Velocity-Matched $LiNbO_3$ Waveguide Optical Modulator Using Inverted Slot Line

Tsukasa Yoneyama, Keiichi Niinuma, and Seiji Kanno

Abstract—**An inverted slot line (ISL) was used to achieve velocity matching in a Ti-diffused $LiNbO_3$ waveguide optical modulator. Phase modulation of 1.38 radian could be observed at an optical wavelength of 0.63 μm with 100 mW microwave power around 10 GHz. This ISL optical modulator is expected to operate at millimeter wavelengths.**

I. Introduction

It is well known that efficiency and bandwidth of a traveling wave optical modulator are maximized if velocity matching between the modulated and modulating waves is attained. In early designs of electrooptic $LiNbO_3$ waveguide modulators, however, optical waves travel twice as fast as microwaves that are guided along planar electrodes. Various techniques for achieving velocity matching have been proposed so far [1]–[7].

An inverted slot line (ISL) that has been proposed by one of the authors [8], [9] is also useful for realizing velocity matching in traveling wave optical modulators. Though it is quite simple in structure, the ISL is able to increase the phase velocity of the modulating microwave up to the level necessary to attain excellent velocity matching. The ISL can be used at millimeter wavelengths without any difficulty.

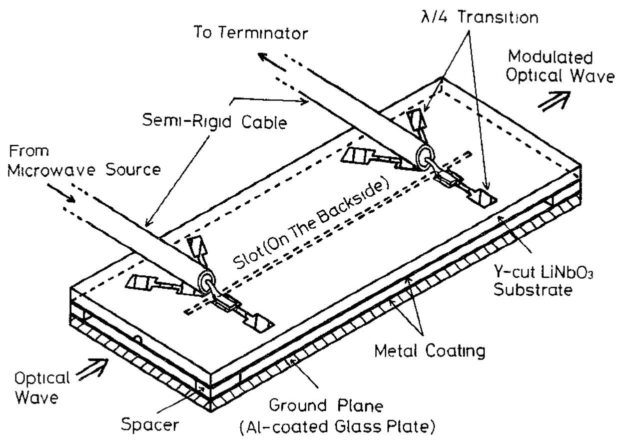
Based on such an ISL, velocity matching has been confirmed experimentally in a Ti-diffused $LiNbO_3$ waveguide optical modulator. Phase modulation of 1.38 radian could be obtained at an optical wavelength of 0.63 μm with 100 mW microwave power at 10 GHz. This is a promising result and the modulating power can be further reduced if parameters of the optical waveguide and the ISL are more precisely optimized.

II. Modulator Fabrication and Measurements

A. Inverted Slot Line

Fig. 1 shows a sketch of the ISL optical modulator in which the slot line is inverted to face the ground plane with small spacing. Since the electric field in the slot line is predominantly parallel to the ground plane, guided microwaves approach the below-cutoff state and hence the phase velocity increases rapidly as the spacing between the slotted surface and the ground plane decreases.

The ISL with a slot 50 μm in width was created by photolithography on an Al-coated $LiNbO_3$ substrate, 30 mm in length, 10 mm in width and 0.2 mm in thickness, the thickness of the Al coating being 1.5 μm. The effective refractive index was measured at 10 GHz and 50 GHz as a function of the spacing by probing VSWR along the ISL. The width of the slot was reduced to 20 μm for measurement at 50 GHz. The results of measurements are shown in Fig. 2. Since the optical refractive index of $LiNbO_3$ is 2.2, it can be seen that the spacing of 220 μm is adequate for velocity matching at 10 GHz, while the spacing of 22 μm is adequate at 50 GHz. Such spacing is by no means difficult to create even at millimeter wavelengths as well as for slots having a narrower width.



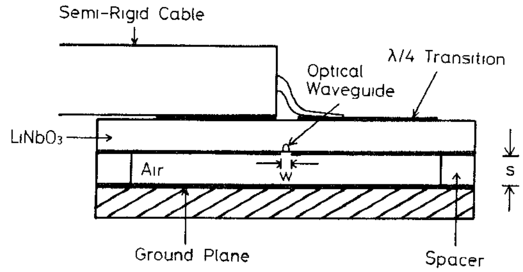


Fig. 1.

