Double-Stub Structure for Resonant-Type Optical Modulators Using 20-μm-Thick Electrode

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Abstract — We propose a resonant-type LiNbO₃ optical modulator with low halfwave voltage. We optimize the phase constant of the electric wave with thick electrodes to reduce the halfwave voltage. The halfwave voltage of the fabricated modulator with 20-μm-thick electrodes is 5.8 V at 10.6 GHz.

Index Terms — Electrode, halfwave voltage, LiNbO₃, optical modulator, resonance.

I. INTRODUCTION

OPTICAL MODULATORS using electric resonant structures will be essential components for band-operation systems such as radio-on-fiber systems [1]. The voltage on the modulating electrode can be enhanced by the resonance of transmission lines which increases the efficiency of the optical modulation even with a short electrode. It is important to set the feeding point of the modulating electrode near the node of the standing-wave voltage profile, because the peak voltage on the electrode is much higher than the voltage at the feeding point. However, the impedance of the electrode at the feeding point is so small that it is necessary to increase the impedance at the feeding point while keeping the feeding point close to the node of the standing wave. We propose the resonant-type modulator using a double-stub structure consisting of a modulating electrode and two stubs [2]. Enhanced voltage can be obtained due to the resonance of the modulating electrode and the stubs. In our previous work [2], we designed the optical modulators with high modulation efficiency per unit length of the electrodes. The fabricated optical modulators were compact in size and had high modulation efficiency but had high halfwave voltages. And Krähenbühl and Howerton proposed several resonant-type modulators [3]. Because they also focused the modulation efficiency, the halfwave voltages of their modulators were high, for example, the halfwave voltage of the reduced-length, short-ended type was 17 V. In this letter, we design resonant-type optical modulators with low halfwave voltages. By changing the thickness of the electrodes, the phase velocity of the electric standing wave on the electrode can be optimized to obtain an optical modulator with low halfwave voltage.
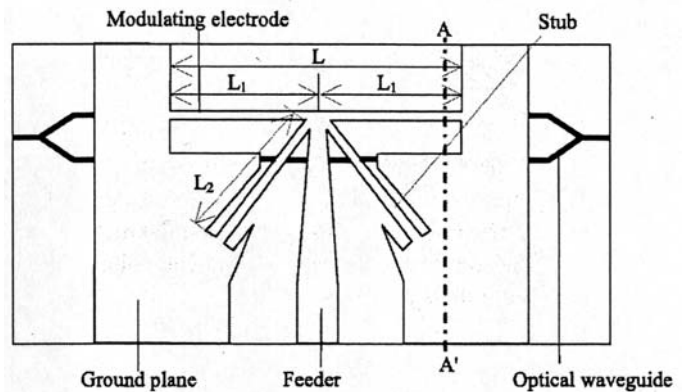
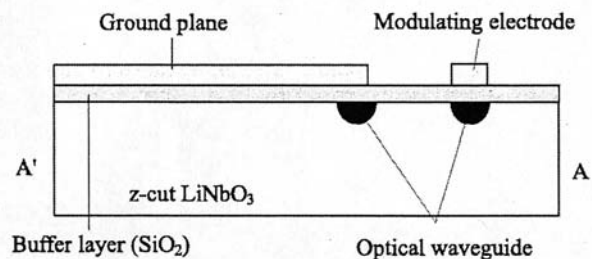Fig. 1.   Top view of optical modulator with double-stub structure.

Fig. 2.   Cross section of optical modulator with double-stub structure.

