AIP | Applied Physics Letters

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Citation: Applied Physics Letters **78**, 1035 (2001); doi: 10.1063/1.1350426
View online: http://dx.doi.org/10.1063/1.1350426
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/78/8?ver=pdfcov
Published by the AIP Publishing

Wide-bandwidth high-frequency electro-optic modulator based on periodically poled $LiNbO_3$

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(Received 18 October 2000; accepted for publication 21 December 2000)

We propose a high-frequency traveling-wave integrated electro-optic modulator based on a periodically poled $LiNbO_3$. The traveling velocity of the optical wave and the electrical wave velocity in the waveguide can be quasimatched due to the periodic structure. Using this design, a modulation frequency of several hundred GHz can be realized. Wide-bandwidth modulation is also achievable by employing an aperiodic domain grating. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1350426]

As an outstanding nonlinear optical material, periodically poled $LiNbO_3$ (PPLN) is attracting more and more attention.[1–5] In PPLN, the spontaneous polarization is periodically reversed, resulting in nonlinear optical properties. For example, the quasi-phase-matching (QPM) technique can be used instead of birefringence phase matching for nonlinear frequency conversions.[1–5] The physical mechanism of QPM is that the nonlinear optical coefficient periodically changes its sign due to the periodic domains. As a result, the excited parametric wave will have a π phase shift when passing through the domain boundary. If each domain thickness is equal to the coherence length, the excited parametric wave from each domain will interfere constructively. In addition to frequency conversion, $LiNbO_3$ (LN) is also widely used in pizeoelectric and electro-optic (EO) processes. The piezoelectric and EO coefficients also change their signs periodically in a PPLN and yield interesting effects.[6–9]

A popular application of the EO effects of LN is the integrated EO modulator (EOM) that has important applications in signal processing and optical communications.[10–12] Driven by the demands of high-speed devices, the modulation frequency of EOM has been increasing. However, high-speed modulation is limited due to the velocity mismatch between the electrical wave and the optical wave.[10,11] To increase the modulation speed, several effective methods have been proposed.[12–14] Since PPLN has enhanced EO properties,[8] and PPLN wafers are now commercially available, the application of PPLN for high frequency EOM is a very attractive option.

Before studying EOM in PPLN, let us look back to the ordinary traveling wave modulator. Since the Mach–Zehnder modulator is based on phase modulation. We can study the phase modulating properties first. For simplicity, we assume the electrode to be impedance matched to the drive cable and termination. The microwave loss is also ignored.

We consider a single frequency (ω_m) drive electrical signal, which propagates in the waveguide along the x direction with the velocity $v_m = c/n_m$. c is the light velocity in vacuum and n_m is the refractive index of the waveguide at the drive frequency. The voltage of the drive signal in the waveguide then could be written as:

$$u(x,t) = u_0 \sin(k_m x - \omega_m t) \quad (0 \leqslant x \leqslant L), \tag{1}$$

where k_m is the wave vector of the electrical wave; L is the total interaction length. The optical wave that enters the interaction zone ($x=0$) at $t=t_0$, meets the drive voltage $u(x,t_0)$. When $t=t_0+\Delta t$, the optical wave has traveled a distance x with the velocity of $v_o = c/n_o$, which takes the time $\Delta t = x/v_o$, where n_o is the refractive index for the optical wave. Thus, the applied voltage that the optical wave actually sees is

$$u(x,t) = u_0 \sin[k_m \alpha x - \omega_m t_0], \tag{2}$$

where $\alpha = 1 - v_m/v_o$. For an ordinary medium, due to the velocity difference between the optical wave and the electrical wave, the voltage changes along the waveguide. We can easily build this physical image with the help of the Fig. 1.

