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Efficient Optical Intensity Modulator Based on the Electrically Tunable $LiNbO_3$ Reflection Grating for Analog Fiber-Optic Links

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We investigate the efficiency of an optical intensity modulator based on an electrically tunable $LiNbO_3$ reflection grating. Assuming a grating coupling coefficient and the waveguide propagation loss, waveguide length is varied to find its effect on the modulator slope efficiency and the device capacitance. With the low propagation loss of the $LiNbO_3$ waveguide, a very efficient optical intensity modulator can be achieved for a low frequency (~1 GHz) as long as the requirement for the grating coupling coefficient is satisfied.

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I. INTRODUCTION

Diffraction gratings can be found in many application areas in optics and fiber optics. A monochromator uses a diffraction grating to separate different wavelength components [1]. A grating also forms an essential element in a single-mode diode laser called the distributed feedback (DFB) laser, where a reflection grating provides the narrow-band optical feedback necessary for laser oscillation [2-3]. Using the reflection window of the grating, one can also make an optical filter that reflects a particular wavelength. Using the grating filter, an optical add-drop multiplexer (OADM) can be realized for optical communication systems that use the wavelength-division multiplexing (WDM) scheme [4]. Another important application of the grating that attracts much interest lately is dispersion compensation [5]. Since different wavelengths undergo different delays in the grating, by tailoring the grating period or by chirping the period, one can achieve dispersion compensation with particular values [6].

In this paper, we investigate a different application of the reflection grating. By forming a reflection grating on an electro-optic (EO) crystal, we can tune the refractive index, thereby changing the effective grating period [7]. This type of device is essentially an electrically tunable optical filter. While others sought to use an electrically tunable optical grating for the tunable OADM [4], we would like to discuss the possibility of using this type of device as an optical intensity modulator for analog fiber-optic links. As the EO polymer was considered previously [8], we consider $LiNbO_3$ in this paper.

We first discuss the theoretical background in Section II. More detailed consideration of the optical intensity modulator based on $LiNbO_3$ is given in Section III, where for the given grating coupling efficiency and the waveguide propagation loss, the modulator efficiency is estimated with varying waveguide lengths. Device capacitance is also considered there. In Section IV, the comparison with existing technologies is made. Conclusions on the optical intensity modulator based on the $LiNbO_3$ reflection grating are drawn in Section V.

II. ELECTRICALLY TUNABLE REFLECTION GRATING

When a_f and a_b represent the amplitudes of the electric fields of the normalized forward- and backward-propagating modes, respectively, wave interactions in a grating can be described by the following coupled-mode equations [9]:

$$\frac{da_f}{dz} = -j\frac{C_0}{2}a_b e^{j\delta_k z} - \frac{\alpha}{2}a_f, \tag{1a}$$

$$\frac{da_b}{dz} = j\frac{C_0}{2}a_f e^{-j\delta_k z} + \frac{\alpha}{2}a_b, \tag{1b}$$

where C_0 is the grating coupling coefficient, and α is the propagation-loss coefficient in intensity of the waveguide. The phase factor, δ_k is given by

$$\delta_k = 2\beta_0 - K = \frac{4\pi n_{eff}}{\lambda} - \frac{2\pi}{\Lambda}, \quad (2)$$

which represents the detuning from the phase-matching condition. Here, n_{eff} is the effective index of the waveguide, λ is the free-space optical wavelength used, and Λ is the period of the grating corrugation. When the phase is matched ($\delta_k = 0$), the effective wavelength in the waveguide and the grating corrugation satisfy the Bragg condition with a grazing incidence:

$$2\Lambda = \lambda / n_{eff}. \quad (3)$$

By solving Eqs. (1a) and (1b), we can obtain the ratios of the reflected (at $z = 0$) and the transmitted (at $z = L$, where L is the grating length) intensities to the incident intensity, which are represented by R (reflection) and T (transmission), respectively [9].

