Ridge Coplanar Waveguide for Optical Amplitude Modulation

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***Abstract*—A novel structure called ridge coplanar waveguide is proposed for Mach–Zhender optical modulator. Numerical modeling using a two-dimensional finite-difference time-domain (2D-FDTD) algorithm has shown that a ridge coplanar waveguide on Y-cut $LiNbO_3$ substrate without SiO_2 buffer layer yields very high efficiency of modulation over a wide frequency bandwidth.**

I. Introduction

TRAVELING-WAVE modulation of lightwaves employing materials with strong electro-optic effect such as $LiNbO_3$ has been a subject of several researchers in order to reach higher frequencies of modulation. Phase modulation of lightwaves has been attained through a variety of interesting techniques, but the corresponding demodulation systems are not quite attractive in the present. Considering this fact, efforts have been concentrated on the investigation of lightwave amplitude modulation because demodulation has been demonstrated to be feasible even at very high frequencies [1], [2].

It is well known that the electrodes for a traveling-wave optical modulator should be designed to achieve maximum lightwave phase modulation which basically depends on wave phase velocity, propagation losses, characteristic impedance and electric field distribution. Mach–Zhender interferometers for converting phase modulation into amplitude modulation have been implemented with several configurations of electrodes.

The coplanar waveguide (CPW) on a Z-cut $LiNbO_3$ substrate presents good phase velocity matching between optical and modulating waves over a wide frequency bandwidth by inserting a SiO_2 buffer layer between the substrate and the electrodes, but the electric field is dispersed due to the thick electrodes needed, resulting in poor efficiency of modulation [3], [4]. The placement of a metallic plate over the CPW electrodes improves the efficiency of modulation by the cost of sophisticated fabrication process [5]. The inverted slotline on Y-cut $LiNbO_3$ substrate has shown very high efficiency of modulation due to the velocity matching achieved over a limited frequency bandwidth [6]. The construction of inverted slotline optical modulator is simple, however, it is by no means convenient to realize the push-pull operation required for amplitude modulation.

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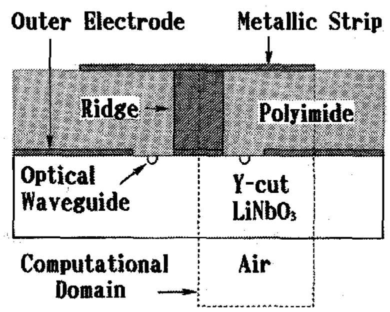

Fig. 1. Cross-sectional view of ridge CPW optical modulator.

This paper proposes a new structure called ridge coplanar waveguide (ridge CPW) which can achieve both the velocity matching and the push-pull operation. Moreover, the ridge CPW optical modulator does not need any complicated fabrication process. Its advantages and disadvantages over the above-mentioned structures will be discussed by focusing modulation efficiency and frequency bandwidth.

II. Structure Description

The ridge CPW, as shown in Fig. 1, consists of a conventional CPW on a $LiNbO_3$ substrate having the inner electrode connected to a metallic strip having a certain width which covers the electrode surface with an appropriate distance. The connection is provided via a rectangular ridge whose width is equal to that of the inner electrode of the CPW. A polyimide film acts as an insulating spacer between the electrodes and metallic strip and allows the structure to be fabricated by material deposition and etching techniques [7].

The Y-cut $LiNbO_3$ substrate is most convenient for the Mach–Zhender ridge CPW modulator and a pair of Ti diffused optical waveguides should be created somewhere in the slots regions in the $LiNbO_3$ substrate. Thus the horizontal electric field component of the modulating wave causes sinusoidal ripples in the $LiNbO_3$ refractive index and consequently modulates the lightwave in amplitude through the Mach–Zhender configuration.

The ridge CPW, in fact, supports a microwave quasi-TEM mode whose refractive index has a value between those of microwaves in $LiNbO_3$ and polyimide, respectively, and which is determined by the arrangement of the electrodes and frequency. In Section IV it will be shown that the careful design of the electrodes takes an important role in adjusting the microwave refractive index to the optical one in $LiNbO_3$ in order to optimize the modulation efficiency by means of phase velocity matching.