From Fig. 1, the wavefront of the optical wave meets a different drive voltage at a different point. The changing period Λ of the actual voltage is the distance for the optical wave to catch up with the electrical wave with 2π phase difference, where Λ is given by:

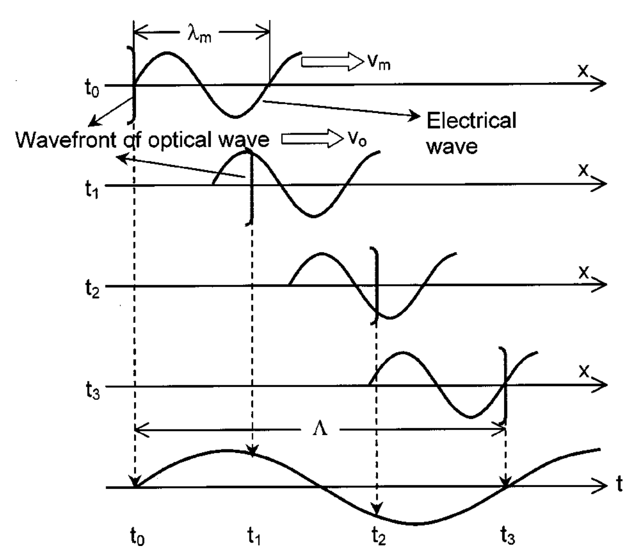

FIG. 1. Velocity mismatch between input optical wave and drive electrical signal.

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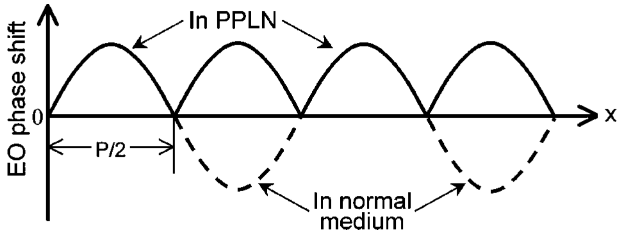

FIG. 2. Electro-optic phase shift in a PPLN and in a normal medium with homogeneous EO coefficient.

$$\Lambda=\frac{2\pi}{|k_m\alpha|}=\frac{\lambda_m}{|n_m-n_o|}. \tag{3}$$

If the interaction length is equal to Λ, the optical wave travels over a whole period of the sinusoidal drive signal, thus the average change of the refractive index is zero. In this case, no modulation can be realized. Likewise, if the interaction length is $\Lambda/2$, the phase modulation reaches its maximum. In general, if the interaction zone has the length of L, the total EO-induced phase shift $\Delta\Phi$ for optical wave incident at $t=t_0$ can be written as

$$\Delta\Phi(t_0)=\int_0^L-\pi n_o^3\gamma\frac{\Gamma u_0}{G\lambda}\sin[k_m\alpha x-\omega_m t_0]dx, \tag{4}$$

where γ is the EO coefficient, λ is the light wavelength, G is the distance between electrodes, and Γ is the field-mode overlapping factor (<1.0). Defining $\Delta\beta_0=-\pi n_o^3\gamma\Gamma u_0/G\lambda$, Eq. (4) can be simplified to be:

$$\Delta\Phi(t_0)=\Delta\beta_0 L\,\sin c\left(\frac{k_m\alpha L}{2}\right)\sin\left(\frac{k_m\alpha L}{2}-\omega_m t_0\right). \tag{5}$$

Equation (5) indicates that, with respect to time, $\Delta\Phi$ replicates the electrical signal $\sin(\omega_m t_0)$ except that both its amplitude and phase depends on the material parameters.

From Eq. (5), the phase shift increases linearly with L if $v_m=v_o$. Increasing L, therefore, decreases the drive voltage. However, for ordinary materials, v_m is different from v_o. In this case, $\Delta\Phi$ changes from positive to negative periodically with the period of Λ. The maximum effective length is only $\Lambda/2$. From Eq. (3), higher the frequency is, smaller the effective interaction length is available. For coplanar strip electrodes on a single domain LN, the 3 dB modulation bandwidth is only 9.6 GHz·cm. Therefore, the velocity mismatch limits the highest frequency response. Overcoming this limitation is the primary consideration for designing a high frequency EOM. To date, there have been several efforts at solving this problem,[12–14] such as selecting more suitable substrate or employing phase-reversed electrodes. In this work, we will demonstrate that an EOM based on PPLN can also work at a very high frequency.

