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A TWYMAN-GREEN ELECTRO-OPTIC LIGHT MODULATOR

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13. ABSTRACT

A Twyman-Green electro-optic light modulator utilizing the transverse electro-optic effect in KD*P is described. Experiments have been performed at 7.1 and 40.6 MHz, and 30 percent modulation can be obtained by applying a voltage of about 40 V.

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Abstract

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1. INTRODUCTION

A number of different electro-optic light modulators have been described in the literature (Kaminov and Turner, 1966). The first such device used an electro-optic crystal operating in the longitudinal mode, which was placed between two crossed polarizers, and the output intensity was modulated by inducing birefringence in the crystal (Billings, 1949). Later, Fabry-Perot type modulators were constructed (Gordon and Rigden, 1963; Ruscio, 1965) where the optical spacing was varied by electro-optically changing the index of refraction of a crystal placed inside the interferometer. Twyman-Green type modulators have also been made where one or both mirrors were mounted on piezoelectric transducers, and the modulation was accomplished by varying the position of the mirrors by applying appropriate voltages to the transducers (Rabinowitz et al, 1962; Mevers and Pollock, 1969). Still another type of modulator described by Rosenblum (1966) utilized a Mach-Zehnder configuration where the phase modulation was achieved by varying the free carrier concentration in a semiconductor placed in one of the light-paths of the interferometer.

This report describes a simple Twyman-Green electro-optic modulator where amplitude-modulated light output is achieved by placing a KD*P phase modulator in one arm of the interferometer. The principle of operation is related to the

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technique of using a Twyman-Green interferometer for demodulating an incident phase-modulated light beam (Rabinowitz et al, 1962; Saito and Kimura, 1964; Saito and Kimura, 1965); the main difference with our method is that phase modulation and amplitude modulation both take place within the same interferometer. The present technique has several advantages above the ones described previously. By operating the crystal with a transverse field instead of a longitudinal field (Billings, 1949), a much lower voltage is usually required to achieve the same degree of modulation since the needed voltage can be decreased by increasing the crystal length and/or decreasing the crystal thickness. Further, since no mechanical movements are involved, the presented method has a significantly higher frequency range than the technique utilizing piezoelectric transducers (Rabinowitz et al, 1962; Mevers and Pollock, 1969). Finally, the typical electro-optic crystals are virtually lossless with respect to the optical beam, while the semiconductor phase modulators (Rosenblum, 1966) are inherently lossy due to free carrier absorption.

In the particular experiments to be described here, modulation frequencies of 7.1 and 40.6 MHz were used. Substantially higher frequencies should easily be possible (Kaminov, 1961; Saito and Kimura, 1963); however, the basic limitation is that the modulation frequency be smaller than half the inverse crystal transit time. But it should be noted that the required electric field is inversely proportional to the crystal length, and thus the higher modulation frequencies might also require higher applied voltages.

2. THEORY

The principle of operation of the modulator can briefly be explained as follows (see Figure 1). Let us assume that the temporal variation of the index of refraction n of the crystal is given by

$$n(t) = n + \Delta n \cos \omega_m t \, . \tag{1}$$

Here ω_m is the modulation frequency and t the time. If a plane wave of intensity I_i is incident on the interferometer, the output intensity I_o is given by

$$I_o = I_i (rt)^2 \, [\, 1/2 \, (r_1^2 + r_2^2) + r_1 r_2 \cos (\phi - 2k \, L \, \Delta n \cos \omega_m t)] \, . \tag{2}$$

Here r and t are the reflectivity and transmittivity of the beam splitter, respectively, and r_1 and r_2 the reflectivity of the two mirrors. Further, $\phi = 2k[L_1 - L_2 + L(1-n)]$ where L_1 and L_2 are the lengths of the two interferometer arms, L the

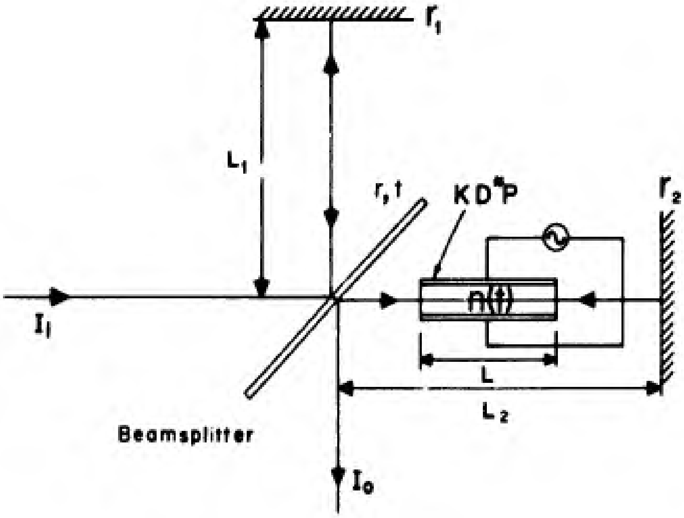

Figure 1. Schematic of the Twyman-Green Modulator

length of the crystal, and k the wave vector. Let us define

$$\alpha = 2k\, L\, \Delta n\ . \tag{3}$$

Then we can write:

$$I_o = (rt)^2\, I_i \left\{ 1/2\, (r_1^2 + r_2^2) + r_1\, r_2 \cos\phi \left[J_o(\alpha) + 2 \sum_{\ell=1}^{\infty} (-1)^{\ell} J_{2\ell}(\alpha) \cos 2\ell\, \omega_m t \right] + r_1\, r_2 \sin\phi \times 2 \sum_{\ell=0}^{\infty} (-1)^{\ell} J_{2\ell+1}(\alpha) \cos (2\ell+1)\, \omega_m t \right\} . \tag{4}$$

Of special interest are the cases when ϕ is some multiple of $\Pi/2$ and $\alpha \ll 1$. We have then:

$$I_o = (r\,t)^2\, I_i \left[1/2\, (r_1^2 + r_1^2) + (-1)^p\, r_1\, r_2\, \alpha \cos \omega_m t \right] \tag{5}$$

for $\phi = (2\,p + 1)\,\Pi/2$ where p is an integer, and

$$I_0 = (rt)^2 I_i \left[1/2\,(r_1^2 + r_2^2) + (-1)^p r_1 r_2 \left(1 - \frac{\alpha^2}{4} + \frac{\alpha^2}{4} \cos 2\omega_m t \right) \right] \tag{6}$$

for $\phi = p\Pi$.

