ANALYSIS OF $LiNbO_3$ OPTICAL MODULATOR USING COPLANAR-TYPE ELECTRODES

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ABSTRACT

A comprehensive study is presented for the coplanar-type TW electrode of the $Ti{:}LiNbO_3$ optical modulator, taking the anisotropy of the $LiNbO_3$, the effect of the SiO_2 buffer layer, the overlay and the electrode thickness into consideration. Accurate hybrid-mode computations reveal that the figure of merit $\Delta f/V_\pi$ is affected significantly by the electrode thickness and the overlay, and that the modulator performance can be improved by utilizing these effects advantageously. Also, numerical computations show that there exist the upper frequency limit f_u, where mode coupling occurs. Therefore, special care should be taken for the choice of the thickness of the $LiNbO_3$.

I. INTRODUCTION

Coplanar types of the traveling-wave (TW) electrodes have been investigated for the use of $Ti{:}LiNbO_3$ optical modulators [1]-[3]. For high-speed operation, the TW electrode permits a wide operation bandwidth. The bandwidth for the modulator is restricted mainly by the conductor loss of the electrodes and the mismatch in velocity between microwaves and optical waves. A number of modified electrode structures have been proposed to reduce the velocity mismatch, e.g., the introduction of overlay and buffer layer, the use of thicker electrodes, and asymmetrical structures. The optimization of TW operation requires an accurate analytical procedure applicable to varieties of structures. Special care should be taken for the analyses of these types of $Ti{:}LiNbO_3$ optical modulators. 1) The strong anisotropy of the $LiNbO_3$ ($\varepsilon_{//} = 28$, $\varepsilon_\perp = 43$) is taken into consideration. 2) Multilayered structures, e.g., buffer layer, overlay and $LiNbO_3$, is treated by the systematic formulation procedure. 3) The electrode thickness effect is taken into consideration. 4) The field singularities near the electrode edge is represented properly for the accurate conductor loss calculation.

Recently, symmetrical CPW (SCPW) electrode was analyzed by the extended spectral domain approach (ESDA)[2], taking the anisotropy of the $LiNbO_3$, the effect of the buffer layer, and the electrode thickness into consideration. But, only the microwave characteristics, i.e, the propagation constant $\gamma = \alpha + j\beta_m$ and the characteristic impedance, were presented in [2]. The modulator characteristics, the figure of merit $\Delta f/V_\pi$, were presented for the SCPW based on the quasistatic analysis[3]. Comprehensive study of the characteristics of the optical modulator is presented here based on an accurate hybrid-mode analysis.

II. METHOD OF ANALYSIS

The performance of the traveling-wave modulator will be investigated under the condition that the electrode characteristic impedance is matched to the source and the connecting cable. Then, the microwave applied along the electrodes is

$$\mathbf{E}(x,y,z) = \mathbf{E}_m(x,y)\exp(-\gamma z) \qquad (1)$$

where $\mathbf{E}_m$ is the electric field at the input end (z=0) and γ is the propagation constant

$$\gamma = \alpha + j\beta_m = \alpha + jn_m k_0 \qquad k_0 = \omega\sqrt{\varepsilon_0 \mu_0} \qquad (2)$$

where n_m is the microwave effective index. β_m and $\mathbf{E}_m$ are obtained for the lossless cases by using the extended spectral domain approach (ESDA)[2],[4]. Then attenuation due to imperfect conductors α is accounted for by the perturbational scheme. Losses due to the imperfect conductor is determined by

$$\alpha = \frac{P_C}{2\,P_0} \qquad (3)$$

where P_0 is the average power flow, and P_C is the power lost in the conductors. Conventional perturbational schemes for P_C have calculated the integral over the conductor surface C, i.e.,

$$P_C = \frac{1}{2} R_s \int_C |\mathbf{H}_t|^2\, dl \qquad (4)$$

where R_s is the surface resistance of an infinitely thick conduc-

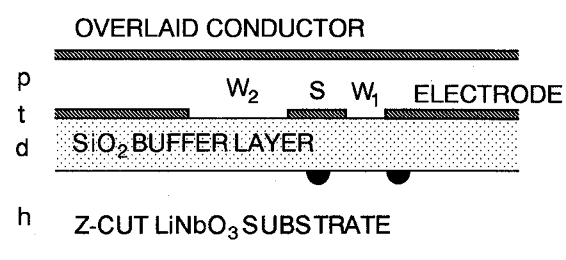

Fig.1 Coplanar-type TW electrode for optical modulator

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tor and $\mathbf{H}_t$ is the tangential component of the magnetic field on the surface of the conductor. This calculation was based on the assumption that the electrode thickness t >> δ, and therefore it cannot be applied to the thinner electrode case. The authors proposed that P_C should be evaluated by the integral over S_C, the region occupied by the electrode conductors[2],

$$P_C = \frac{1}{2}\int_{S_c} \sigma|\mathbf{E}|^2 dS \qquad (5)$$

The electric field **E** inside the electrode conductors can be related to the tangential component of the magnetic field on the conductor surface $\mathbf{H}_t$ easily .