LN is a uniaxial ferroelectric crystal. In a negative domain, the crystal structure rotates 180° about the a axis to make the b axis and c axis change to their opposite directions. Under this rotation, the EO coefficients should change its sign like the nonlinear coefficient.[8] The signs of the induced-EO phase shift should then be different in different domains.

We consider a PPLN based EO phase modulator, which has the period of p and the period number of N. Each domain thickness l is thus $p/2$ if the duty cycle is 50%. From Fig. 2, the phase shift in each domain can add in phase and consequently the total interaction length is $L=Np$ if $p=\Lambda$. The interaction length thus can be arbitrarily long (in absence of loss). As a result, the required drive voltage for the complete modulation depth can be reduced. Although the velocity of the optical wave and the electrical wave are still different, the periodic EO coefficient changes phase shift periodically and results in a continuous increase of the total phase shift. Similar to the QPM in nonlinear optics, this approach can be termed quasi-velocity-matching (QVM). The condition $p=\Lambda$, i.e., $k_m\alpha l=\pi$, can be named QVM condition. For EO modulating, the 1.55 μm light in a Z-cut PPLN waveguide at 100 GHz, the effective index of the guided optical modes is 2.14 while the effective index of the guided electrical wave mode is 4.225.[10,11] The calculated modulation period of PPLN for QVM is 1.44 mm. Even if the desired modulation frequency reaches 500 GHz, the corresponded PPLN period is only 288 μm that is still easy to be fabricated for current electrical filed poling or Czochralski technique.[15]

In the general case, the total phase shift of a PPLN based EOM is obtained as

$$\Delta\Phi=\int_0^{Np}-\pi n_o^3\gamma f(x)\frac{\Gamma u(x,t)}{G\lambda}\,dx. \tag{6}$$

Unlike ordinary EOM, γ is multiplied by a factor $f(x)$ with

$$f(x)=\begin{cases}+1 & \text{if } x \text{ is in the positive domains}\\ -1 & \text{if } x \text{ is in the negative domains,}\end{cases} \tag{7}$$

thus,

$$\Delta\Phi=\Delta\beta_0\int_0^{Np}f(x)\sin(k_m\alpha x-\omega_m t_0)dx$$
$$=\frac{-4\Delta\beta_0}{k_m\alpha}\sin^2\frac{k_m\alpha l}{2}\sum_{i=0}^{N-1}\cos[(2i+1)k_m\alpha l-\omega_m t_0]. \tag{8}$$

If $k_m\alpha l\neq m\pi$, i.e., the QVM condition is not satisfied,

$$\Delta\Phi=-N\Delta\beta_0 p\tan\left(\frac{k_m\alpha l}{2}\right)\sin c(Nk_m\alpha l)$$
$$\times\cos(Nk_m\alpha l-\omega_m t_0), \tag{9}$$

whose amplitude does not increase continuously with increasing period number. Only if the QVM condition is satisfied does

$$\Delta\Phi=\frac{2}{\pi}N\Delta\beta_0 p\cos(\omega_m t_0), \tag{10}$$

and reaches its maximum value. This result coincides with the earlier analysis.