II. DEVICE STRUCTURE

As shown in Figs. 1 and 2, the optical modulator consists of a Mach-Zehnder-type optical waveguide, a feeder, a modulating electrode, and two stubs. The modulating electrode has two arms of the same length and is an asymmetric coplanar waveguide (ACPW). This configuration has several merits. Conductor loss is low and the electric field efficiency of the optical waveguide is high relative to a coplanar-waveguide (CPW) structure, thus providing higher modulation efficiency than that afforded by a CPW structure. A feeder, which is a CPW, is connected at the center of the modulating electrode. Two stubs, which are also CPWs of the same length are also connected at the junction of the modulating electrode and the feeder. We call this a double-stub structure. The equivalent circuit model is shown in Fig. 3. The total impedance is given by

$$Z_L = \frac{Z_{01} Z_{02} \tanh \gamma_1 L_1 \tanh \gamma_2 L_2}{2\left(Z_{01} \tanh \gamma_1 L_1 + Z_{02} \tanh \gamma_2 L_2\right)} \tag{1}$$

when the modulating electrode and the stubs are short-ended. L_i, γ_i, and Z_{0i} denote the lengths, the propagation constants,
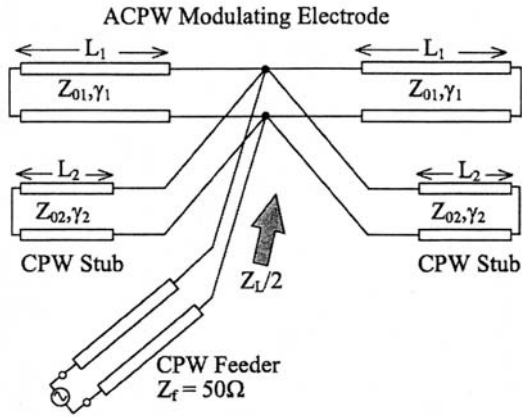
Fig. 3.   Equivalent circuit of double-stub structure.

and the characteristic impedances of the modulating electrode ($i = 1$), and the stub ($i = 2$), respectively. The voltage on the modulating electrode is given by

$$V(y,t) = \frac{2Z_L}{Z_L + Z_f} \frac{\sinh \gamma_1(L_1 - |y|)}{\sinh \gamma_1 L_1} V_{\text{in}} e^{j2\pi f(t-t_0)} \quad (2)$$

where $V_{\text{in}} e^{j2\pi f(t-t_0)}$ is the input voltage at the frequency f. Z_f is the characteristic impedance of the feeder. The induced phase at each optical waveguide is given by the sum of the phase shift due to the Pockels effect. Thus, the difference of the induced phases of two optical waveguides, which consists of the Mach-Zehnder structure, can be expressed by

$$\phi = \frac{\pi}{\lambda_0} n_0^3 r_{33} \frac{\Gamma}{s} L \Phi V_{\text{in}} \quad (3)$$

$$\Phi \equiv \frac{1}{V_{\text{in}} L} \int_{-L_1}^{L_1} V\left(y, \frac{y}{c} n_0 + t\right) dy \quad (4)$$

where c is the speed of light. λ_0 and n_0 are the wavelength and the refractive index of the lightwave, respectively. s is the gap between the ground plane and the hot electrode of the modulating electrode. $L \equiv 2L_1$ is the total length of the modulating electrodes. τ is the overlap integral between the field of the lightwave and the field induced by the electrode. The integral of the voltages on the electrodes defined by (4), $|\Phi|$, is called the normalized induced phase, and shows the modulation efficiency per unit length of the electrode. The halfwave voltage V_π of an optical modulator is given by $V_{\text{in}}\pi/|\phi|$.