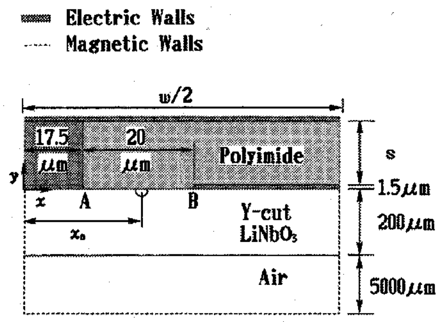

Fig. 2. Model used to simulate microwaves in the ridge CPW.

TABLE I
CONSTITUTIVE PARAMETERS OF MATERIALS EMPLOYED IN RIDGE CPW

Material	Relative Permittivity		
	ε_{rx}	ε_{ry}	ε_{rz}
Polyimide	3.3	3.3	3.3
Y-cut $LiNbO_3$	28	43	43
Air	1.0	1.0	1.0

III. Microwave Simulation

Since the boundary conditions for the microwave in the ridge CPW are much more complicated than those for the lightwave in the optical waveguide, the microwave required careful simulation while aproximated formulas are sufficient to describe the lightwave in this case.

In order to investigate the properties of microwaves in the ridge CPW, an electromagnetic field solver based on a two-dimensional finite-difference time-domain (2-D-FDTD) algorithm [8] is applied to the model shown in Fig. 2.

Due to the symmetry of the structure, only the right half of the cross section is considered in the model. The computational domain is truncated by the covering metallic strip on the top and by magnetic walls on the bottom and on both sides as indicated in Fig. 2. Magnetic walls are surfaces at which the tangencial magnetic and normal electric field components are maintained at zero. These conditions can truncate approximately unbounded regions when there is no radiation and they are much simpler to implement rather than absorbing boundary conditions. On the left side, the magnetic wall imposes the electromagnetic field symmetry similar to a conventional CPW mode and, on the right side, it suggests the field of the parallel plate transmission line configuration formed by the electrodes. The latter introduces an approximation which is acceptable if the separation s between the covering strip and outer electrode is much smaller than the strip width w. The magnetic wall on the botom is sufficiently far away from the $LiNbO_3$ surface with the assumption of a thick air layer.

The geometrical and the constitutive parameters together with the phase constant β_m are the input data which establish the boundary conditions. The initial condition is, by convenience, a vertical magnetic field with Gaussian and quadratic distributions in the vertical and horizontal axes, respectively, being both centered in the middle of the slot. Unfortunately, several microwave modes are simultaneously excited and in order to converge to the dominant mode, an electromagnetic field time-average technique is required [9]. The process is stopped after a certain number of additional simulations when the electromagnetic field reaches sinusoidal variation in time.

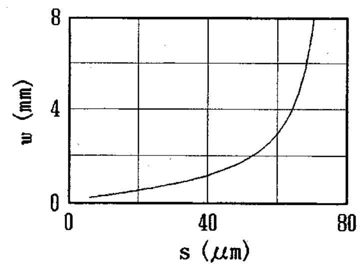

Fig. 3. Calculated relationship between w and s for the velocity matching condition at 50 GHz.

The performance of the optical modulator can be easily previewed in terms of a few parameters extracted from the results above. They are microwave refractive index N_m, conductor and dielectric attenuation constants α_{mc} and α_{md}, characteristic impedance Z_c and overlap integral factor Γ.

IV. Numerical Results

The performace of the ridge CPW will be discussed using one example whose geometrical and constitutive parameters are shown in Fig. 2 and Table I, respectively. The electromagnetic field solver is able to deal with finite metallization thickness and dielectric materials having on-diagonal anisotropy. The calculations are carried out to allow the amplitude modulator to operate at 633 nm and 1300 nm optical wavelengths and modulation frequencies up to 50 GHz at least.

A. Refractive Index Matching

The ridge CPW is well suited for traveling-wave modulators because the phase velocity of the microwave can be controlled within a certain range by means of an unique pair of parameters: the width w of the metallic strip and its separation s from the electrodes. The phase velocity matching is achieved if microwave and optical refractive indices, N_m and N_o, are identical.

