Optical Modulator with Superconducting Resonant Electrodes for Subcarrier Optical Transmission

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ABSTRACT: We have studied a low voltage optical modulator employing high Tc superconducting resonant-type electrodes for use in the sub-carrier optical transmission system in which microwave signals are carried by intensity modulated lightwave. It is shown that microwave modulation of lightwave can be made efficient by using superconducting electrodes with high Q-factor. A preliminary experiment using $LiNbO_3$ (LN) optical modulator with $YBa_2Cu_3O_x$ (YBCO) electrode demonstrates dc and microwave modulation of the optical wave.

1. INTRODUCTION

In the conventional optical transmission system, which transmits digital data by optical pulses, optical modulators with extremely broad bandwidth are necessary to broaden its bandwidth of the base-band transmission system. Recently, sub-carrier transmission system in which microwave or millimeter wave signals are carried by intensity modulated lightwave has been intensively studied (Sueta and Izutsu 1990), (Dagli 1999). In this system, optical modulators are not required to have such broadband modulation characteristics. Resonant type optical modulators (Izutsu et al. 1988), (Yoshida et al. 1994) are suited as the devices because they can drive with high modulation efficiency at the expense of the narrowing the bandwidth.

We have been studied so far the application of the superconducting electrodes to travelling-wave-type LN optical modulators with broad bandwidth (Yoshida et al. 1997, 1999), and it has been demonstrated that the optical modulator with superconductors which have low loss and low dispersion is superior to that using normal-conductors. In this paper we have studied the resonant type LN optical modulator with high Tc superconducting electrodes. Theoretical performance of resonant type optical modulators is presented in Sec. 2. The design of resonant type optical modulators with impedance matching circuits is presented. YBCO thin films on MgO substrate were employed as the electrodes. In Sec. 3 we present a preliminary experiment on the optical modulator which was realized by flip-chip bonding of LN and MgO substrates.

2. THEORETICAL PERFORMANCES OF THE MODULATOR WITH SUPERCONDUCTING ELECTRODES

Figure 1 shows the schematic of a resonant type optical modulator, which has Mach-Zehnder type Titanium diffused optical waveguides on LN substrates. Input light is split into the two waveguides. The splitted lightwaves are phase modulated by the signal voltage at each waveguide, and they are added interferentially at the output end, giving rise to intensity modulated optical wave. Since resonant type optical modulators employ the standing-wave voltage singal, high efficient modulation can be obtained even at microwave or millimeter wave frequencies if we introduce a high Q resonance circuit composed of high Tc superconducting electrodes.

The electrode consists of a feeder line, a matching circuit, resonance circuits, and a dc bias line as shown in Fig. 2. In order to obtain high efficiency, the circuit is designed so as to satisfy the impedance matching condition. A stub line is added for impedance matching. The impedance of the feeder line is designed as 50Ω, but that of the resonance line is not 50Ω because the size of the coplanar waveguide (CPW) is determined by the shape of the Mach-Zehnder type optical waveguides. Therefore, by adding a stub with a proper length L_2, the input impedance can be adjusted to be 50Ω. When the width and the gap of the resonance line are 10µm and 15µm, respectively, the length of the impedance matching stub is adjusted to be 20µm in the case of Q=10000 at 1GHz. In this case the resonance frequency was 12.45GHz when impedance matching is satisfied for the resonance line of 2.5mm length. In the calculation, the loss of the resonance circuit was represented by the Q-factor which includes conductor, dielectric and radiation losses.

Figure 2 shows a pattern of an electrode, which was designed by CPW including the stub for impedance matching. The stub and resonance lines were terminated by the shorted end. In addition, the dc bias line was introduced to adjust the operating point.

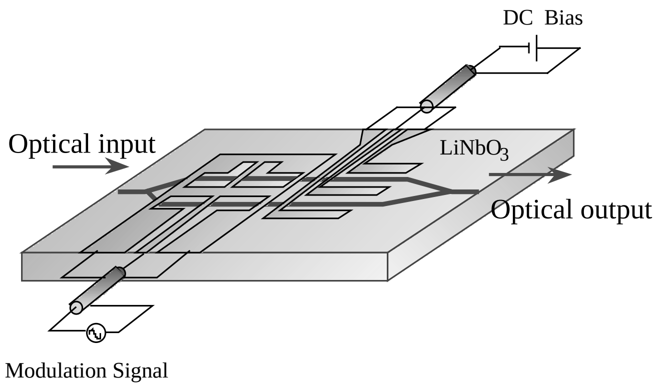

Fig. 1 Schematic of a resonant type optical modulator

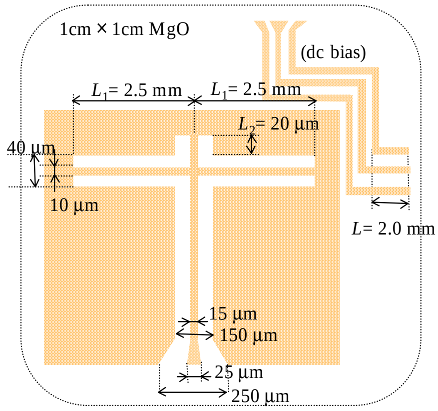

Fig. 2 A pattern of an electrode of a resonant type optical modulator by CPW transmission lines

