A novel super-broadband travelling-wave modulator with nonperiodic domain inversions and ridge structure

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In order to obtain large broadband, a novel travelling-wave modulator with nonperiodic domain inversions and ridge structure is proposed. The composite structure is designed to achieve velocity matching between the optical wave and the microwave, to get a 50 Ω characteristic impedance and to reduce the loss of the microwave electrodes with finite element method (FEM). The calculation results show that the frequency response of the new device is flat up to 350 GHz with interaction length of 1 cm, characteristic impedance of 49 Ω, and microwave refractive index of 2.5.

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An important factor, which limits the high frequency performance of a travelling-wave modulator is the velocity mismatch between the optical wave and the modulating microwave. To eliminate the velocity mismatch, nonperiodic phase reversal electrodes have been studied[1], as shown in Fig. 1(a). In this method, however, the microwave refractive index, attenuation and impedance match are not considered by the researchers. In this paper, a new device is proposed to solve the problems mentioned above.

To reduce the loss of the microwave electrodes and fabrication complexity, we use a alternative technique whereby quasi-phase-matching is achieved by using reverse-poled wave-guides and uniform thick electrodes in a Z-cut $LiNbO_3$ as shown in Fig. 1(b). Simultaneously, a ridge structure is used to reduce the microwave refractive index and get impedance match[2], as illustrated in Fig. 2.

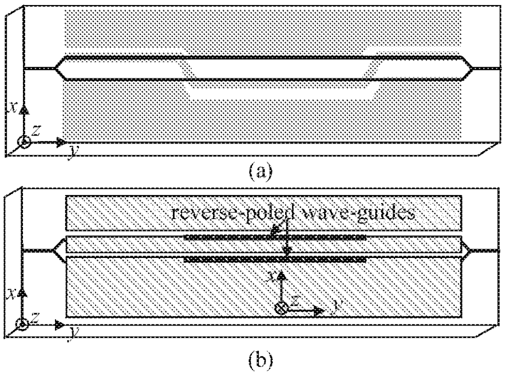

Fig. 1. Mach-Zehnder modulators with (a) electrode reversal and (b) domain inversion in Z-cut $LiNbO_3$.

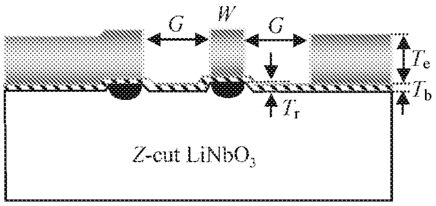

Fig. 2. Cross-sectional view of ridge-type modulator.

To achieve a broader bandwidth modulation, optimum design has been made with finite element method (FEM). The results are shown in Fig. 3. We have found that a tradeoff scheme can be obtained by using gap $G = 15$ μm, electrode thick $T_e = 10$ μm, buffer thick $T_b = 1$ μm, and ridge depth $T_r = 4$ μm. In this case, we can get that the microwave refractive index $N_{eff} = 2.25$, and characteristic impedance $Z_c = 49$ Ω.

Based on the optimum design structure, the characteristic impendence as a function of the frequency response has been given, shown in Fig. 4. The frequency range is only chosen from 0 to 100 GHz since the main purpose here is to show the trend of characteristic impedance

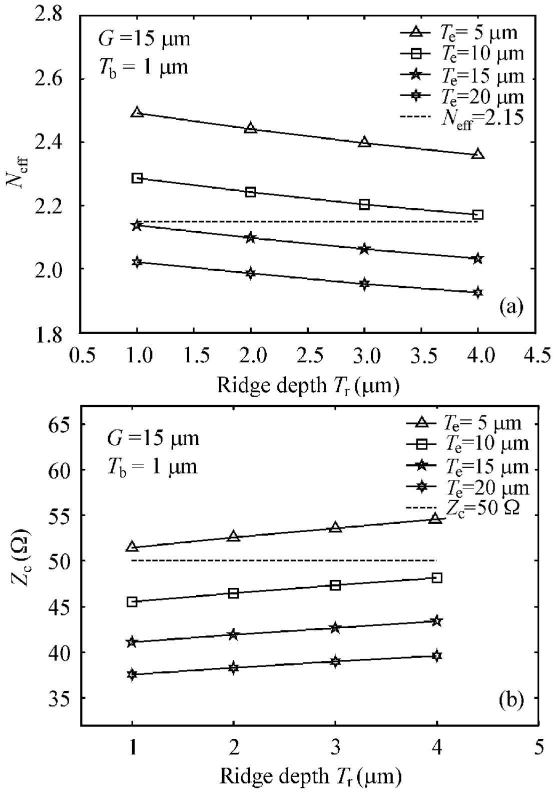

Fig. 3. Microwave refractive index (a) and impedance (b) as a function of ridge depth for an optimized ridge-type modulator.