In Fig. 3, the calculated relationship between w and s is shown when the matching condition is satisfied at 50 GHz with the assumption of $N_o = 2.2$. Velocity matching at 50 GHz cannot be attained if s is larger than 76 μm because the strip width w is no longer able to compensate for the increase of s.

B. Refractive Index Deviation

Since N_m is a function of frequency due to dispersion effects, the matching condition is perfectly verified at 50 GHz only. The refractive index deviation $\Delta N = N_o - N_m$ at frequencies below 50 GHz have to be taken into account when estimating the performace of the modulator.

The maximum deviation is reached at dc and it is plotted as a function of s as shown in Fig. 4. For small s the curve suggests good efficiency of modulation over a wide bandwidth.

C. Microwave Attenuation Constant

Since the microwave power lost in the ridge CPW acts toward a lower efficiency of modulation, the consideration

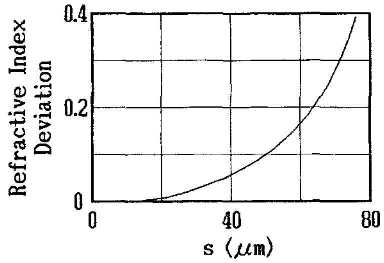

Fig. 4. Calculated refractive index deviation at dc.

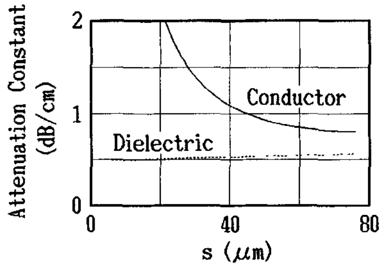

Fig. 5. Calculated conductor and dielectric attenuation constants at 50 GHz.

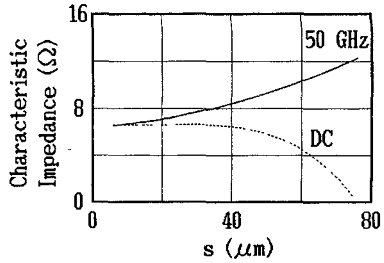

Fig. 6. Calculated characteristic impedance at dc and 50 GHz.

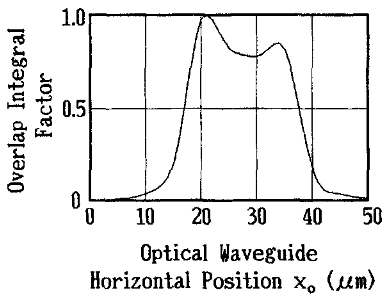

Fig. 7. Calculated overlap integral factor at 50 GHz with $s = 46$ μm.

for loss characteristics cannot be neglected specially at high frequencies.

In the present paper, both conductor and dielectric attenuation constants are calculated through the perturbation approach using the field distributions simulated for the lossless case [10]. The attenuation constants are calculated at 50 GHz and plotted against s, as shown in Fig. 5, under the refractive index matching condition. The conductivity of the electrodes is assumed to be $\sigma = 3.54 \times 10^7$ S/m and the loss tangent of both polyimide and $LiNbO_3$ is assumed to be $\tan\delta = 0.001$, identically. The proximity between electrodes and metalic strip results in high conductor losses indicating that wide bandwidth of operation is obtainded by the cost of power loss increase.

D. Characteristic Impedance

Since the modulation in $LiNbO_3$ is produced by the electric field strength, the microwave power requirement is inversely proportional to the characteristic impedance of the ridge CPW.

The non-TEM nature of the microwave mode at 50 GHz, which is more evident when s is increased, emphasizes the importance of the characteristic impedance definition to be used within the calculations. The most appropriate one is given by

$$Z_c = \frac{V_{AB}^2}{2P} \tag{1}$$

where P is the microwave power flowing in the ridge CPW and V_{AB} is the peak voltage across each slot with A and B indicating the corners of the ridge and the outer electrode, respectively, as shown in Fig. 2. This formulation is consistent with the optical modulation theory to be employed later.