When the microwave (1) is applied to the electrodes of the TW Mach-Zehnder optical modulator, the phase shift experienced by the optical signal over the interaction length L is

$$\Delta\phi = \pi \frac{V_m}{V_\pi}\cdot\left\{\frac{1-2\exp(-\alpha L)\cos\theta+\exp(-2\alpha L)}{(\alpha L)^2+\theta^2}\right\}^{1/2} \qquad (6)$$

θ is a measure of the velocity mismatch between the optical and microwave signals

$$\theta = (n_m - n_o)\,k_0\,L \qquad (7)$$

where n_o is the effective index of the optical waveguide mode. V_m is the modulation voltage at the input end and is evaluated by integrating $\mathbf{E}_m$ over the aperture. V_π , the half-wavelength voltage, can be evaluated as [5]

$$V_\pi L = \frac{\lambda}{n_0^3\, r_{33}\, \Gamma} \qquad (8)$$

where r_{33} is Pockels constant and Γ is the overlap integral between the microwave electric fields E_m and the optical mode fields E_o ,

$$\Gamma = \frac{1}{V_m}\iint E_m |E_o|^2\, dS \qquad (9)$$

3 dB modulation bandwidth Δf is defined as the frequency for which Δφ is reduced by 50 percent from its value for f=0. The figure of merit of the optical modulator is then evaluated as the ratio $\Delta f/V_\pi$ [1].

IV. NUMERICAL RESULTS

Hybrid-mode characteristics of the electrode is investigated first. Fig.2 shows the frequency-dependence of the microwave effective index n_m of the z-cut Ti:$LiNbO_3$ CPW optical modulator with and without the overlaid conductor. The values of the case of the zero electrode thickness without the overlaid conductor (p -> ∞) are in good agreement with those in [1]. The electrode-thickness effect becomes smaller for the case with the overlaid conductor. It should be noted that there exist the

