Analysis of CPW for $LiNbO_3$ Optical Modulator by Extended Spectral-Domain Approach

Toshihide Kitazawa, *Student Member, IEEE*, David Polifko, *Student Member, IEEE*, and Hiroyo Ogawa, *Member, IEEE*

***Abstract*— A $LiNbO_3$ optical modulator using CPW with a SiO_2 buffer layer is analyzed accurately by incorporating the TW electrode thickness effect as well as anisotropic effect. By introducing a finite electrode thickness, the loss calculation becomes available for the lines with thinner as well as thicker conductors. Numerical computations show that the electrode thickness is as a dominant parameter as is the buffer layer thickness for the line characteristics. The use of thicker electrodes increases the velocity of microwaves in the interaction part and decreases the conductor loss significantly, and it can be utilized advantageously for the modulator's design.**

A LARGE number of papers have been devoted to the investigation of traveling-wave (TW) optical modulators. The operation bandwidth of the modulator is restricted mainly by the conductor loss of the TW electrodes and the mismatch in velocity between microwaves and optical waves. Accurate analysis is indispensable to the design of these modulators. Recently, a Ti:$LiNbO_3$ optical modulator using coplanar waveguide (CPW; inset of Fig. 1) was analyzed by spectral-domain approach. The study incorporated the strong anisotropy of the $LiNbO_3$ $(\varepsilon_{//} = 28, \varepsilon_{\perp} = 43)$, but assumed that the TW electrode thickness is zero [1]. It is well known that the electrode thickness effect of CPW is larger than that of other transmission lines, and that the loss calculation, which neglects the electrode thickness, becomes erroneous.

An accurate analysis is presented here by using the extended spectral-domain approach (ESDA) [2]. ESDA can evaluate the TW electrode thickness effect accurately taking the anisotropy of the $LiNbO_3$ and the effect of the SiO_2 buffer layer into consideration. In the ESDA, electromagnetic fields in each region are related to the aperture fields at the upper and lower surface of the slot region. By enforcing the continuities of the magnetic fields at the aperture surfaces, the integral equations for the aperture fields are obtained. Employing Galerkin's procedure in the spectral domain [2], phase constants and then characteristic impedances can be evaluated accurately.

Fig. 1 shows the frequency dependence of the microwave effective index n_m and the characteristic impedance Z for the interaction part (a) and the feedthrough part (b) of the Ti:$LiNbO_3$ CPW optical modulator. The interaction part consists of a narrow center conductor (S = 8 μm, W = 15 μm) [1],

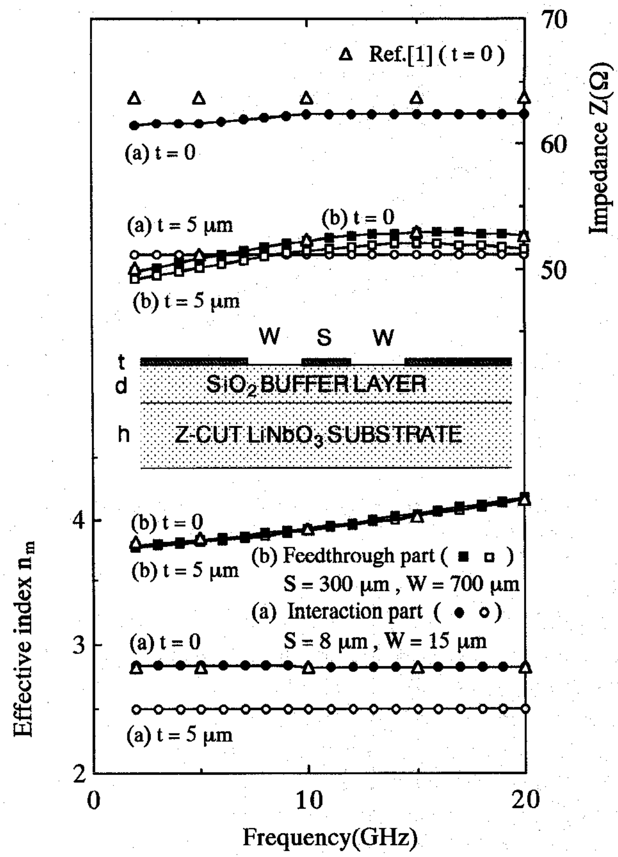

Fig. 1. Frequency dependence of effective index n_m and characteristic impedance Z. $\varepsilon_{//} = 28, \varepsilon_{\perp} = 43, h = 500$ μm. (a) Interaction part; S = 8 μm, W = 15 μm. (b) Feedthrough part; S = 300 μm, W = 700 μm.

