Design and Performance of a Velocity-Matched Broadband Optical Modulator with Superconducting Electrodes

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***Abstract*—The performance of a $LiNbO_3$ optical modulator employing superconducting electrodes as a transmission line for a traveling-wave signal has been studied theoretically as well as experimentally. In the case of velocity matching between signal and optical waves using a shielding plane on top of a coplanar waveguide, numerical calculations of the attenuation constants of both superconducting and normal-conducting transmission lines indicate that the performance of the optical modulator can be far superior to that using normal-metals with respects to the figure of merit of bandwidth/driving-voltage. Microwave operation of a velocity-matched traveling-wave-type optical modulator with superconductor electrodes (NbN) has been successfully demonstrated. In the freqency range between dc and 26.5GHz it is shown that the obtained modulation depth is in good agreement with the theoretically expected one.**

I. Introduction

In the high-speed optical communications of 10 Gbit/s, external optical modulators using an electro-optic material $LiNbO_3$ (referred to as LN hereafter)[1-3] and those using semiconductor deveces[4] have already been put to practical use in Japan in place of the direct modulation of semiconductor lasers, owing to their low chirping and high-speed modulation characteristics. There have still been great needs for realizing larger bandwidths and smaller driving voltages for these optical modulators due to increasing demands for multimedia communications.

Among various optical modulators with $LiNbO_3$, an optical modulator with a transmission line for a traveling-wave signal (a traveling-wave type optical modulator) is widely used. The factors limiting the performance of this modulator are known to be i) phase-velocity difference between an optical wave and a signal wave (velocity mismatch), and ii) attenuation of a signal wave in the transmission line. The first problem has been solved by devising a novel electrode shape [2] or introducing a shielding plane and a buffer layer [3], [10]. In order to overcome the latter problem, we have proposed to introduce a superconducting electrode which has extremely low loss and low dispersion instead of a normal-conducting electrode: It has been shown theoretically [5] that the performance of the traveling-wave type optical modulator with a superconductor electrode is far superior to that with a normal-conductor electrode, and preliminary experiments in the case of velocity mismatch have been reported earlier [5]-[8].

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In this paper we have fabricated a superconducting shielding plane for velocity matching and studied the microwave characteristics of the velocity-matched traveling-wave type $LiNbO_3$ optical modulator with superconductor electrodes (NbN) in the frequency range between dc and 26.5GHz, and demonstrated the theoretical prediction.

II. Theoretical Performance

In this section we study the theoretical performance of the traveling-wave type Mach-Zehnder optical modulator as shown schematically in Fig.1. When we apply a modulation voltage

$$v(x,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} V(0,\omega)e^{-\gamma(\omega)x}e^{j\omega t}d\omega \qquad (1)$$

with

$$V(0,\omega) = \int_{-\infty}^{\infty} v(0,t)e^{-j\omega t}dt \qquad (2)$$

$$\gamma(\omega) = \alpha + j\beta \qquad (3)$$

the optical phase difference at the output end of the modulator, $\Delta\phi$, can be expressed as [9],

$$\Delta\phi(t) = \frac{\pi}{V_\pi}\frac{1}{2\pi}\int_{-\infty}^{\infty} V(0,\omega)F(\omega)e^{j\omega t}d\omega \qquad (4)$$

with

$$V_\pi = \frac{\lambda s}{2\Gamma N_0^3\gamma_{33}L} \qquad (5)$$

$$F(\omega) = \frac{1-e^{-\alpha L - j\theta}}{\alpha L + j\theta} \qquad (6)$$

$$\theta(\omega) = \frac{1}{c}(N_m - N_0)\omega L \qquad (7)$$

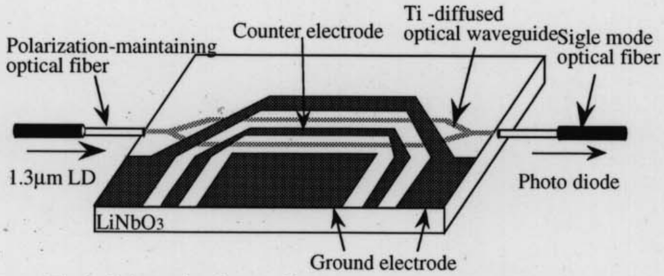

Fig.1 Schematic of a traveling-wave type optical modulator with Ti:$LiNbO_3$