When the grating corrugation is made on the EO waveguide, the detuning δ_k can be changed by the applied electric field on the EO waveguide. In other words, the effective index of the waveguide, n_{eff} can be changed by the EO effect, thereby changing δ_k given by Eq. (2). As the reflection window widens with increasing C_0, an initial phase mismatch is applied to utilize the sharp change of reflectivity with respect to the applied electric field at the edge of the reflection window. Let us define the initial phase mismatch, δ_{k0} by

$$\delta_{k0} = \frac{4\pi n_{eff0}}{\lambda} - \frac{2\pi}{\Lambda}, \quad (4)$$

where n_{eff0} denotes the effective index when there is no electric field applied on the waveguide. Then, we can rewrite Eq. (2) as follows:

$$\delta_k = \delta_{k0} + \frac{4\pi\Delta n_{eff}}{\lambda}. \quad (5)$$

Here, Δn_{eff} represents the effective-index change due to the EO effect, i.e., $\Delta n_{eff} = n_{eff} - n_{eff0}$.

In principle, the grating modulator can be used in either the transmission or the refection modes. We will only consider operating the grating modulator in the reflection mode. In the reflection mode, the input fiber also works as the output fiber with the aid of an optical circulator. Removing one optical fiber simplifies the packaging at the expense of an optical circulator. The loss induced by the circulator is typically < 1 dB.

The equivalent half-wave voltage, V_π for the reflection-type modulator is calculated using

$$V_\pi = \frac{\pi}{2|R'_{max}|}, \quad (6)$$

where R'_{max} denotes the derivative of the normalized reflection with respect to the applied bias voltage, evaluated at the maximum slope point. Since the slope is negative with respect to the applied bias, the absolute value of R'_{max} is taken to give the positive V_π. The V_π represents the efficiency of the modulator in the analog fiber-optical link [10]. As V_π is inversely proportional to the slope of the modulator response (normalized reflection), a smaller V_π represents a higher efficiency for an optical modulator. The normalized reflection is obtained by dividing the reflection R by the maximum reflection value. The value V_π is used throughout this paper to estimate the performance of the grating optical modulator.

The wavelength of interest is 1.3 μm, as 1.3 μm is still popular in analog optical links. We assume that the grating length is the same as the waveguide length, i.e., the grating corrugation is made over the whole waveguide. In the case where the two lengths are not the same, we can easily adjust the calculation results by including an additional propagation loss induced by the waveguide section without the grating.

III. GRATING MODULATOR BASED ON THE $LiNbO_3$ WAVEGUIDE

1. Waveguide and electrode geometry

Figure 1 shows the schematic cross-sectional geometry of the x-cut $LiNbO_3$ waveguide we consider. A straight channel waveguide is assumed along the +y direction. r_{33} of the $LiNbO_3$ (30.8 pm/V) is used for calculating δ_k given as Eq. (5). The grating is assumed to be on the photoresist (refractive index = 1.5). In the actual fabrication, the grating can be fabricated on the SiO_x film deposited on the $LiNbO_3$.

Figure 2 shows how the applied electric field changes Δn_{eff}. For the configuration shown in Fig. 1, two

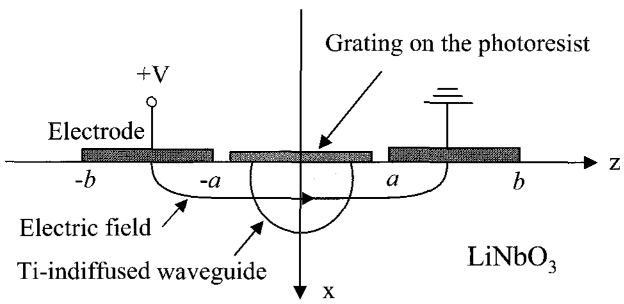

FIG. 1. Cross-sectional view of the $LiNbO_3$ waveguide assumed in the calculation.

different overlap integral values (Γ) of 0.5 and 1.0 have been considered. However, Γ of 0.5 is used as a reasonable example value throughout the calculation. An electrode gap spacing of 6 μm is used to calculate the electric field for a given voltage applied to the electrodes.

2. Normalized reflection as a function of the applied bias

In this section, C_0 of 5 mm^{-1} is assumed as an example value that we can achieve with a grating on the $LiNbO_3$. Two waveguide propagation losses are assumed in this section, 0.1 and 0.3 dB/cm. A propagation loss of 0.1 dB/cm represents the state-of-the-art $LiNbO_3$ waveguide. Calculated results are shown in Figs. 3 (a) and (b) for 0.1 and 0.3 dB/cm, respectively. As reported previously [8], the larger the waveguide loss, the smaller the change in the reflected intensity with the applied voltage. The loss also prevents the dips from going to zero. When the waveguide length is reduced, the number of dips is reduced, due to smaller $\Delta n_{eff}L$ and C_0L products. On the other hand, the absolute value of the slope increases with the waveguide length, leading to a higher V_π.

