Effect of Substrate Modes in 40Gbit Travelling Wave $LiNbO_3$ Modulators

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Abstract - **In this paper, substrate modes which influence the bandwidth of travelling wave $LiNbO_3$ Mach-Zehnder modulators are reviewed. Criteria for the appropriate choice of RF electrode geometry to minimize losses have been presented. Finally, the effect of backside metalization due to metallic packages has been discussed, along with suitable modifications to mitigate the losses due to the presence of the backside ground.**

I. INTRODUCTION

Traveling wave integrated electro-optic modulators, particularly, the $LiNbO_3$ Mach-Zehnder modulators, have received a lot of attention due to their applications in broadband long-haul optical communication systems [1] -[3], [6]. The potential for very broadband operation in these devices emerges from the ability to achieve synchronous coupling between the optical and microwave signals using a number of techniques. These techniques include increasing the thickness of the microwave electrodes, using a shielding plane and using a thin layer of low dielectric material (e.g. SiO_2) on the $LiNbO_3$ substrate. When perfect velocity match between the optical and microwave signals is achieved, the bandwidth, although very wide, is still limited by the electrical losses of the electrode, impedance mismatches along the RF path and losses due to coupling to substrate modes [2]. Coplanar Waveguide (CPW) electrodes, which are commonly used in traveling wave modulators, can couple energy from the dominant propagating mode into the higher order substrate modes [4]. To begin with, in this paper, the nature of substrate modes in CPW lines on $LiNbO_3$ substrate is reviewed. Following this, the effect of CPW geometry and substrate thickness on the substrate mode losses is discussed so as to provide guidelines for optimal choice of geometrical parameters to minimize the aforementioned losses. Next, CPW substrate modes in a metallic package environment, which includes a backside ground plane, are discussed. Finally, the use of suitable backing material for $LiNbO_3$ substrate to mitigate the losses in CPW with backside metalization is investigated.

II. SUBSTRATE MODES OF CPW ON $LiNbO_3$

Fig. 1 shows the top view and cross section of CPW electrodes in a Mach-Zehnder travelling wave modulator. The electrode section has three regions: a) the launch section, b) the launch to interaction section transition and c) the interaction region where the optical and microwave signals couple. The CPW at the launch section is wider than the CPW at the interaction region so as to feed the RF signal source to the CPW electrodes, which typically includes a coax to CPW transition. The launch section CPW, especially if it is very wide, can trigger leakage of energy to higher order substrate modes. The higher order modes of a CPW with wide ground planes and no backside metalization correspond to the surface wave modes of a grounded dielectric slab [4], [7]. Fig. 2 shows the plot of the surface wave modes of a grounded $LiNbO_3$ slab, whose dielectric constant values in the x, y and z directions are $\varepsilon_x = 43$, $\varepsilon_y = 28$ and $\varepsilon_z = 43$ respectively (Fig. 1). While the first higher order mode is the TM0 mode with a zero cut off frequency, it can be seen from Fig.2 that it's velocity is much higher than that of the propagating CPW mode which is designed to have a target microwave index close to 2.1. For a given substrate thickness, no significant energy is leaked into the substrate modes upto the frequency where the CPW mode is synchronous with the substrate mode. As the frequency increases, the velocity of the substrate mode decreases and at the frequency where it's velocity is equal to the velocity of the dominant CPW mode, dispersion occurs and is noticed in the form of a dip in the insertion loss. Above that frequency, the attenuation of the CPW electrodes increases with frequency [4].

III. EFFECT OF CPW GEOMETRY ON LOSSES DUE TO SUBSTRATE MODES

As the substrate thickness increases, the frequency at which power leaks into substrate modes decreases. This is reflected in Fig. 3, which plots substrate thickness versus frequency where the surface wave dominant TM0 mode and the CPW mode become synchronous, for a range of CPW microwave indices. For a given substrate thickness, the frequency where the CPW and surface wave mode become synchronous is obtained