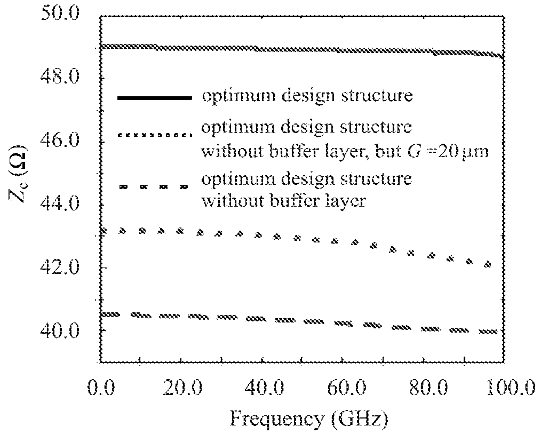

Fig. 4. Characteristic impedance as a function of frequency response for the different structures.

change in different structures when the frequency increases. We can find that the characteristic impendence is various for the different structures and reduces while the frequency increases. Therefore, a buffer layer is required between the waveguides and the electrodes to avoid the absorption of the optical modes and to get a stable characteristic impedance at high frequency.

Consider the Mach-Zehnder modulator shown in Fig. 1. The co-planar electrode structure supports a CW travelling microwave electric field given by

$$E = E_m \exp[j(\omega t - \beta z) - \alpha z], \tag{1}$$

where ω, β and α are the angular frequency, propagation coefficient and attenuation of the microwave field, respectively, and E_m is in general complex. The refractive-index change caused by the linear electro-optic effect is

$$\Delta n = -\frac{1}{2} n_{\mathrm{e}}^3 \gamma_{33} E_m \exp[j(\omega t - \beta z) - \alpha z], \tag{2}$$

where n_{e} is the effective refractive index in the waveguide and γ_{33} is the electro-optical coefficient. The microwave phase velocity is given by $\nu_m = \omega/\beta$, and for small index change the optical phase velocity is constant. Thus, an optical phase front starting at time t_0 and $z = 0$ will be experienced an electric field

$$E = E_m \exp[j(\omega t_0 - \beta' z) - \alpha z], \tag{3}$$

where $\beta' = \frac{2\pi N_m}{\lambda_m}\left(1 - \frac{\nu_m}{\nu_0}\right)$, N_m, λ_m, ν_0 are the effective refractive index of the microwave in the material, the microwave length, and the optical phase velocity, respectively.

Such a phase front will experience an electro-optically induced phase shift $\mathrm{d}\phi$ within the length $\mathrm{d}z$

$$\mathrm{d}\phi = -\frac{n_{\mathrm{e}}^3 \gamma E_m k}{2} \exp[j(\omega t_0 - \beta' z) - \alpha z]\mathrm{d}z, \tag{4}$$

where k is the free space optical propagation coefficient. Considering all optical phase fronts with various t_0, we can see that $\mathrm{d}\phi$ contains the time varying function $\exp(j\omega t_0)$. Thus

$$\mathrm{d}\phi = F \exp(-rz)\mathrm{d}z, \tag{5}$$

where the excitation function $F = \left(-\frac{n_{\mathrm{e}}^3 \gamma E_m k}{2}\right)\exp(j\omega t_0)$, and $r = \alpha + j\beta'$. For a phase reversal structure in which the microwave phase is reversed at the end of each section, the total induced optical phase shift ϕ is given by

$$\frac{\phi}{FL} = \frac{1}{L}\sum_{m=0}^{M-1}(-1)^m \int_{z_m}^{z_{m+1}} \exp(-rz)\mathrm{d}z, \tag{6}$$

where M is the number of sections, z_m is the position of the mth reversal, $z_0 = 0 < z_1 < \cdots < z_m < z_M = L$, and L is the total interaction length. So, we can get

$$\begin{aligned}\left|\frac{\phi}{FL}\right|^2 = {} & \frac{1}{(\alpha^2 + \beta'^2)L^2}\sum_{m=0}^{M-1}\sum_{n=0}^{M-1}(-1)^m(-1)^n \\ & \times\{\cos[\beta'(z_m - z_n)]\exp[-\alpha(z_m + z_n)] \\ & + \cos[\beta'(z_{m+1} - z_{n+1})]\exp[-\alpha(z_{m+1} + z_{n+1})] \\ & -2\cos[\beta'(z_m - z_{n+1})]\exp[-\alpha(z_m + z_{n+1})]\}.\end{aligned} \tag{7}$$

To obtain a large bandwidth, the condition of the velocity match between the optical wave and microwave in a travelling wave modulator with nonperiodic structure is satisfied. Therefore, we must find the arrangement of z_p which gives the maximum value of $|\phi/(FL)|$ and require a solution which gives

$$\frac{\partial\left|\frac{\phi}{FL}\right|^2}{\partial z_p} = 0, p = 1, 2, \cdots, M-1 \text{ and } M > 1, \tag{8}$$

when $\alpha = 0$

$$\frac{\partial\left|\frac{\phi}{FL}\right|^2}{\partial z_p} = \frac{4(-1)^p}{\beta' L^2}(A\cos\beta' z_p - B\sin\beta' z_p), \tag{9}$$

where

$$A = 2\sum_{m=1}^{M-1}(-1)^m \sin\beta' z_m + (-1)^M \sin\beta' z_m,$$

$$B = 1 + 2\sum_{m=1}^{M-1}(-1)^m \cos\beta' z_m + (-1)^M \cos\beta' z_m.$$

Using Eq. (9) with N_{eff}=4.2, 3.5, and 2.5, respectively, $|\phi/(FL)|$ is plotted for the lossless nonperiodic structure, illustrated in Fig. 5. It is shown that the rather flat frequency is achieved while N_{eff} decreases. Especially, the frequency response of the new device is flat up to 350 GHz with N_{eff}=2.5. So, it should be required to obtain large bandwidth applying nonperiodic domain inversions and ridge structure to the travelling wave modulator.