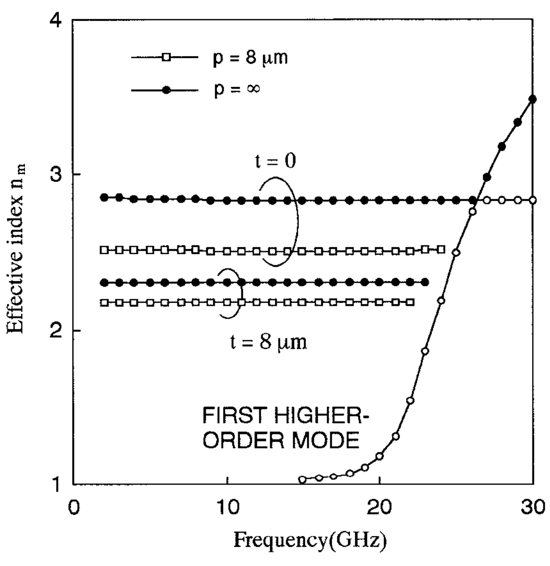

Fig.2 Frequency dependence of effective index and characteristic impedance

S = 8 μm , $W_1 = W_2$ = 15 μm

SiO_2 : $\varepsilon_{//} = \varepsilon_\perp$ = 3.9, d = 1.2 μm

$LiNbO_3$: $\varepsilon_{//}$ = 28 , $\varepsilon_\perp$ = 43 , h = 500 μm

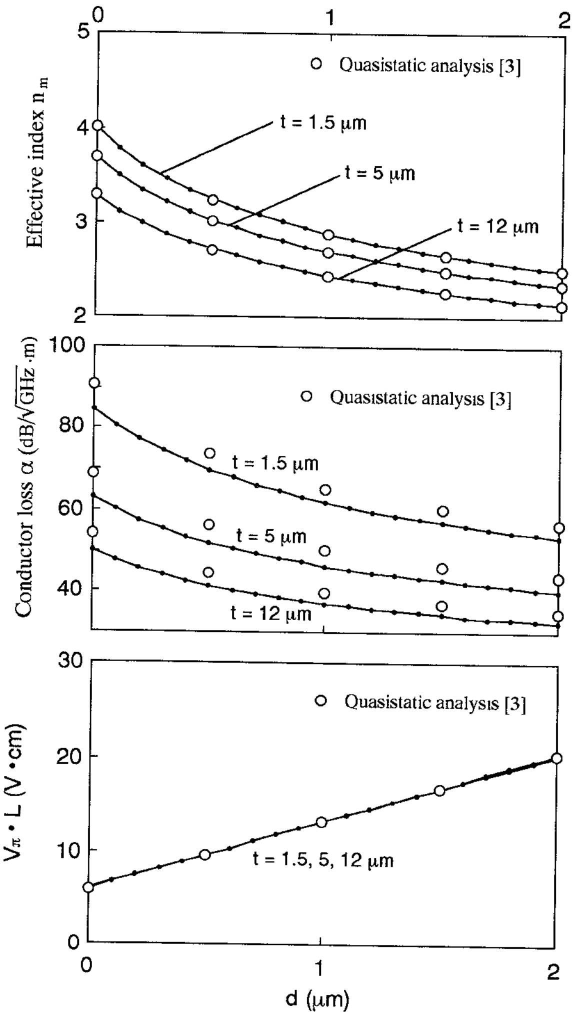

Fig.3 Influence of the buffer layer thickness and the electrode thickness

S = 8 μm , W_1 = 15 μm , W_2 = 30 μm , p = ∞

SiO_2 : $\varepsilon_{//} = \varepsilon_\perp$ = 3.9

$LiNbO_3$: $\varepsilon_{//}$ = 28 , $\varepsilon_\perp$ = 43 , h = 500 μm upper frequency limit f_u, where mode coupling occurs between the dominant and the first higher order mode which has the close relation with the TM_0 surface mode[4]. The TM_0 mode characteristics is insensitive to the dimensions of the electrode, but is affected significantly by the dielectric constant and thickness of the substrate. Therefore, special care should be taken for the choice of the thickness of the $LiNbO_3$.

Fig.3 shows the influence of the buffer layer on n_m, α and V_π for the asymmetrical CPW (ACPW) optical modulator. It should be noted that n_m can be reduced approaching to that of optical waves by increasing the buffer layer thickness. But the use of thicker buffer layer also increases V_π. That is, there exists a trade-off relationship[1]. The effect of electrode thickness t is included in Fig.3. n_m can be reduced by increasing t. And the use of thicker buffer layer decreases the conductor loss significantly. Also, it should be noted V_π is insensitive to t.

The influence of the overlaid conductor are investigated in Fig.4. The overlaid conductor may be used to reduce the velocity mismatch. But it should be noted that, the closer the overlaid conductor to the electrodes, the larger the conductor loss.

Fig.5 shows the figure of merit $\Delta f/V_\pi$ of the ACPW optical modulator as a function of the buffer layer with different electrodes thickness t. Fig.6 shows $\Delta f/V_\pi$ as a function of the spacing p between the overlaid conductor and the TW electrodes. Higher values of $\Delta f/V_\pi$ are obtained by utilizing thicker TW electrodes and the overlay. The conductor losses are taken into consideration in these calculations, therefore the figure of merit remains finite even at the best velocity matching.