whereas the dimensions of the electrodes for the feedthrough part are S = 300 μm, W = 700 μm. Our results for the electrode of zero-thickness are in good agreement with those in [1] for n_m as well as Z of the interaction and the feedthrough part . Fig. 1 includes the electrode thickness effect on n_m and Z of CPW with realistic values of t = 5 μm. The thickness effect in the feedthrough part is negligibly small, whereas the effect in the interaction part is much greater, i.e., 12% decrease in n_m and 17% in Z.

An SiO_2 buffer layer was introduced to reduce the conductor loss and to decrease n_m for the velocity matching [1]. Fig. 2 shows the influence of the buffer layer and the electrode thickness on n_m and Z for the interaction part. Again, our results for the zero electrode thickness cases (t = 0) agree well with those of [1]. Also, we mention that the TW elec-

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T. Kitazawa is with the Department of Electrical Engineering, Ibaraki University Nakanarusawa, Hitachi, 316 Japan.

D. Polifko and H. Ogawa are with the ATR Optical and Radio Communications Research Laboratories, Sanpeidani, Inuidani, Seika-cho, Soraku-gun, Kyoto, 619-02, Japan.

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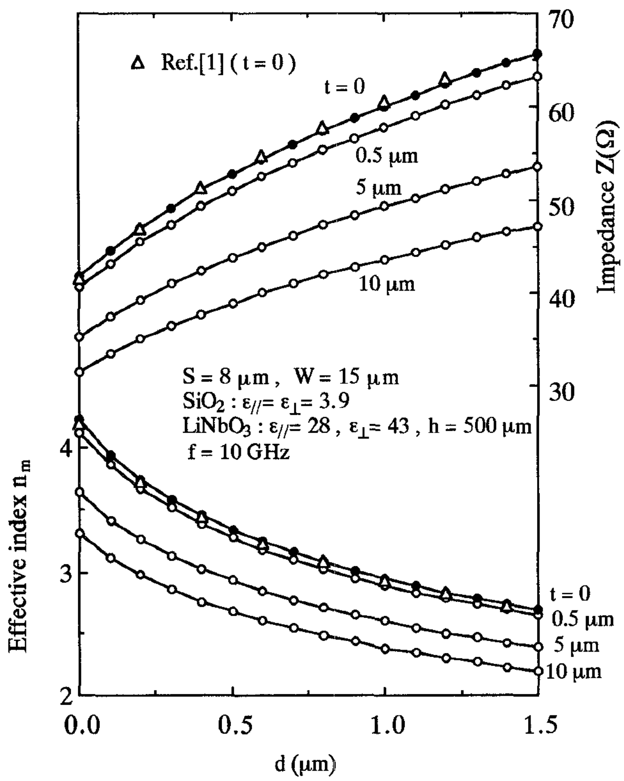

Fig. 2. Influence of the buffer layer thickness d and the electrode thickness t on n_m and Z. $\varepsilon_{//} = 28$, $\varepsilon_{\perp} = 43$, $h = 500$ μm, $S = 8$ μm, $W = 15$ μm, $f = 10$ GHz.

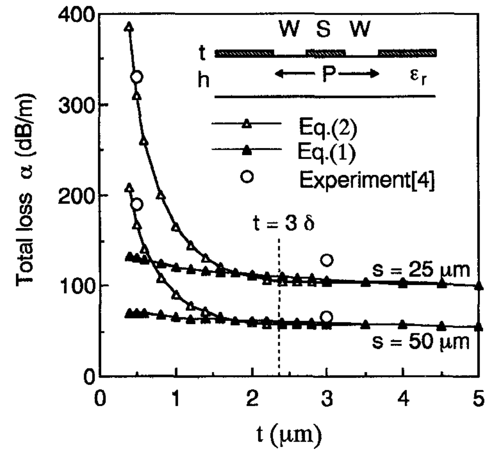

Fig. 3. Losses of CPW on a GaAs substrate. GaAs substrate; $\varepsilon_r = 12.9$, tan $\delta = 0.0003$, $h = 500$ μm conductor $\sigma = 4.1 \times 10^7$ S/m, S/P = 0.4, $f = 10$ GHz.