III. Design and Experimental Results

We can reduce V_π by using long electrodes when the normalized induced phase can be kept the same as in the case of the short electrode. However, the normalized induced phase strongly depends on the length of the electrode and on the phase constants of the electric wave and lightwave. Generally, when the length of the modulating electrode is long, the electric wave at the modulating electrode is not in phase with the lightwave in the optical waveguide. Because we needed to match the phase constant of the electric wave with that of the lightwave, the
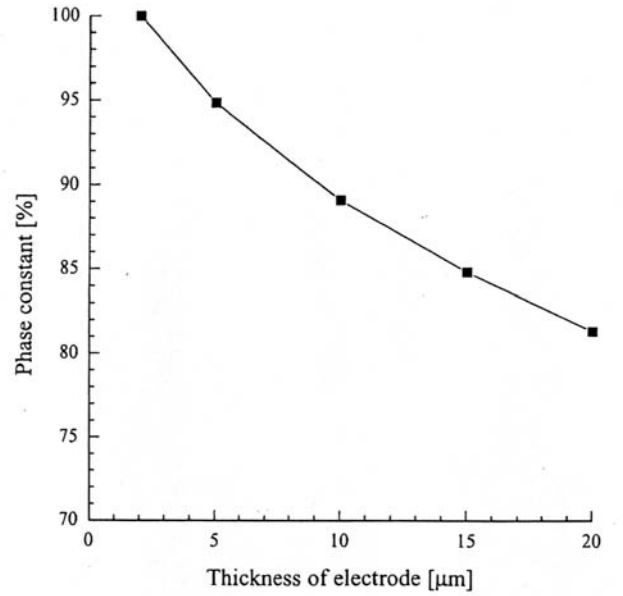

Fig. 4.   Phase constant as a function of electrode thickness. The values on the vertical axis are normalized by the phase constant when the thickness of the electrode is 2 μm. When the thickness is 2 μm, the phase constant is 735.2 rad/m.

thickness of the electrodes was changed to optimize the phase constants of the electric waves. We needed to accurately calculate the phase constants of the electric waves at the modulating electrodes. We considered the shape of the designed electrodes rectangles but the shape of the fabricated electrodes is not rectangular when the electrodes are thick. Deformation of the electrodes makes a difference between calculated phase constants and measured ones. We have confirmed that this influence is large when the thickness is larger than 20 μm, because we calculated the structures whose electrodes are smaller than 20 μm. The phase constants were calculated by using the finite element method, HP HFSS ver.5.4, as shown in Fig. 4. The following parameters were used for numeric calculations: $t_{\text{SiO}_2} = 0.55$ μm, $\varepsilon_{\text{SiO}_2} = 4.0$, $\varepsilon_{\text{LiNbO}_3[x]} = 43.0$, $\varepsilon_{\text{LiNbO}_3[z]} = 28.0$, and $\sigma_{\text{Au}} = 4.3 \times 10^7$ $(\Omega\text{m})^{-1}$. $\varepsilon_{\text{LiNbO}_3[x]}$ and $\varepsilon_{\text{LiNbO}_3[z]}$ denote permittivities of LiNbO$_3$ in x and z directions, respectively. t_{SiO_2} and $\varepsilon_{\text{SiO}_2}$ are the thickness and the permittivity of the buffer layer (SiO$_2$). σ_{Au} is the conductivity of the electrodes (Au). For each thickness of the electrodes, we calculated the minimum V_π at 10 GHz by optimizing the length of the electrodes, when the modulating electrodes are open-ended or short-ended. The results are shown in Table I. The parameter to obtain the minimum V_π is that the modulating electrode and the stubs are short-ended, the thickness is 20μm, $2L_1 = 29.624$ mm ($L_1 = 1.41\lambda_m$), and $L_2 = 1.370$ mm ($L_2 = 0.12\lambda_s$), where λ_m and λ_s are the wavelength on the modulating electrode and the stubs, respectively.

We measured the optical response of the fabricated modulator using an optical network analyzer for the 1.55-μm region. As a result, the maximum of the optical response, where the V_π is the minimum, is obtained at 10.6 GHz. Fig. 5 shows the experimental result of the halfwave voltage calculated from the optical response and the V_π measured at 10.6 GHz. The measured V_π is 5.8 V at 10.6 GHz, though the calculated V_π is 7.3 V at 10 GHz.