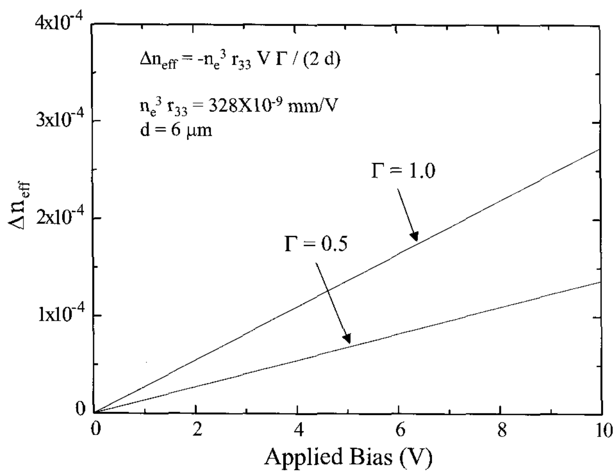

FIG. 2. Effective refractive index change, Δn_{eff} as a function of the electrical bias for two different overlap integral values, Γ.

3. Bandwidth estimation from the *RC*-time analysis

The capacitance per unit length of the electrode geometry shown in Fig. 1 had been calculated previously for the $LiNbO_3$ waveguide using the conformal mapping technique [11]. The result was expressed with parameters, a and b, which are the distances of the inner and the outer electrodes from the center line, respectively. For example, for an electrode gap spacing of 6 μm and an electrode width of 5 μm (a = 3 μm, b = 8 μm: a/b = 0.375), the capacitance per unit length is determined to be 0.23 pF/mm from [11]. For a 5-mm long waveguide, this corresponds to a 3-dB bandwidth of 2.8 GHz, based on the consideration of a simple *RC* circuit. For a 10-mm long waveguide, the 3-dB *RC*-bandwidth is 1.4 GHz.

4. V_π as a function of the waveguide length

For the electrode gap spacing of 6 μm, for which the normalized reflections were shown in Figs. 3 (a) and

