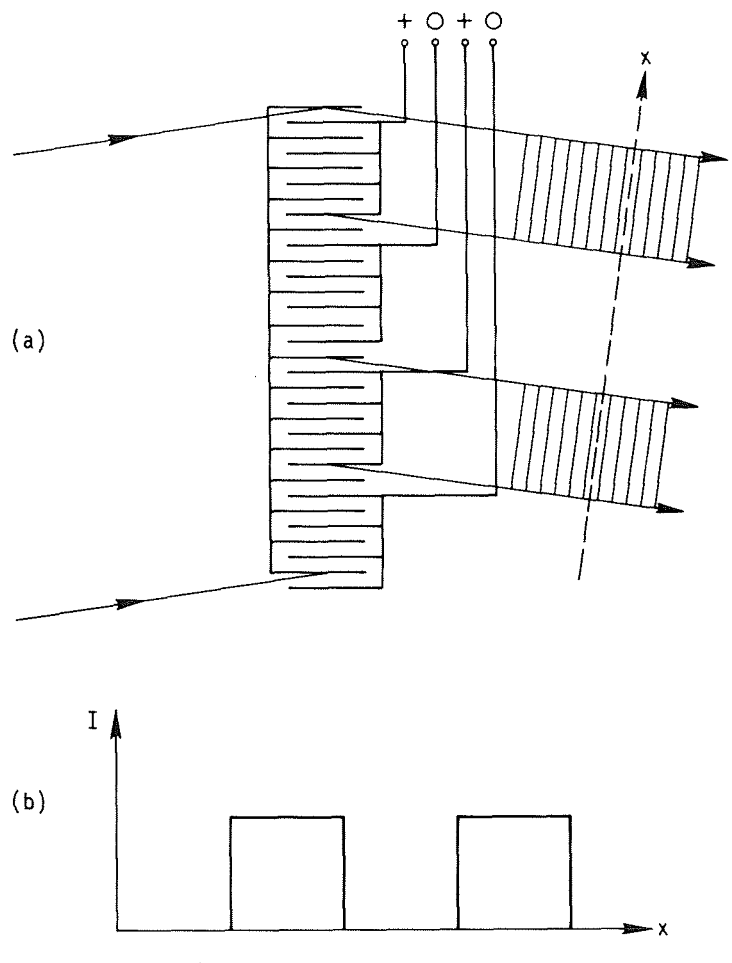

Figure 2.- The electrode structure is addressable in segments to form an integrated optical spatial light modulator. If the common electrode is at zero potential then the voltage pattern indicated in (a) produces the transverse amplitude modulation shown in (b).