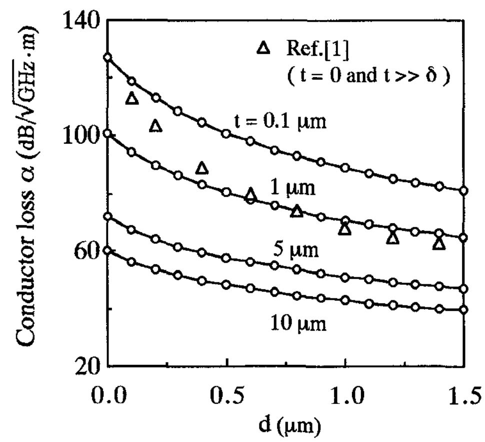

Fig. 4. Influence of the buffer layer thickness d and the electrode thickness t on the conductor loss α. $\varepsilon_{//} = 28, \varepsilon_{\perp} = 43, h = 500$ μm, $S = 8$ μm, $W = 15$ μm, $f = 10$ GHz.

trodes thickness t is a dominant parameter as the buffer layer thickness d for the velocity matching between microwaves and optical waves, i.e., the use of thicker electrode increases the velocity of microwaves in the interaction part significantly.

ESDA is combined with the perturbation method to evaluate the loss characteristics [2]. Conventional perturbational schemes require the contradictory assumptions, i.e., the TW electrode thickness is zero, as well as it is sufficiently greater than the skin depth δ, where the fields in the conductor will die out before they reach the other surface. The power lost in the conductors, P_C, has been calculated by the integral over the conductor surface C,

$$P_c = \frac{1}{2} R_s \int_C |\boldsymbol{H}_t|^2 \, dl, \tag{1}$$

where R_s is the surface resistance of an infinitely thick conductor and $\boldsymbol{H}_t$ is the tangential component of the magnetic field on the surface of the lossless conductor of zero thickness [1]. It has been pointed out that the zero-thickness assumption causes a $\Delta^{-1/2}$ variation near edge [2] and produces a divergence when the integral of (1) is performed up to the edge. The assumption that $t \gg \delta$, on the other hand, limits the applicability of the method, i.e., the procedure cannot be applied to the thinner electrode case, where the fields penetrating from both surfaces of the electrode overlap each other. In the present method, we take the finite thickness of the electrode into consideration, and the power loss P_C is evaluated by [3]

$$P_C = \frac{1}{2} \int_{S_C} \sigma |\boldsymbol{E}|^2 \, dS, \tag{2}$$

where S_C stands for the region occupied by the electrode. The electric field $\boldsymbol{E}$ inside the electrode conductors can be related to the tangential component of the magnetic field on the conductor surface $\boldsymbol{H}_t$ easily, and the integral over the conductor S_C can be reduced to an integral over the conductor surface C [3].

Fig. 3 shows the electrode thickness effect on the attenuation constants of a CPW on a GaAs substrate, comparing with the measured values [4] . The attenuation constants by the integral (2) are in good agreement with the measured values for both thinner as well as thicker metallization, while the values by (1) are too low for thinner metallizations.

The conductor loss of the interaction part the Ti:$LiNbO_3$ CPW optical modulator with the SiO_2 buffer layer is shown against the buffer layer thickness d for different electrodes thickness t in Fig. 4. The reduction of the conductor loss due to the increase of the buffer layer thickness in our calculation is smaller than that in [1], which assumes $t = 0$ and $t \gg \delta$. We have found that the TW electrodes thickness has a significant effect on the conductor loss, too. Specifically, the use of thicker electrode reduces the conductor loss significantly.

In conclusion, the $LiNbO_3$ optical modulator using CPW with the SiO_2 buffer layer is analyzed accurately, incorporating the electrode thickness effect as well as anisotropic effect. By introducing a finite conductor thickness, the simple perturbational method for loss calculation can be utilized for the lines with thinner conductors, where the fields penetrating from both surfaces of the conductor overlap each other and attenuation become more significant. Numerical computations show that the electrodes thickness is as a dominant parameter as the buffer layer thickness for the microwave effective index, the characteristic impedance and the conductor loss. The use of thicker electrodes increases the velocity of microwaves in the interaction part and decreases the conductor loss significantly, and it can be utilized advantageously for the design of the modulators.

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