The modulation depth of resonant type optical modulators is given by (Yoshida et al. 1994)

$$F(\omega) = T(\omega) \cdot \frac{\cosh\{\gamma(\omega) L_1\} - \cosh(\beta_0 L_1)}{(\gamma(\omega) L_1)^2 - (\beta_0 L_1)^2} \cdot \frac{\gamma(\omega) L_1}{\sinh\{\gamma(\omega) L_1\}} \qquad (1)$$

where $\gamma(\omega)$ is the propagation constant, and $T(\omega)$ is the ratio of the voltage of incident wave to that at the feeder point. When a stub is used as the matching circuit, $T(\omega)$ is given as

$$T(\omega) = \frac{2}{1 + y_1 + y_2} \qquad (2)$$

where y_1 and y_2 are the admittances of the resonant electrode and the stub, respectively, which are normalized by the characteristic admittance.

The frequency dependence of modulation depth was numerically obtained by changing Q-factors as free parameters. In the calculation, the best-suited stub lengths were used for impedance matching for a given Q-factor. Figure 3 shows the results of the calculation. It has become clear that modulation depth increases as Q-factor increases. It is also seen that the peak frequencies change with Q-factors, because the frequencies satisfying impedance matching condition are different for each Q.

Figure 4 shows that the relationship between Q-factor and the driving voltage which is defined by the amplitude of the applied ac voltage necessary for π radian phase shift of lightwave. This result indicates that the driving voltage can be decreased by employing high Q superconductor electrodes.

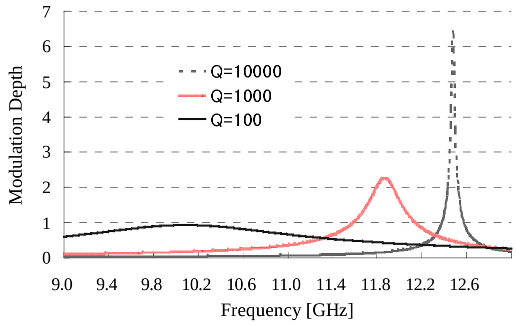

Fig. 3 Frequency dependence of modulation depth using stub circuit

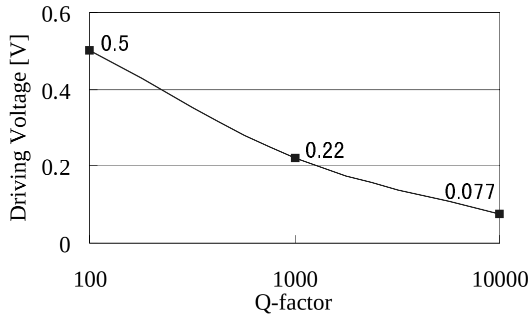

Fig. 4 Relationship between Q-factor and driving voltage

3. EXPERIMENTAL

In our previous studies (Yoshida et al. 1997, 1999), modulation experiments employing low Tc superconductors (Nb and NbN) for resonant type optical modulators were carried out. In the case of low Tc superconductors, the fabrication of a thin film electrode directly on an LN substrate was possible. In the present experiment, high Tc superconductor was fabricated on a MgO substrate. Subsequently, as shown in Fig. 5, the MgO substrate was glued by flip-chip bonding to the LN substrate in which optical waveguides are fabricated. The photo of the setup is shown in Fig. 6. Optical fibers were connected to both ends of the LN substrate. DC bias voltage and microwave signal were supplied to electrodes on the MgO substrate by micro probes, respectively. This module was installed into the cryostat. The modulator was then cooled down by a refrigerator. A block diagram of the measurement system is shown in Fig. 7.

From the dc modulation experiment, the threshold voltage was obtained. Using this value, the overlap integral (Γ) between optical and microwave fields (Izutsu 1988) are estimated as 0.21, which compares favorably with the result of numerical simulation: $\Gamma = 0.20$. This means that the electric field was effectively applied to optical waveguides even by the flip-chip bonding of LN and MgO substrates. Secondly, the return loss (S_{11}) of the feeder line was obtained at 26K as shown in Fig. 8. It is seen that the resonance frequency was 13.2GHz, and that impedance matching was also satisfied at this frequency.