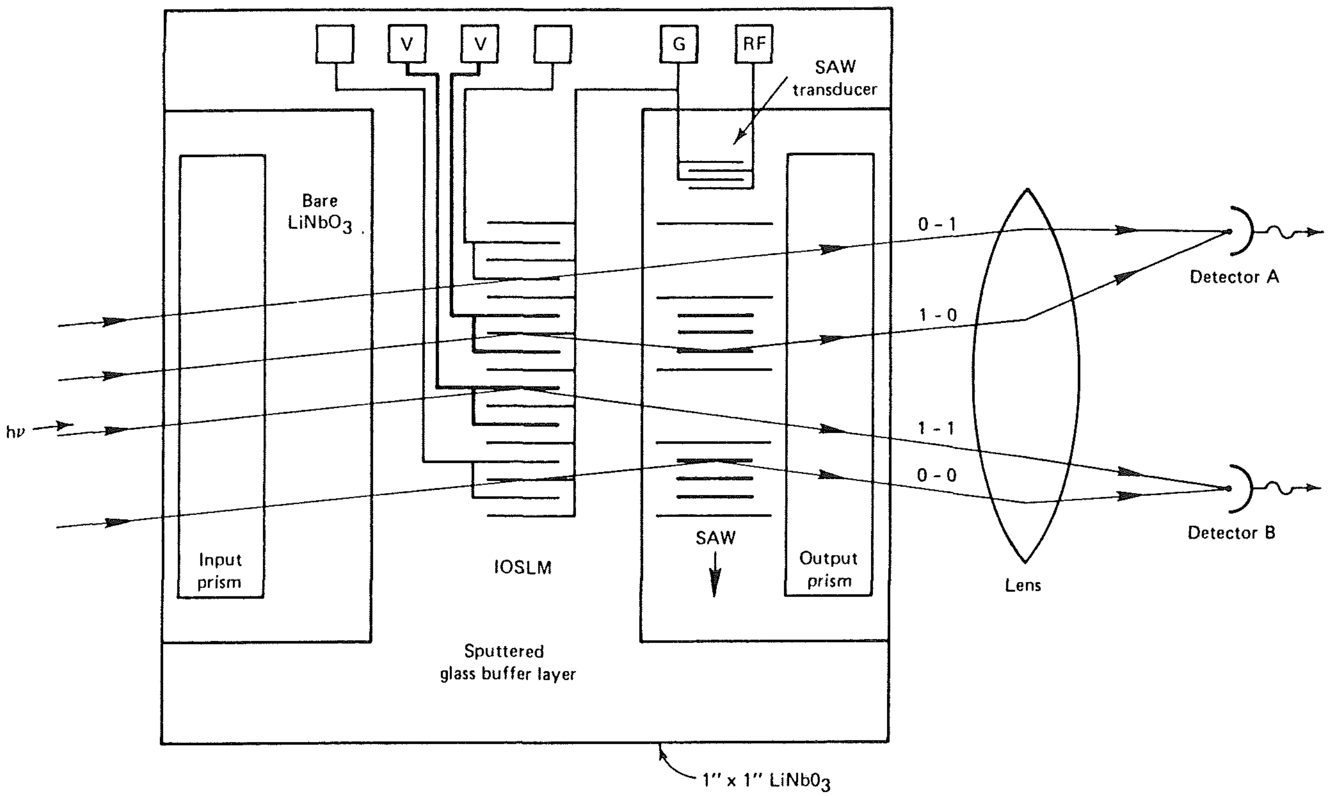

Figure 3.- Correlator incorporating a programmable IOSLM and a SAW transducer with digital modulation.

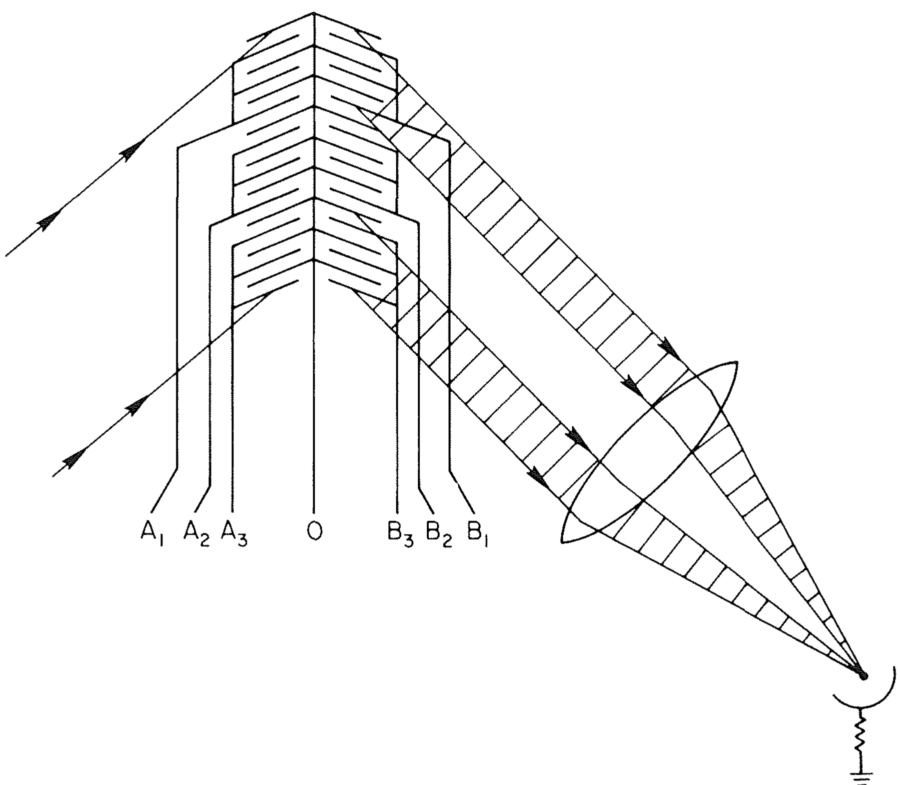

Figure 4.- Electrode structure for vector multiplication.