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from the point of intersection of the propagation constant Vs. frequency curves of the CPW mode and the surface wave mode. To validate the aforementioned effect of substrate thickness on CPW attenuation, electrode structures with identical geometries were measured on substrates with different thickness. Fig. 4 shows the insertion loss (S21) of a 1900 μm long CPW through line of width and gap 125 μm and 350 μm respectively, on 10, 14 and 28 mil thick $LiNbO_3$ substrates. Figs. 5 and 6 show the return loss and insertion loss respectively of a complete CPW modulating electrodes (geometry in Fig. 1 with 2 cm long interaction region, launch region CPW W/G = 125μm/350μm, interaction region CPW W/G = 6μm/28μm, 1.2 μm thick SiO_2 layer between $LiNbO_3$ and CPW electrodes and 14 μm thick CPW electrodes) on 10, 14 and 28 mil thick $LiNbO_3$ substrates. From Figs. 4 – 6, it can be seen that the substrate thickness plays a critical role in controlling the attenuation of the RF lines, especially at high frequencies, and limits the bandwidth of the device. This has been seen from measurements of various structures, especially when the CPW gap (G) is wide compared to the $LiNbO_3$ substrate thickness.

As mentioned above, the CPW RF launch section feeds RF signal to the modulator. Optimizing it's design to match the input impedance looking into the modulator to the impedance of the RF feed circuitry is crucial for the wideband, lowloss performance of the device. In addition to satisfying broadband impedance matching criteria, care must be taken in the design of this section so as to minimize triggering the substrate modes discussed in section II. The amount of energy that couples from the propagating CPW mode into these higher order modes is a function of the field overlap of these modes as well as the frequency dependent propagation constant. Since the CPW width and gap influence the field overlap between the CPW mode and the substrate modes, in this study, CPW lines were designed with a range of aspect ratios and input impedance values. The purpose of this was to measure the return loss and insertion loss/attenuation of these lines so as to obtain guidelines for optimal design of the launch section for improving bandwidth by reducing signal attenuation while maintaining broadband impedance match. Fig. 7 shows the insertion loss (S21) of a range of 1900 μm long CPW through lines on 28 mil thick $LiNbO_3$ substrate along with the dimensions and computed impedances of these lines. In all cases, the CPW electrode thickness was 14μm and the thickness of SiO_2 layer was 1.2μm. From the figure it can be seen that by choosing smaller widths and gaps, the insertion loss can be dramatically reduced while maintaining similar characteristic impedance (Zo). It is clear from this study that optimizing the design parameters of the RF transmission sections can significantly reduce RF signal attenuation in 40Gbit $LiNbO_3$ travelling wave modulators.

IV. SUBSTRATE MODES OF CPW ON $LiNbO_3$ IN A METALLIC PACKAGE

While the higher order modes in CPW structures with wide topside ground planes and no backside metalization correspond to the surface wave modes of a grounded dielectric slab, those of CPW lines with backside ground (e.g. in a packaged environment) correspond to the modes of a parallel plate waveguide [4]. Fig. 8 shows a plot of the propagation constant vs. normalized frequency for the modes a parallel plate waveguide filled with $LiNbO_3$. From the figure it can be seen that the dominant parallel plate mode which has a zero cutoff is slower than the propagating CPW mode and hence this mode is a source of energy leakage and contributes to signal attenuation and reduced bandwidth. It can be shown that backing the $LiNbO_3$ substrate with a low dielectric backing material can mitigate this problem by increasing the velocity of the dominant mode [5]. Fig. 9 plots the modes of a parallel plate waveguide with $LiNbO_3$ backed by different materials. From the figure, it can be seen that the low dielectric backing material reduces the propagation constant of the substrate modes, consequently reducing losses in CPW electrodes on $LiNbO_3$ in a package environment with backside ground.

V. CONCLUSION

Higher order substrate modes in traveling wave $LiNbO_3$ Mach-Zehnder modulators, which increase attenuation and decrease bandwidth, have been discussed in this work. It has been shown that appropriate choice of substrate thickness and CPW geometry play a critical role in reducing attenuation and increasing bandwidth, especially for 40 GBit devices. Also, the significance of appropriate choice of low dielectric backing between the $LiNbO_3$ substrate and the backside/package ground has been discussed.

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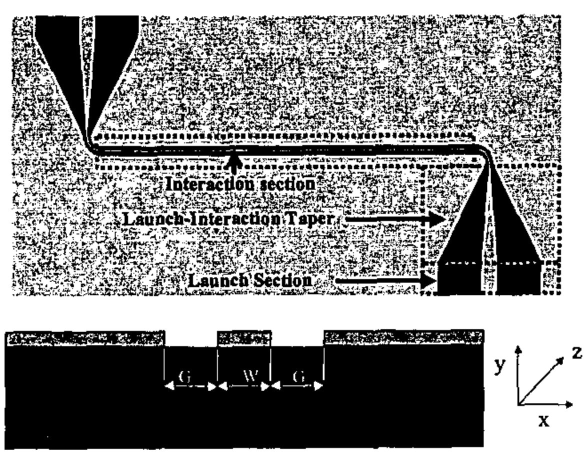