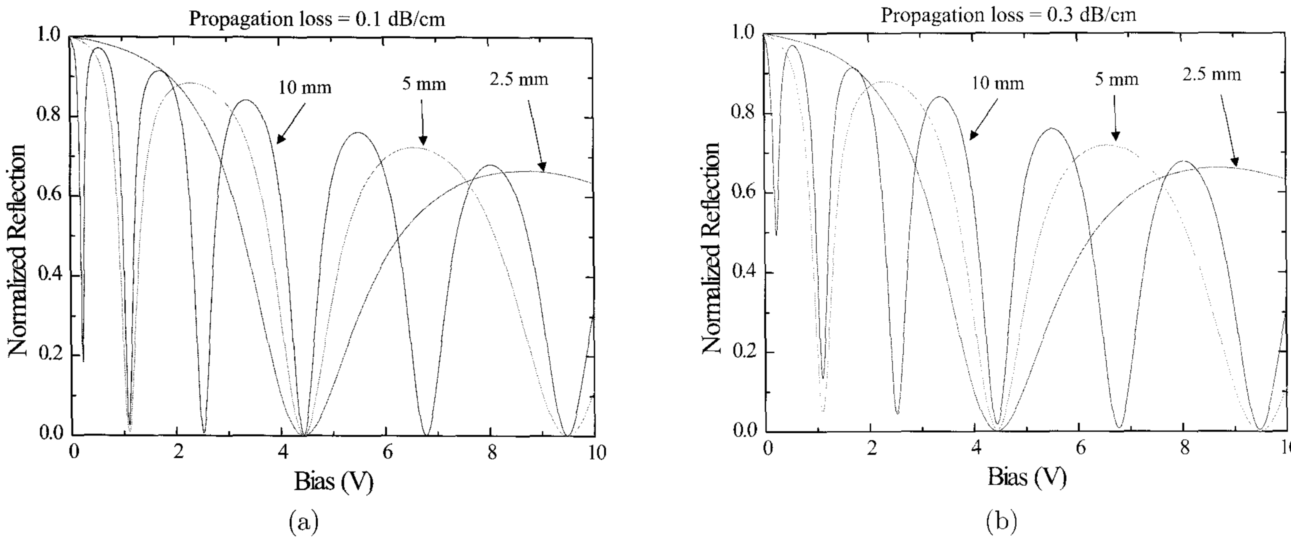

FIG. 3. Normalized reflections of the optical modulator based on the electrically tunable $LiNbO_3$ waveguide for C_0 = 5 mm^{-1} with two different waveguide losses, (a) 0.1 and (b) 0.3 dB/cm, and three different waveguide lengths, 2.5, 5, and 10 mm. The electrode gap spacing is assumed to be 6 μm.

(b), the V_π's are estimated as a function of the waveguide length (therefore the 3-dB bandwidth) in Fig. 4. For a propagation loss of 0.1 dB/cm, V_π can be close to 0.1 V for 10- or 20-mm long waveguides. However, the maximum waveguide length that can be used for a given application may be limited by the *RC*-time bandwidth requirement. Fig. 4 demonstrates that a highly efficient intensity modulator with a very small V_π (V_π < 1 V) can be realized with ~5 mm long waveguide when C_0 is larger than 5 mm^{-1} irrespective of the waveguide loss (whether it is 0.3 or 0.1 dB/cm). It is also seen that the minimum V_π values that can be achieved are determined by the waveguide propagation loss. When the propagation loss is 0.3 dB/cm, the minimum V_π value increases from ~0.1 to 0.3 V.

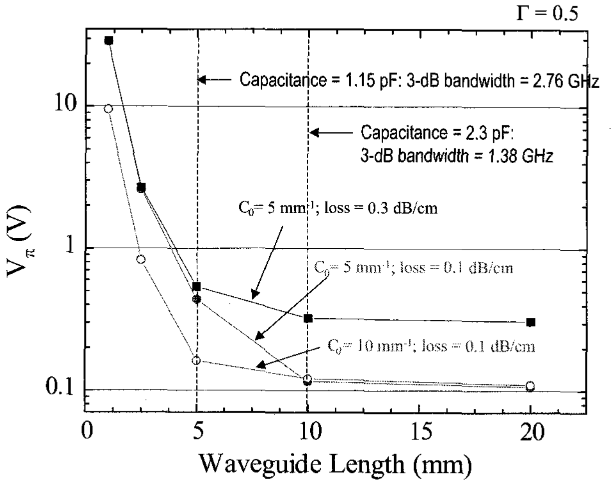

FIG. 4. V_π as a function of the waveguide length for the results given in Figs. 3 (a) and (b). The electrode gap spacing is 6 μm. Also shown is the data for the case when C_0 = 10 mm^{-1} and propagation loss = 0.1 dB/cm.

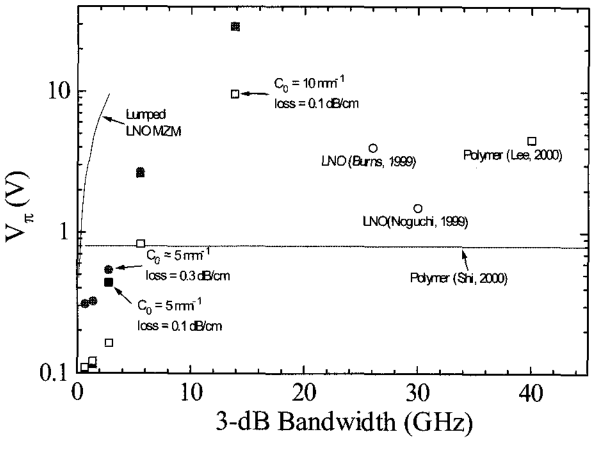

FIG. 5. V_π as a function of the 3-dB bandwidth for various cases [12-15].

IV. PERFORMANCE COMPARISON WITH EXISTING TECHNOLOGIES

As we have seen in Section III. 4, for a propagation loss of 0.1 dB/cm, V_π can be close to 0.1 V for 10- or 20-mm long waveguides. Fig. 5 shows V_π as a function of the bandwidth for the state-of-the art $LiNbO_3$ waveguides in Fig. 4 and compares with the existing technologies based on the $LiNbO_3$ or polymer Mach-Zehnder-type EO modulators [12-15]. The effect of increasing C_0 for the grating modulator is also considered by using C_0 = 10 mm^{-1}.