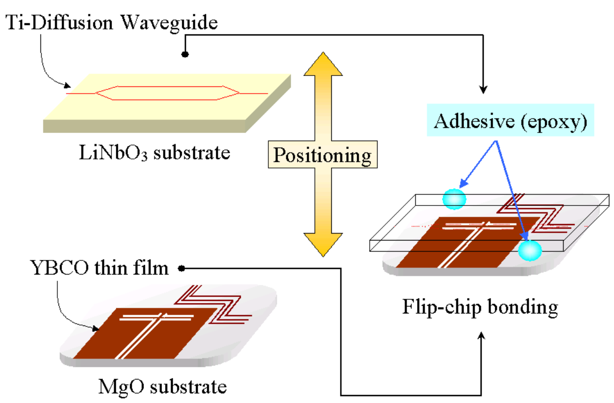

Fig. 5 Schematic of the flip-chip bonding of LN and MgO substrates

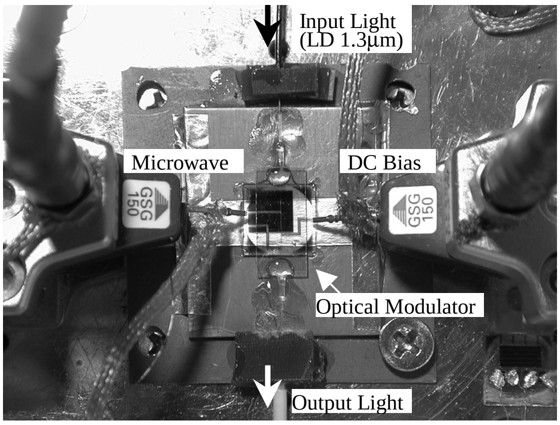

Fig. 6 Photo of the setup of the resonant type optical modulator

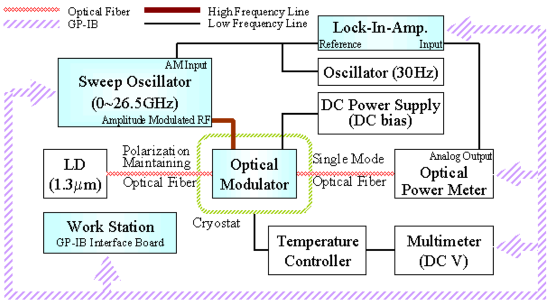

Fig.7 Experimental System

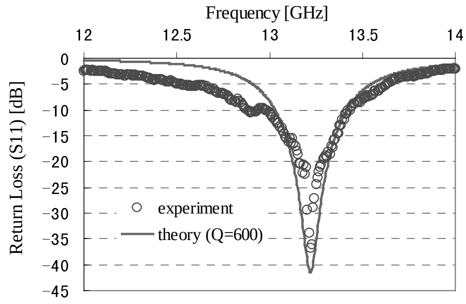

Fig. 8 Resonance characteristics at 26K

In Fig. 9 microwave modulation depth was obtained by the envelope detection method (Izutsu et al. 1988), whose measurement system is shown in Fig. 7. Modulation characteristic was successfully observed around 13GHz. This result shows that optical wave was modulated effectively by the microwave signal, which was supplied through high Tc superconducting electrode. Detailed studies are in progress.

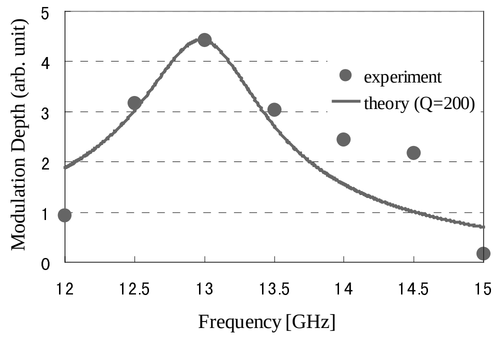

Fig.9 Modulation characteristics at 26K

4. CONCLUSION

The design and experiment of a resonant type optical modulator with high Tc superconducting electrodes was presented. The impedance matching of the electrode was realized by using a stub line. It is shown by numerical calculation that the modulation efficiency increases when high Q superconductors are used as the electrodes. The experimental optical modulator was realized by a flip-chip bonding of LN and MgO substrates. Based on the design and calculation, modulation experiments were carried out at low temperatures. It was demonstrated that the optical modulator with high Tc superconducting electrode by the flip-chip bonding method operated effectively.

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