Fig.1 Top view and Cross section of CPW electrodes in the Travelling wave $LiNbO_3$ Modulator

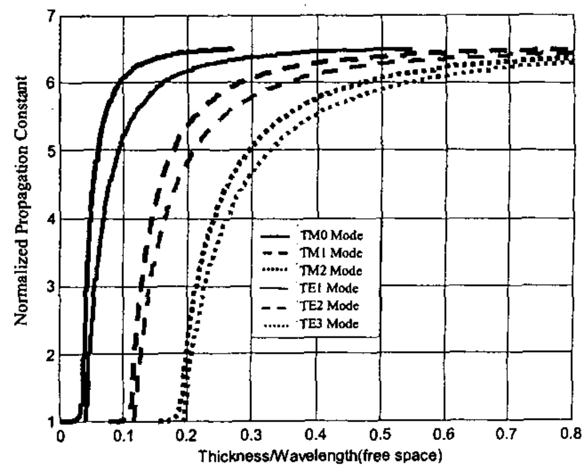

Fig. 2 Substrate Modes of CPW on $LiNbO_3$

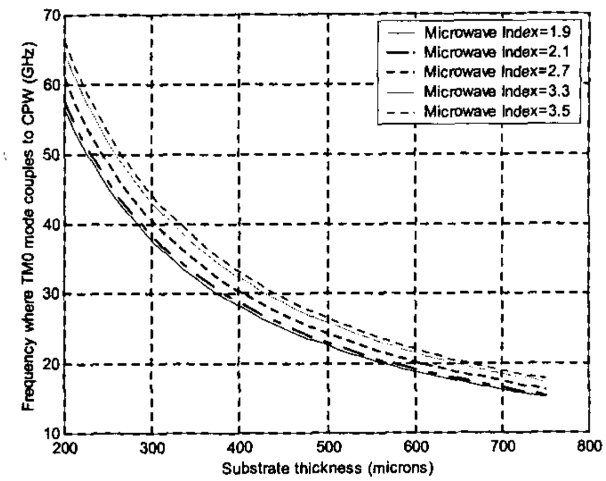

Fig. 3 $LiNbO_3$ substrate thickness Vs. Frequency where CPW and TM0 modes are synchronous for a range of CPW microwave indices

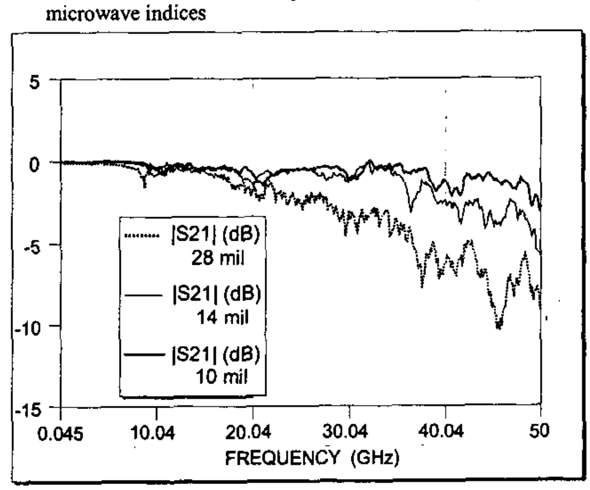

Fig.4: S21 Comparison of 1900 μm long CPW through lines on $LiNbO_3$ substrates of different thickness: CPW width (W) = 125μm, gap (G) = 350μm

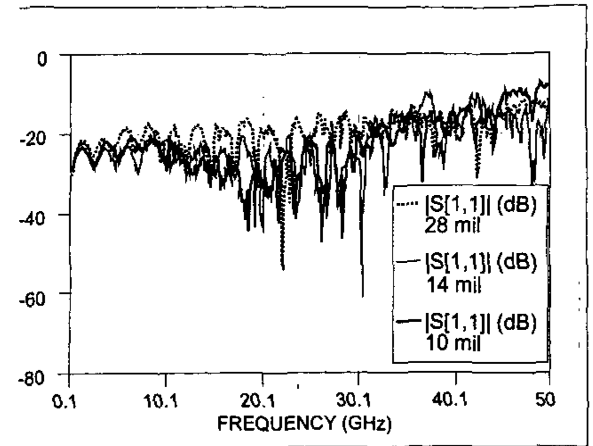

Fig. 5: S11 Comparison of complete CPW RF electrodes with 2 cm long interaction length on substrates of different thickness: CPW at the launch region: W=125μm, G=350μm; CPW at the interaction region: W=8μm, G=28μm

