Design of a broadband electro-optic modulator with very low V_π

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I. Abstract

The goal of DARPA's RF Lightwave Integrated Circuits (RFLICs) program is to demonstrate a modulator with $V_\pi \leq 0.3$ V and $f_{3dBe} \geq 50$ GHz. We approach this challenge by first recognizing that, for an external modulator in which traveling-wave electrodes of length L impose the modulation voltage, the product of V_π and L is fixed for a given electro-optic material. We report on investigations to achieve a low V_π by both minimizing increasing the magnitude of the electro-optic coefficient and maximizing L. First we examine the magnitude of the electro-optic coefficient for a wide variety of electro-optic materials. We conclude by examining the extent to which the maximum L (and, consequently, the minimum V_π in a given material) is limited by three different frequency-dependent effects: 1) dielectric loss in the substrate; 2) RF attenuation in the electrodes, and; 3) microwave-optical velocity mismatch.

II. Introduction: The $V_\pi \cdot L$ Product

External modulators of the Mach-Zehnder interferometric variety have been demonstrated with $f_{3dBe} \geq 50$ GHz (see, for example, [1] and [2]); however such broadband modulators have consistently exhibited V_π's of ~ 6 V or greater. It has been shown previously [3] that a fiber-optic link with a broadband RF gain of ~ 0 dB requires a modulator with $V_\pi \leq 0.3$ V (assuming external modulation of a CW laser with an output power of ~ 10 mW). The goal of DARPA's RF Lightwave Integrated Circuits (RFLICs) program is to enable broadband RF fiber-optic links with RF gain of ~ 0 dB by demonstrating a modulator for which $f_{3dBe} \geq 50$ GHz and $V_\pi \leq 0.3$ V. Such a demonstration requires a breakthrough to reduce V_π by at least a factor of 20 relative to what has been achieved in modulators made in inorganic materials such as $LiNbO_3$.

For an external modulator in which traveling-wave electrodes of length L impose the modulating electric field, the product of V_π and L is fixed for a given electro-optic material, as expressed by the following equation:

$$V_\pi \cdot L = \frac{\lambda\, g}{p\, n^3\, r\, \Gamma}.$$

In Equation (1), λ is the optical wavelength, g is the inter-electrode gap width), n is the optical refractive index of the electro-optic material, r is the magnitude of the appropriate electro-optic tensor, Γ is the electrical-optical field overlap factor (a

dimensionless number between 0 and 1), and the magnitude of the dimensionless factor p is a function of the electrode geometry and the cut of the anisotropic electro-optic crystal.

Figure 1 shows the results of a survey of inorganic materials (including $LiNbO_3$) that was conducted to identify the best material in which to pursue development of a modulator that will meet the RFLICs program goal. The strength of the electro-optic effect in various materials is indicated by horizontal position on the plot, and the corresponding $V_\pi \cdot L$ product for that material at λ = 1550 nm is plotted along the vertical axis. The extent to which the data points fall along a straight line is an artifact of the fact that the same values of g and Γ were used to calculate $V_\pi \cdot L$, and that n varied only slightly from one material to the next. For some of the materials, data points are shown for more than one element r_{mn} of the electro-optic tensor matrix.

For the inorganic materials $KNbO_3$ and $BaTiO_3$, r_{51} = 380 pm/V and 820 pm/V, respectively. These magnitudes are respectively 13x and 27x larger than the r_{33} of $LiNbO_3$. Unfortunately, because r_{51} is an off-diagonal element of the tensor matrix, an applied voltage doesn't produce a simple optical phase change that can be converted to intensity modulation in an interferometer; rather, it induces coupling between the waveguide's orthogonal TE and TM modes. Thus the only type of modulator one can fabricate in either $KNbO_3$ or $BaTiO_3$ that exploits the magnitude of the r_{51} tensor element is a *mode-conversion* modulator (sometimes called a *polarization* modulator), which has to be followed by a passive polarization filter in order to convert the polarization modulation into an intensity modulation that can be directly detected.