To get a complete description of the device performance in the frequency domain, the argument of the function $\phi/(FL)$ is also given with different refractive indices, shown in Fig. 6.

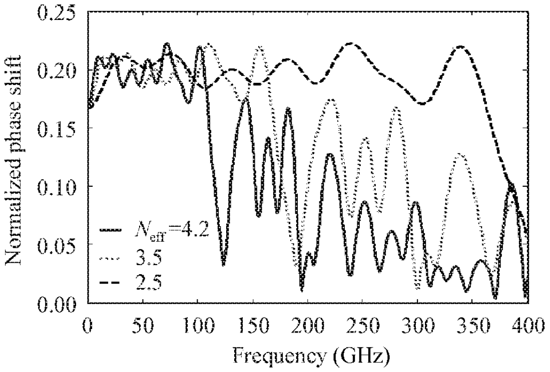

Fig. 5. Optimum results of normalized phase shift and frequency response.

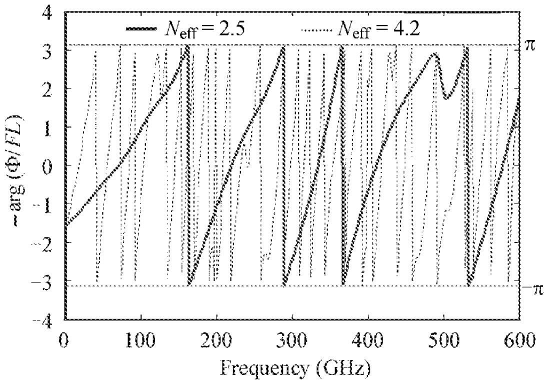

Fig. 6. Frequency response of the argument of the phase shift for different refractive indices N_{eff}.

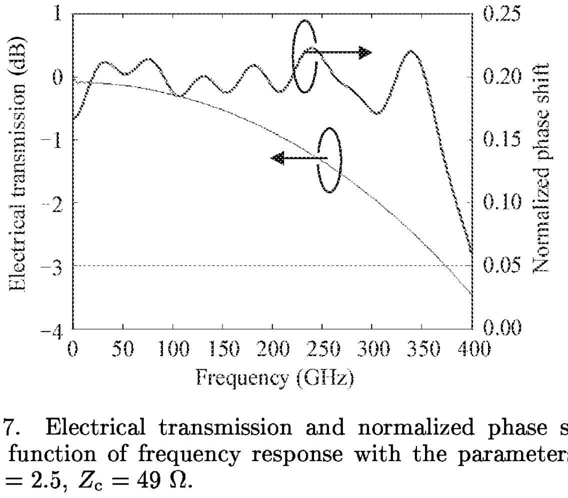

Fig. 7. Electrical transmission and normalized phase shift as a function of frequency response with the parameters of $N_{eff} = 2.5$, $Z_c = 49\ \Omega$.

Figure 7 illustrates that electrical transmission and normalized phase shift as a function of frequency response with the parameters of $N_{eff} = 2.5$, $Z_c = 49\ \Omega$, $L = 1$ cm. We can find that the frequency response relative to normalized phase shift is in good agreement with electrical transmission, and are both flat over 350 GHz.

In order to obtain wide flat frequency response in broadband electro-optical intensity modulator, we propose a novel device with nonperiodic domain inversions and ridge structure. Theoretical analysis and calculation with FEM are made on this structure. Results have shown that the frequency response is flat up to 350 GHz with an interaction length of 1 cm, characteristic impedance of 49 Ω, and microwave refractive index of 2.5. Moreover, N_{eff} is assumed 2.5 when we calculate, since its value is difficult to obtain 2.25 in practice fabrication.

Due to the structure with nonperiodic domain inversions, thick electrodes and large gap, the microwave attenuation can be reduced[3]. Here, the relations between the attenuation coefficient and parameters of the device are not given because the purpose of this paper is to propose a new super-broadband device. Therefore, we assume the attenuation coefficient $\alpha_0 \approx 0$ for our calculations.

In addition, technologies of domain-reversal fabrication[4], such as electric field poling, Ti-diffusion under high temperature and proton-exchange, etc, are all developed, however, how to increase the degree of inversion in the fabrication of device, i.e., how to realize the equality of γ_{33} coefficient and opposition of the sign of it in normal-poled and reverse-poled domain $LiNbO_3$ substrates, is still a key problem. Therefore, it could be a new device in high-speed modulation after the above problems are resolved.

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