The values of Z_c at dc and 50 GHz are plotted against s, in Fig. 6. The separation of the curves is caused by dispersion effects which are in qualitative agreement with the refractive index deviation shown in Fig. 4.

E. Overlap Integral Factor

The overlap integral factor indicates the efficiency of lightwave modulation in terms of microwave eletric field distribution over the optical waveguide cross section [11].

The overlap integral factor Γ calculated with the assumption of Ti diffused optical waveguides having 4 μm in width and 2 μm in depth is shown in Fig. 7. The origin of the waveguide horizontal position x_o is taken on the plane of symmetry. The maximum efficiency of modulation is indicated by the peak of the curve where $\Gamma = 1$ for $x_o = 21$ μm. This profile does not depend significantly on the metallic strip parameters, s and w, neither microwave frequency.

The advantage of the ridge CPW over similar structures is the fact that the best position of the optical waveguides are in the slot regions and not in contact with the electrodes. Hence a SiO_2 buffer layer is dispensable and Γ reaches a higher value. A comparison with other traveling-wave structures is available in [12].

F. Performance of Modulator

In order to achieve full amplitude modulation, a single tone microwave power P has to produce $\pi/2$ rad. of lightwave phase deviation in each optical waveguide arm which forms the push-pull Mach–Zhender interferometer. Considering traveling-wave modulators, an expression has been derived elsewhere [13] and is conveniently rearranged here as

$$P = \frac{F}{2Z_c}\left(\frac{\lambda_o}{2N_o^2\gamma_o} \cdot \frac{x_B - x_A}{\Gamma L}\right)^2 \tag{2}$$

with

$$F = \frac{(\alpha_m L)^2 + (\Delta\beta_{mo} L)^2}{1 - 2e^{-\alpha_m L}\cos(\Delta\beta_{mo} L) + e^{-2\alpha_m L}} \tag{3}$$

where λ_o is the optical wavelength in vacuum, $\gamma_o = 30.8 \times 10^{-12}$ m/V is the electro-optic coefficient of $LiNbO_3$, $L = 25$

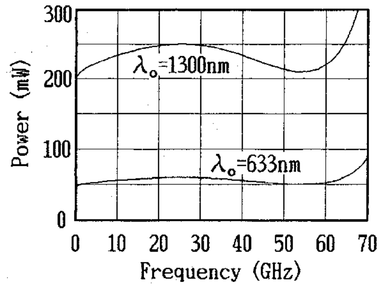

Fig. 8. Calculated microwave power to produce full amplitude modulation with $s = 46$ μm.

mm is the active length of the modulator and $x_B - x_A = 20$ μm is the distance between the corners B and A, in Fig. 2. The frequency dependence of the microwave parameters can be closely approximated as

$$\Delta\beta_{mo}(f) \approx \frac{2\pi f}{c}\Delta N(0)[1 - (f/f_0)^2], \quad (4)$$

$$\alpha_m(f) \approx \alpha_{mc}(f_0)\sqrt{f/f_0} + \alpha_{md}(f_0)f/f_0, \quad (5)$$

$$Z_c(f) \approx [Z_c(f_0) - Z_c(0)](f/f_0)^2 + Z_c(0) \quad (6)$$

where $f_0 = 50$ GHz and c is the velocity of lightwave in vacuum.

There are several ways of choosing s and the specific criterion depends on the application which the modulator will be designated for and on the frequency characteristics of both the microwave power source and launching circuitry. As shown in Fig. 8, the parameter s is optimized to give an equal-ripple characteristic over the frequency band from dc to 60 GHz, considering 633 nm and 1300 nm optical wavelengths. Based on such a criterion, at 633 nm, the modulator is expected to operate up to 64 GHz requiring not more than 60 mW of microwave power in the ridge CPW for 100% modulation.

V. Conclusion

The ridge CPW is a good solution for realizing a high efficiency Mach–Zhender configuration needed for an optical amplitude modulator. It is possible to preview a great future for this novel modulator in fiber optic systems employing millimeter wave subcarries in which wide bandwidth signals can be multiplexed. Experiments are under development to confirm the theoretical predictions.

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