Using Eqs. (8)–(10), the phase shift as a function of the modulation is shown in the solid curve of Fig. 3. The calculation is based on a PPLN with the modulation period of 1.44 mm and a period number of 20, given an interaction length of 28.8 mm. The drive voltage is 4 V and we took $G=10\,\mu$m and $\Gamma=0.7$. From this curve, if there is a 1.55 μm light input into the waveguide, the half-wave voltage of such a PPLN EOM operating at 100 GHz is 4 V. If the working

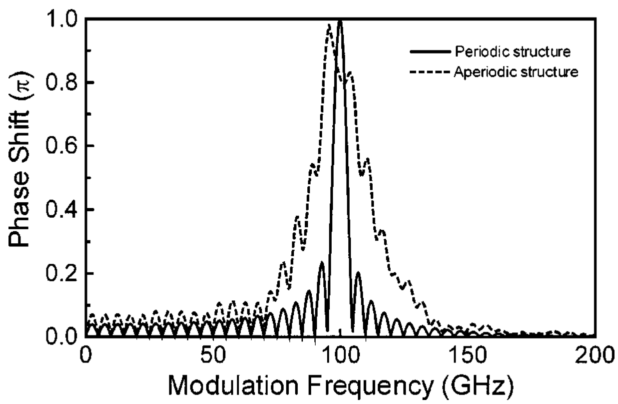

FIG. 3. Frequency response of the PPLN EOM, where the solid curve shows the total EO phase shift as a function of drive frequency in a PPLN waveguide with the period of 1.44 mm. The dashed curve is for an aperiodic sample with cascade periods.

frequency has a bias at 100 GHz, the phase shift decreases. The 3 dB bandwidth of the modulation frequency is 6 GHz. The reason for the narrow bandwidth is that Λ is frequency dependent, only limited frequency range can match the QVM condition for enhancing the phase shift.

However, for many applications, a wide bandwidth is needed. For getting a wider modulation bandwidth, a simple but effective method is using the aperiodic domain grating.[16] Since different periods correspond to different matching frequencies, if the domain thickness changes, the corresponding frequency response range could also be widened.

The total phase shift for an aperiodic sample is also easily obtained as:

$$\Delta\Phi = \frac{-4\Delta\beta_0}{k_m\alpha}\sum_{i=0}^{N-1} \sin^2\frac{k_m\alpha l_i}{2} \times\cos[k_m\alpha(x_i+l_i)-\omega_m t_0], \tag{11}$$

where x_i is the staring position of the i-th ''period'' and l_i is its domain thickness.

The dashed curve in Fig. 3 shows the theoretical result for an aperiodic sample composed of five cascade four-period PPLN's whose periods are 1.26 mm, 1.38 mm, 1.45 mm, 1.49 mm, and 1.62 mm, respectively. The total interaction length is also 28.8 mm. The center modulation frequency is still around 100 GHz but the bandwidth is widened to 24 GHz. The drive voltage for a π phase shift is 7 V. Obviously, we can easily design a sample that has a wider bandwidth but with a higher half-wave voltage, so balancing the wide bandwidth and the low drive voltage should be considered for a practical EOM based on PPLN.

If we compare the PPLN-based EOM with conventional EOM with phase-reversed electrodes, the former has some advantages. The simpler configuration makes the design of the EOM easier. The impedance calculation should also be simplified. Changing the relative positions of the waveguide zone and the electrodes for obtaining a larger Γ is more feasible. The PPLN-based EOM can also be constructed with a-cut or b-cut LN wafer by using the largest EO coefficient γ_{33}. The buffer layer is now unnecessary since the electrodes need not cover the waveguide zone as in the case of the phase-reversed electrodes, and thus the drive voltage can be decreased. The improved stability is also an advantage. This is due to the simpler electrode configuration and the high curie temperature of LN. In addition, PPLN is a versatile material.[6,8] It is possible to combine several functions in a PPLN wafer. This is an exciting feature since integrated optical circuits that simultaneously contain light generation, modulation, and switching together on a chip is a target for modern opto-electronic systems.

In conclusion, we have demonstrated that high-frequency and wide-bandwidth EOM can be constructed based on PPLN. At last, we should point out that our results could also be extended to an EOM based on similar material with a periodic EO coefficient, e.g., PPLT, PPKTP, or even a photonic crystal.

The authors acknowledge the funding support from the National Science Foundation and the Army Research Office.

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