TABLE I
THE MINIMUM HALFWAVE VOLTAGES $V\pi$ AT 10 GHz ARE CALCULATED BY EQUIVALENT CIRCUIT MODEL. L_1 AND L_2 ARE THE LENGTH OF THE MODULATING ELECTRODE AND THE STUB, RESPECTIVELY. EACH CHARACTERISTIC PARAMETER OF THE ELECTRODES is CALCULATED BY THE FINITE-ELEMENT METHOD

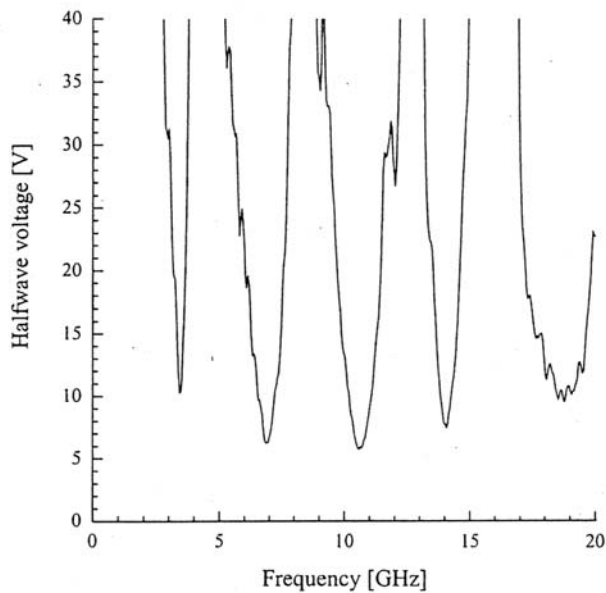| Thickness of electrode [μm]	Modulating electrode : Open-ended Stub : Short-ended			Modulating electrode : Short-ended Stub : Short-ended		
	L_1 [1/wavelength]	L_2 [1/wavelength]	$V\pi$ [V]	L_1 [1/wavelength]	L_2 [1/wavelength]	$V\pi$ [V]
2	0.68	0.09	13.8	0.92	0.10	10.9
5	1.18	0.10	12.0	0.92	0.10	9.8
10	1.17	0.10	10.1	1.42	0.11	9.0
15	1.16	0.11	9.0	1.41	0.12	7.9
20	1.16	0.11	8.4	1.41	0.12	7.3

Fig. 5. Measured halfwave voltage V_π as a function of radio-frequency. The minimum halfwave voltage of the fabricated modulator is 5.8 V at 10.6 GHz.

The frequency at which the minimum V_π Was obtained in the experiment was in agreement with the calculated one. The value of V_π in the experiment is slightly different from the calculated one because the overlap integral and the propagation constants in the calculation are different from the values of the fabricated structures.

IV. CONCLUSION

We have investigated a resonant-type optical modulator with low halfwave voltage. Long electrodes and phase matching are required to reduce the halfwave voltage. We have optimized the phase constants by changing the thickness of the electrodes. The minimum halfwave voltage of the fabricated modulator with a 20-μm-thick electrode is 5.8 V at 10.6 GHz, when the length of the modulating electrode is 29.624 mm.

REFERENCES

[1] C. Lim, A. Nirmalathas, D. Novak, and R. Waterhouse, "Optimization of baseband modulation scheme for millimeter-wave fiber-radio systems," *Electron. Lett.*, vol. 36, pp. 442−443,2000.
[2] T. Kawanishi, S. Oikawa, K. Higuma, Y. Matsuo, and M. Izutsu, "LiNbO$_3$ resonant-type optical modulator with double-stub structure," *Electron. Lett.*, vol. 37, no. 20, pp. 1244−1246, 2001.
[3] R. Krähenbühl and M. M. Howerton, "Investigations on short-path-length high-speed optical modulators in LiNbO$_3$ with resonant-type electrodes," *J. Lightwave Technol.*, vol. 19, pp. 1287−1297, Sept. 2001 .