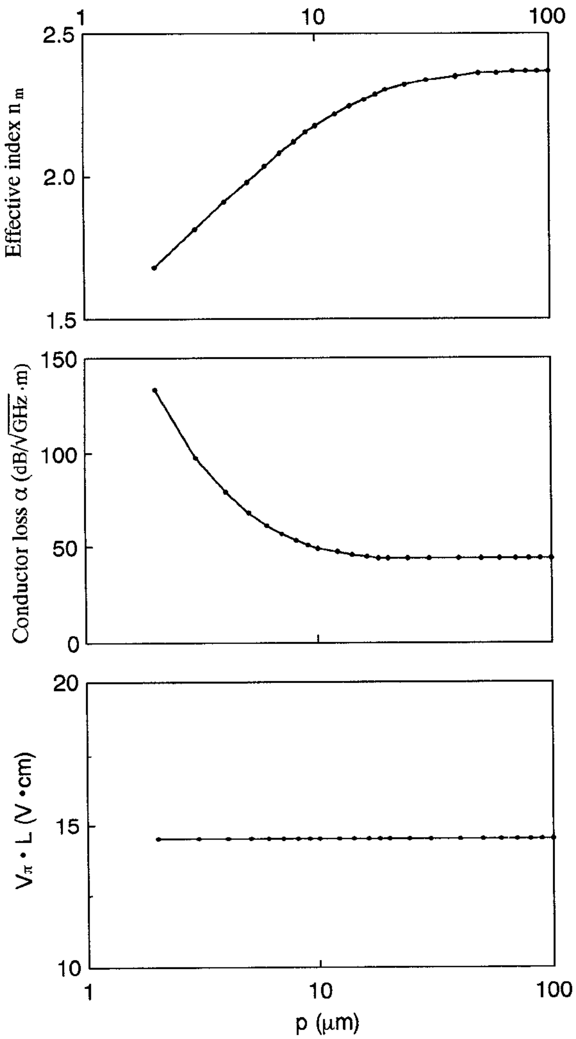

Fig.4 Influence of the overlaid conductor

S = 8 μm, W_1 = 15 μm, W_2 = 30 μm, t = 8 μm
SiO_2 : $\varepsilon_{//} = \varepsilon_\perp = 3.9$, d = 1.2 μm
$LiNbO_3$: $\varepsilon_{//} = 28$, $\varepsilon_\perp = 43$, h = 500 μm

V. CONCLUSIONS

A comprehensive study is presented for the coplanar-type TW electrode for the use of the Ti:$LiNbO_3$ optical modulator. The formulation procedure is based on the extended spectral domain approach (ESDA) and the anisotropy of the $LiNbO_3$, the effect of the SiO_2 buffer layer and the electrode thickness can be taken into consideration easily. Numerical results reveal the microwave characteristics of the electrodes and the modulator characteristics, e.g., V_π and $\Delta f/V_\pi$. The TW electrodes thickness and the overlay affect the modulator characteristics significantly, and they can be utilized to reduce the velocity mismatch without increasing the half-wavelength voltage V_π. Also, numerical computations show that there exists the upper frequency limit f_u, where mode coupling occurs.

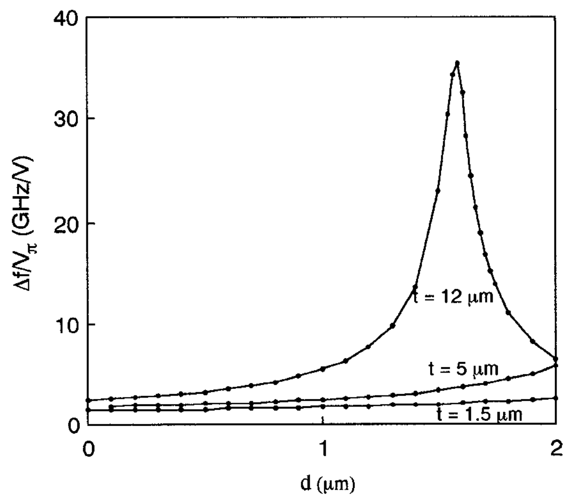

Fig.5 Influence of the buffer layer thickness d and the electrode thickness t on the figure of merit

S = 8 μm, W_1 = 15 μm, W_2 = 30 μm, p = ∞
SiO_2 : $\varepsilon_{//} = \varepsilon_\perp = 3.9$
$LiNbO_3$: $\varepsilon_{//} = 28$, $\varepsilon_\perp = 43$, h = 500 μm

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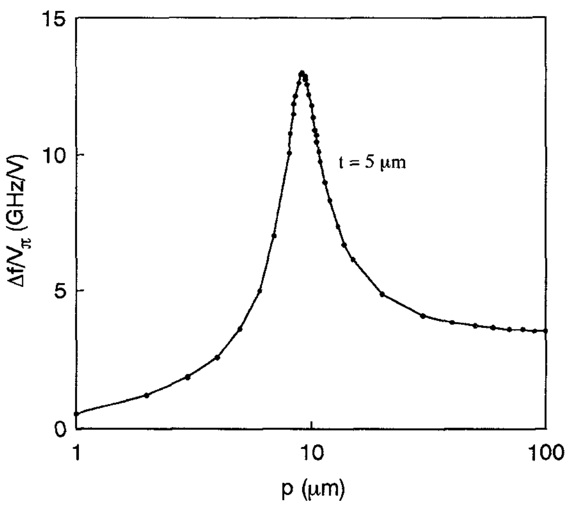

Fig.6 Influence of the overlaid conductor on the figure of merit

$S = 8\ \mu m$, $W = 15\ \mu m$

$SiO_2 : \varepsilon_{//} = \varepsilon_{\perp} = 3.9$

$LiNbO_3 : \varepsilon_{//} = 28$, $\varepsilon_{\perp} = 43$, $h = 500\ \mu m$