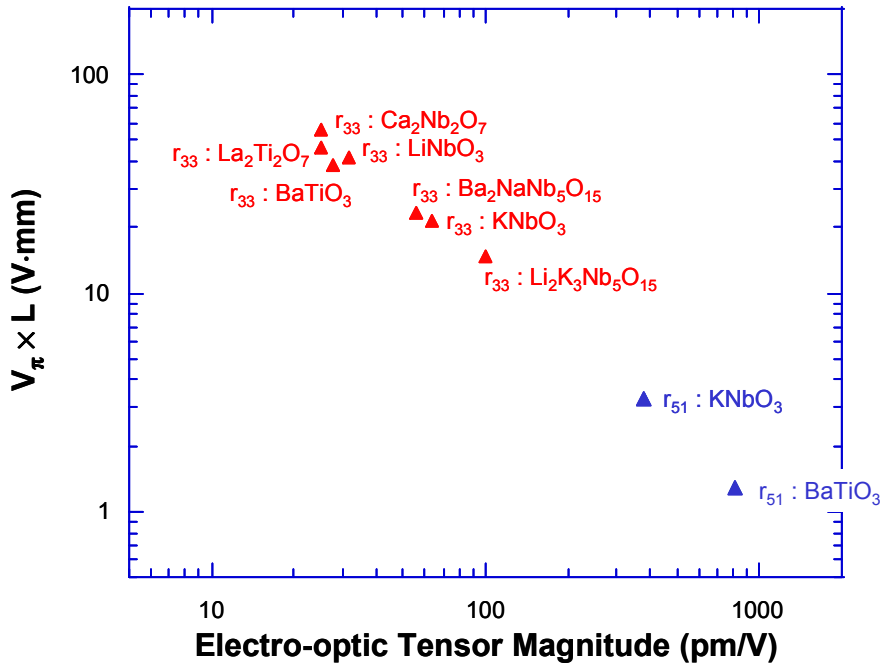

Figure 1 Electro-optic tensor element magnitudes and corresponding $V_\pi \cdot L$ products for various inorganic materials (assuming g = 15 μm and Γ = 0.7).

III. CHARACTERIZATION OF HIGH-EO-COEFFICIENT MATERIALS

$KNbO_3$—The anisotropy of inorganic materials causes their dielectric constants to have different magnitudes along each of their crystalline axes. 10 x 10 x 1-mm samples of two different cuts of $KNbO_3$ were purchased and sent to a thin-film vendor for patterning of the transmission line structures necessary for measuring the material's dielectric properties. Because of $KNbO_3$'s relatively low Curie temperature, we collaborated with the vendor to develop a process requiring temperatures no greater than 60°C. When the metallization and electrode patterning shown in Figure 2 was complete, the samples were sent to the National Institute of Standards and Technology (NIST) for characterization across a broad range of microwave frequencies. Table 1 shows the results of the measurements performed at NIST for two different crystal orientations.

$BiTaO_3$—Initial measurements at 3 GHz of some of $BaTiO_3$'s properties were performed in conjunction with Professor Mark Reeves at George Washington University. The results appeared consistent with the only published data we could find (in a Russian journal from the 1960's [4]). However, we suspended our effort to develop a broadband, low-V_π modulator in $BaTiO_3$ for RFLICs because of the processing difficulties imposed by its very low Curie temperature and high permittivity at microwave frequencies (see Table 1).