The measured transmission loss of the ISL with the optimum spacing of 220 μm is 1.4 dB/cm at 10 GHz. This is nearly the same as the transmission loss of the asymmetrical traveling-wave electrodes [6] and more than twice the transmission loss of an ordinary slot line which was measured to be 0.6 dB/cm at the same frequency. The increase of the transmission loss is obviously due to the close proximity of the ground plane.

The dispersion nature of the ISL was also investigated in

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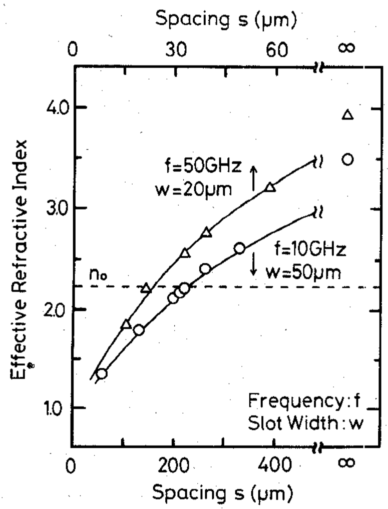


Fig. 2.

the frequency range from 7 GHz to 13 GHz. It was found that the effective refractive index of the ISL increases almost linearly with an increment of 0.1/GHz as frequency increases in the frequency range previously mentioned.

B. Launching of Microwaves

Microwaves are usually launched into the slot line by bringing a semirigid cable into contact with the slot line. In the case of the ISL, however, such direct contact is impractical because the slotted surface is too close to the ground plane and there is no room for inserting a semirigid cable.

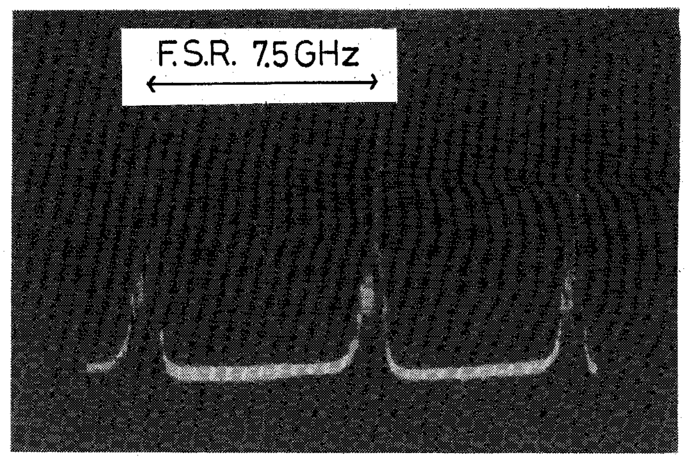
As a substitute, noncontact excitation was tried through a transition, namely, a pair of cascades consisting of high and low impedance $\lambda/4$ lines formed on the top-side of the substrate as shown in Fig. 1. The inner and outer conductors of the semirigid cable were connected to each element of the transition separately. Since the characteristic impedance of the ISL was estimated to be 16 ohms, a semirigid cable of low characteristic impedance (25 ohms) was used in the present experiment. A $\lambda/4$ length of the slot line has to be provided at each end for impedance matching. This reduces the interaction length of the modulator to 21 mm. The conversion loss of the transition was measured to be 0.9 dB at 10 GHz.