Since the Mach-Zehnder EO modulators based on the polymer tend to have large device insertion loss, a modified V_π, which is defined as V_π/t_m, is considered in Fig. 6 (a). Here, t_m represents the modulator transmission factor and the device insertion loss defined by -logt_m. In Fig. 6 (b), corresponding t_m is shown. In analog fiber-optic links, V_π/t_m, not just V_π, determines

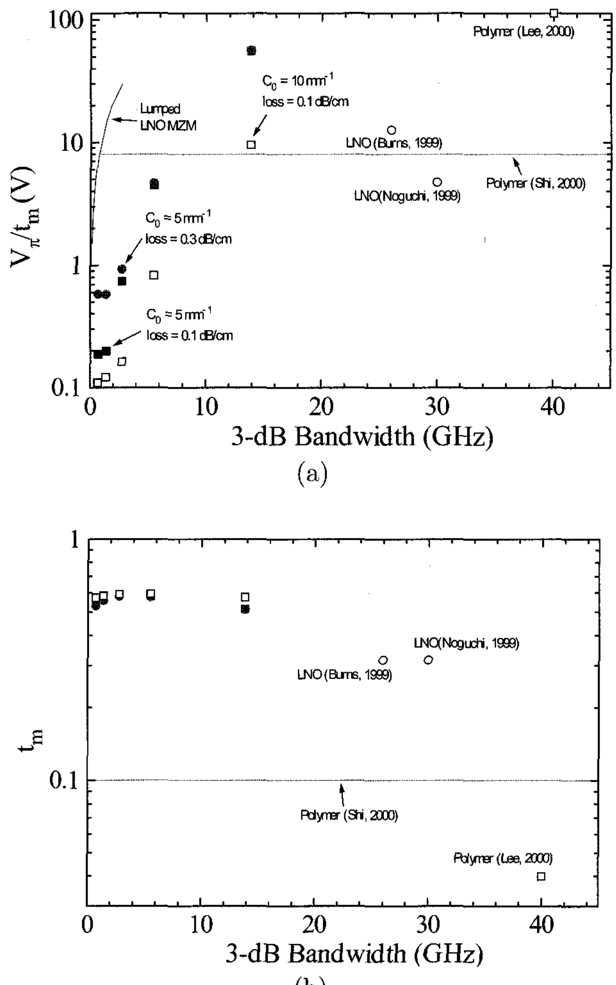

FIG. 6. (a) Modified V_π (V_π/t_m) as a function of the 3-dB bandwidth for various cases. (b) The corresponding t_m is plotted using the same legend in (a).

the link efficiency represented by the RF gain.

Considering both Figs 5 and 6, it can be seen that there is an advantage of using the optical modulator based on the tunable $LiNbO_3$ grating for the low-frequency (< 10 GHz) applications.

V. CONCLUSIONS

We have investigated the efficiency of the electrically tunable reflection grating based on the $LiNbO_3$ as an optical intensity modulator for analog fiber-optic links. By analyzing the EO $LiNbO_3$ waveguide, we have examined the effect of the grating coupling coefficient, the propagation loss, and the waveguide length on the performance of the intensity modulator based on the electrically tunable reflection grating.

In general, a larger C_0 and a smaller propagation loss are favorable for the steeper slope in the reflection vs. applied bias curve. For a given length and C_0, the smaller propagation loss makes the slope higher. For a given propagation loss and C_0, the longer waveguide length yields the higher slope.

There is a limit in further increasing the slope by increasing the waveguide length and/or C_0. This is due to the fact that the adverse effect of the propagation loss on the slope increases with the waveguide length and C_0. Therefore, the propagation loss plays a key role in determining the maximum slope of the optical modulator based on the tunable grating.

The state-of-the-art $LiNbO_3$ with the propagation loss of 0.1 dB/cm can reduce V_π much less than 1 V. Due to the relatively large capacitance of the electrode design, however, this will be useful only for applications with bandwidth requirement less than 10 GHz.

To experimentally demonstrate the optical intensity modulator based on the electrically tunable reflection grating with $LiNbO_3$, one should focus on the fabrication of the reflection grating with a high C_0. This type of device can be very useful in the application where a very efficient optical intensity modulator is required with a relatively low data rate.

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