From Eqs. (5) and (6) it can be seen that by properly adjusting ϕ, either the fundamental modulation frequency or the second harmonic can be generated.

3. EXPERIMENT

The experimental configuration was basically as shown in Figure 1. The incident beam was provided by a Spectra-Physics Model 119 He-Ne laser This laser can be locked to the center of the atomic line and is highly stable provided there is no feedback into the laser. The feedback can be prevented by either using a filter in front of the laser to reduce the intensity if enough signal is available, or by using an optical isolator (Mevers and Pollock, 1969). The modulated output from the interferometer was detected by a photomultiplier and displayed on an oscilloscope. Due to noise problems in the photomultiplier, it was found advantageous to use a 1-MHz bandwidth power amplifier between the photomultiplier and the oscilloscope.

One of the end mirrors in the Twyman-Green interferometer was attached to a piezoelectric driver. This allowed the spacing to be adjusted for any desired ϕ. The KD*P crystal phase modulator was cut at Brewster angle and had dimensions 5-cm long, 0.6-cm wide and 0.5-cm thick. The electric field was applied transversly along the C-axis, and the crystal was oriented so that the beam would propagate along one of the induced axis and with the other induced axis parallel to the E-vector of the incident plane polarized wave. The crystal constituted part of the capacitance of a tuned circuit, and the energy was coupled into the circuit inductively. In the beginning of the experiment the RF field was pulsed on and off to prevent heating of the KD*P crystal, but it was later found that the field needed to give a modulation of 20 to 30 percent could be applied continuously without causing any apparent damage to the crystal.

The voltage needed to give approximately 30 percent modulation can be calculated from Eq. (3). For KD*P we have $\Delta n = 1/2\, r_{63} n_0^3 E$, where E is the applied electric field, and r_{63} the electro-optic coefficient. Assuming $r_{63} = 23.6 \times 10^{-12}$ m/V (Yariv, 1967), $n_0 = 1.5$, $\lambda = 632.8$ nm, $L = 5$ cm and a crystal thickness of 0.5 cm, one finds that the required voltage to give $\alpha = 0.3$ is about 38 V. The measured Q of the circuit was 25, and the dissipated power with a voltage of 38 V was thus 0.18 W.

4. RESULTS

Modulation experiments were carried out at 7.1 and 40.6 MHz. An example of the modulated signal for the 40.6 MHz is seen in Figure 2a. This signal was observed when the piezoelectric drive was adjusted to give maximum first harmonic. By changing the piezoelectric drive voltage the first harmonic can be made to virtually disappear, and now the second harmonic becomes strong (see Figure 2b). When the interferometer was covered to limit air currents, the stability of the output signal was quite good. But if necessary, it would be possible to make a servomechanism to keep ϕ fixed as described by Mevers and Pollock (1969).

From Eq. (5), it can be seen that the degree of modulation is limited by the amount of higher harmonics that can be tolerated. A 100 percent modulation could be obtained, by using a circularly polarized beam and replacing the phase modulator used here with a crystal where the induced axes of the index ellipsoid would be rotating at the modulation frequency (Crane, 1969). Such a modulator can be constructed from a crystal having a 3-fold rotation axis and nonvanishing linear electro-optic effect by applying two electric fields transversely and at 90° to each other both in time and space (Buhrer et al, 1960). A good candidate for such a modulator is $LiNbO_3$ (Campbell and Steier, 1971).

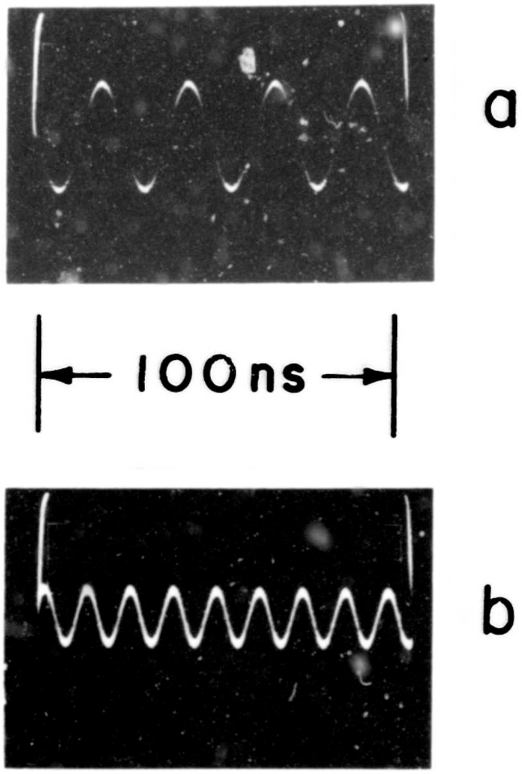

Figure 2. Modulated Output Signal at 40.6 MHz Driving Frequency. (a) Phase angle ϕ adjusted for maximum amplitude of the fundamental; and (b) phase angle ϕ adjusted for maximum amplitude of the second harmonic

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