C. Optical Waveguide

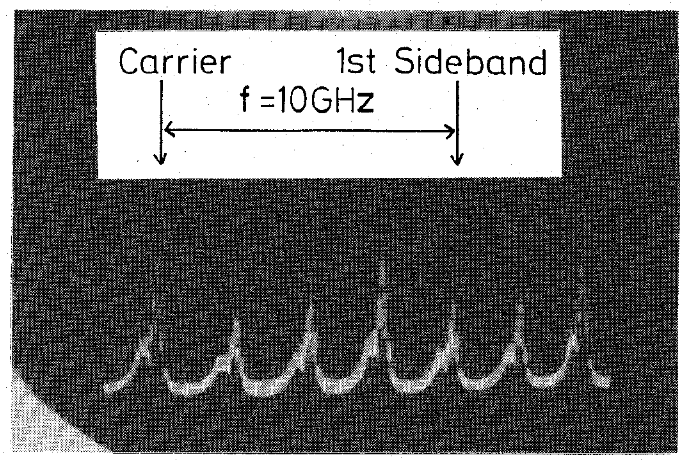
A Ti-diffused $LiNbO_3$ optical waveguide was fabricated by depositing a Ti layer 7 μm in width and 600 Å in thickness on a *Y*-cut $LiNO_3$ substrate and carrying out thermal diffusion of Ti at 1050°C for six hours. It was found that the fabricated waveguide could support three lateral modes at an optical wavelength of 0.63 μm. This may deteriorate modulator performance somewhat. No attempt was made to reduce transmission loss in the optical waveguide because emphasis was placed on observation of the modulation phenomenon.

D. Experimental Results

The output frequency spectra of the modulator were observed by using a scanning Fabry–Perot interferometer with a free spectrum range of 7.5 GHz, and are shown for unmodulated and modulated cases in Fig. 3. The modulated spectrum was obtained with drive power of 100 mW at 10 GHz. Fig. 4 shows frequency characteristics of the phase modulation depth for modulating power of 100 mW. Since measured values are scattered probably due to the multimode interference in the optical waveguide, the solid curve was fitted by the method of least squares. The modulation depth is 1.38 radian on the average. Data in Fig. 4 can also be interpreted to indicate that 53 mW microwave power is sufficient for 1 radian phase modulation at 10 GHz.



(a)



(b)
Fig. 3.

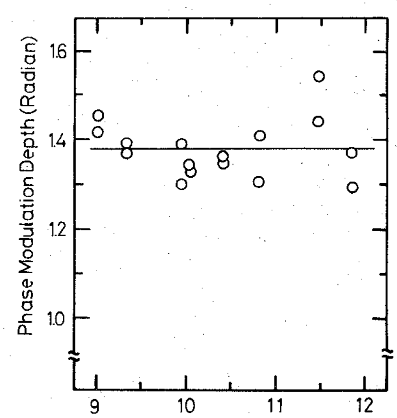


Fig. 4.

By using this value of microwave power for 1 rad. phase modulation, the figure of merit $P/\Delta f$ for the device is calculated to be 8.1 mW/GHz, which is large compared to the value of 1.5 mW/GHz reported elsewhere [1]. In the present case, $P/\Delta f$ is limited by the bandwidth of the transition (Δf = 6GHZ) rather than that of the optical modulator and hence it would be improved considerably with use of direct launching of microwaves into the device. Since measurements were carried out in the limited frequency range around 10 GHZ, another important parameter $V\pi$ could not be found at dc, but it was estimated to be 4.1 V at 10 GHz by taking into account the characteristic impedance of 16 ohms for the ISL.

A disadvantage of the ISL optical modulator is the low characteristic impedance of the microwave circuit. It is estimated that the drive power required for 1 radian phase modulation can be reduced to about 17 mW if the characteristic impedance of the ISL is 50 ohms. A relatively thick SiO_2 buffer layer (1.2 μm or more in thickness) may be effective for increasing the impedance as well as for decreasing the transmission loss of microwaves [4].

III. Conclusion

The ISL optical modulator is simple in structure, easy to fabricate, and is expected to exhibit high efficiency at microwave frequencies and presumably at millimeter wave frequencies. At present, an average phase modulation depth of 1.38 radian can be obtained with 100 mW microwave power at 10 GHz. Performance of the ISL optical modulator is expected to be further enhanced with narrowing of the slot width to more tightly confine the electric field and with use of a single mode optical waveguide. A technique for direct launching of microwaves remains to be developed.

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