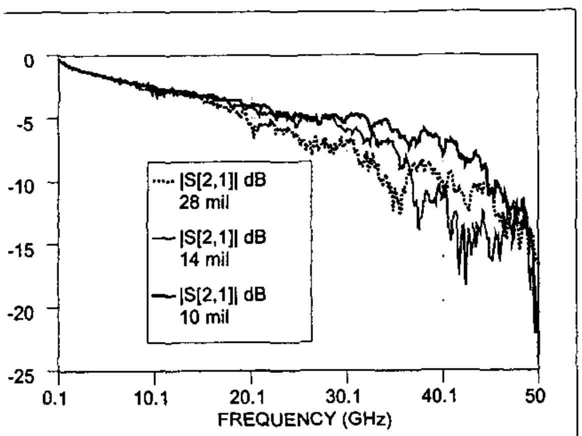

Fig. 6: S21 Comparison of complete CPW RF electrodes with 2 cm long interaction length on substrates of different thickness: CPW dimensions same as in Fig. 5

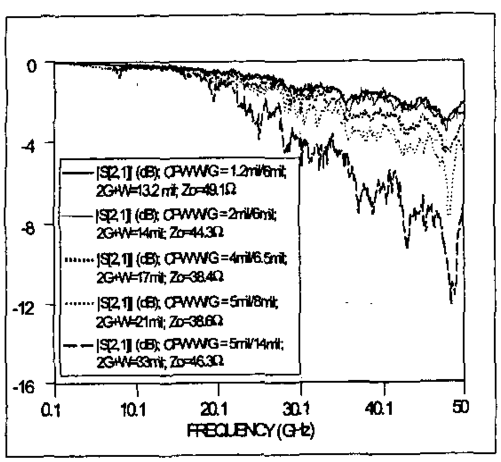

Fig.7: S21 of 1900 μm long CPW launch through lines on 28 mil $LiNbO_3$ with different aspect ratios

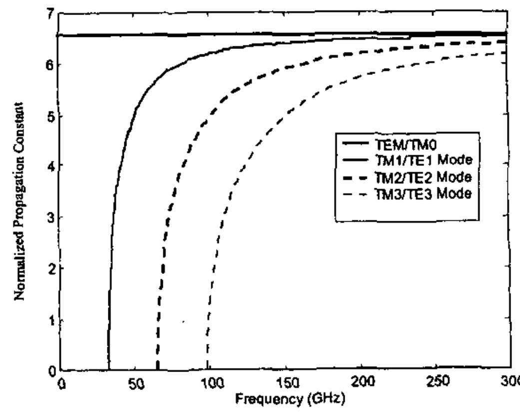

Fig. 8 Parallel Plate Modes of CPW on 28 mil thick $LiNbO_3$ with backside metalization

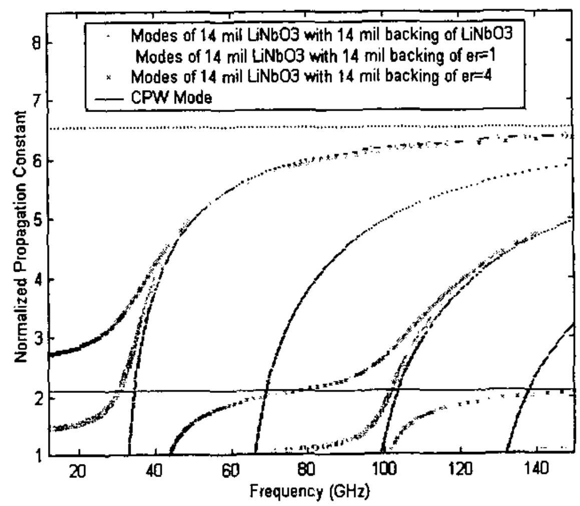

Fig. 9 Comparison of modes of CPW on 14 mil $LiNbO_3$ with 14 mil backing of different materials: a) $LiNbO_3$, b) $\varepsilon_r = 4$, c) $\varepsilon_r = 1$. Also included is propagation constant of the CPW mode (target microwave index ~ 2.1 for CPW on $LiNbO_3$)