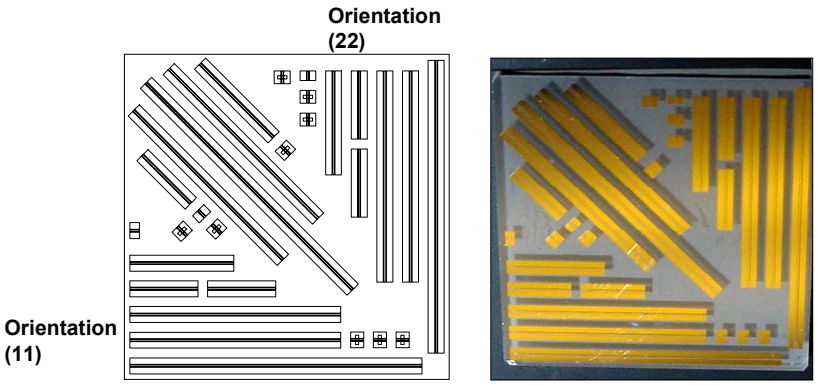

Figure 2 Designed (left) and completed (right) electrode patterning for measurement of $KNbO_3$ dielectric properties in two crystal orientations. Processing on two different cuts of material enables measurement of dielectric properties along all three crystal axes.

Material	r coefficient (pm/V)		$n_{optical}$	Relative Permittivity	Dielectric loss $(GHz\text{-}cm)^{-1}$	T_c (°C)
	r_{33}	r_{51}				
$LiNbO_3$	32.6	—	2.3, 2.2	$\varepsilon_{33} = 29$ $\varepsilon_{11} = 85$	$\alpha_1 = 0.0013$	> 1000
$KNbO_3$	64	380	2.28, 2.33, 2.17	$\varepsilon_{33} = 55$ $\varepsilon_{22} = 1000$ $\varepsilon_{11} = 160$	$\alpha_{1\,(22)} = 0.008$ $\alpha_{1\,(11)} = 0.0010$	225
$BaTiO_3$	26	820	2.44, 2.37	$\varepsilon_{33} = 135$ $\varepsilon_{11} = 3700$	Not measured	120

Table 1 Measured optical and properties of inorganic electro-optic materials.

IV. LIMITS TO MAXIMUM L FOR A GIVEN BANDWIDTH

In a modulator with traveling-wave electrodes, V_π increases with increasing RF frequency because of three effects: 1) the dielectric loss in the electro-optic material itself; 2) attenuation in electrodes; 3) mismatch between the velocities of the light in the waveguides and the modulating RF signal along the electrodes. The first two effects are quantified in the following expression for how the modulating electric field intensity, E, decays as it propagates along the electrodes:

$$E = E_0\, e^{-(\alpha + j\beta)z},$$

where β is the propagation constant, E_0 is the electric field intensity at the input end of the electrodes ($z = 0$), and $\alpha = \alpha_0\sqrt{f} + \alpha_1 f$. This accounts for loss in the electrodes (proportional to α_0) and the dielectric (proportional to α_1). In the (22) orientation of $KNbO_3$, for example, Table 1 shows that α_1 = 0.0010 $GHz^{-1}\cdot cm^{-1}$, so that at f = 50 GHz, $\alpha_1 f$ = 0.05 cm^{-1}. In other words, a 50 GHz signal could propagate more than 13 cm down electrodes on $KNbO_3$ before dielectric loss would cause its electric field to decay to half its initial intensity. Loss in the electrodes themselves could attenuate the signal to a much greater extent if α_0 is very large. It has been shown, however [5], that metal electrodes with thicknesses of 30 μm or more can minimize α_0 to permit 50 GHz modulation on traveling-wave electrodes up to 20 cm in length.

In materials with large permittivity like $KNbO_3$, electrical-optical velocity mismatch can impose a severe limit on the electrode length for modulation at high RF frequencies. In a polarization modulator that exploits $KNbO_3$'s large r_{51} magnitude, TE-TM intermodal dispersion can also limit the length of electrodes if they are not properly designed. However this problem is only about as severe as it is in $LiNbO_3$ polarization modulators, in which researchers have demonstrated interdigitated electrode structures that compensate for the dispersion effect [6, 7].

V. REFERENCES

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