LETTER

Electro-Optic Sampling Measurement of the Electric Field Distribution on a Resonant Electrode for a Band-Operation Optical Modulator

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SUMMARY By using electro-optic sampling technique, the electric field distribution on a resonant electrode for optical modulation was measured with a resolution in the micrometer range, while the range of measurement area was a few millimeters. The electric field on the asymmetric resonant, electrode is enhanced by series and parallel resonance at thc electrode. The resonance frequency was shifted by the presence of the electro-optic crystal, which was placed on the electrode for use in the sampling technique. We also showed that the measured electric field distribution at the edge of the electrode was different from the results numerically obtained by an equivalent circuit model.

key words: *electro-optic sampling, electric field distribution, frequency response, resonant state, asymmetric resonant electrode*

1. Introduction

Resonant-type optical modulators have attracted attention in micro/millimeter-wave radio-on-fiber communication systems because effective modulation can be obtained by using resonance on the electrodes of such modulators [1],[2]. Recently, we have proposcd the asymmetric resonant structure consisting of a short-ended electrode arm and an open-ended electrode arm [3],[4]. An optimized electrode structure can be obtained by using an equivalent circuit model. The enhancement factor due to thc resonance was 4.94. The actual resonancc frequency of a fabricatcd device that had a designed resonance frequency of 10GHz was 6.2GHz. This is due to imperfections of the circuit model. To improve the resonant structure, it is. necessary to directly measure the electric field distribution on the electrode. This result can then be fed-back to the design of thc electrode structure. By the electro-optic (EO) sampling technique, we can detect the electric field of a high-frequency signa1 at up to approximately 100 GHz without requiring that a metal probe be attached to the electrode [5]-[8]. Thus the deformation due to the electric field measurement is small enough for the technique to be applied on high-speed devices whose sizes are a few micrometers.

In this letter, we measured the electric field distribution on the asymmetric resonant electrode by using the EO sampling technique. A crystal having the EO effect is placed on the electrode of the rcsonant structure; this allows us to obtain the amplitude and phase of the electric field by measuring the polarization of lightwaves reflected from the bottom face of the EO crystal [5]-[8]. However since the resonance is sensitive to changes in the erectrode structure, the deformation due to the EO crystal is not negligible in the electric field measurement on the resonant structure. We measured the frequency response of the electric field by sweeping the repetition frequency of the pulse laser source which illuminates the EO crystal. The shift of the resonance frequency due to the EO crystal was shown by comparing with the results of the conventiona1 measurement: the electric reflectivity of the resonant electrode and the optical response of the modulator. The width of the resonant electrode is small in the micrometer range, while its length is a few millimeters, so that the resolution should be very high with respect to the area of the measurement. The EO crystal we used in obtaining the map of the elec:tric fleld has an area of 1.5 mm^2; the area under measurement was thus larger than the crystal. The EO sampling system we used includes an optical microscope lens for the illumination of and detection of signals from very small areas. It was shown that the measured electric field distribution at the edge of the electrode was different from the results calculated by the equivalent circuit model for the asymmetric resonant structure .

2. Experimental Setup

Figure 1 shows the experimental setup. The optical pulses have a pulsewidth of approximately 2ps and are generated in an active mode-locked fiber laser. The optical pulse is divided into two optical pulses using an optical coupler. One is provided to the EO sampling prober, and the other is fed a high-speed photo-detector for reference signal generation. The harmonic compo-

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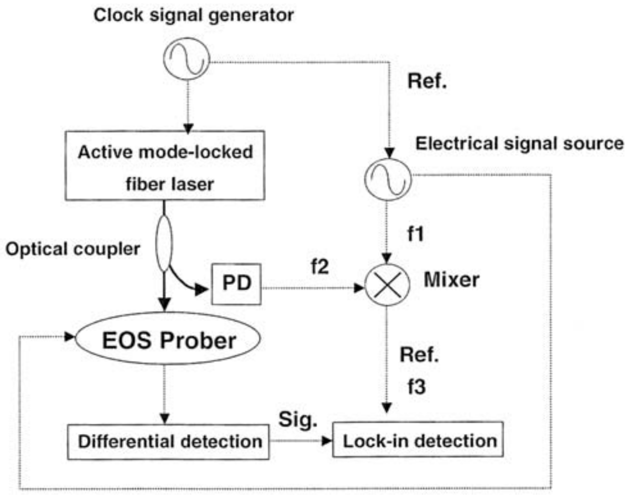

Fig. 1 Experimental setup.

nents of measured repetition frequency of the optica1 pulse should be synchronized with an electrical signal from an electrical signal source. The reference signa1 is generated by harmonic mixing method between one of the harmonic components and the electrical signal. The reference signal frequency f_3 is set in relational equation a.s

$$f_1 = n \times f_2 + f_3 \quad (n = 1, 2, 3, \cdots),$$

where f_1 is the electrical signa1 frequency and f_2 is the measured repetition froduency of the optica1 pulse and n is the harmonic number of the measured repetition frequency of the optical pulse. In this experiment, the reference signal frequency f_3 was set to 60kHz. The fundamenta1 frequency of the active mode-locked fiber laser is approximately 3.4MHz. If the repetition frequency of the optical pulse is swept down in 3.4MHz intervals, the electrica1 signal can be synchronized with the nth harmonic component of the measured repetition frequcncy in 3.4×n MHz intervals. Because the 7th harmonic of the measured repetition frequency of the optica1 pulse was used in this experiment, the operating frequency interval of the electrical signal source was 23.8MHz. In the synchronization, the average power of the electrical signals was constant. In the EO sampling prober, to measure the EO signa1 obtained from a small change of the polarization state of the optical pulse two methods both of differentia1 detection and lock-in detection are used together.

Figure 2 shows a configuration of thc EO crystal on the electrode for longitudina1-field (E_z) probing. we used the EO crystal of CdTe, which has sensitivity for longitudinal-field. The sizes of length and width and height of the EO crystal placed on the asymmetric resonant electrode are 1.5 mm and 1 mm and 0.1 mm, respectively. The bottom face of the EO crystal is coated with dielectric mirror and an antireflective coating is applied to its opposite face to avoid undesirable reflec-

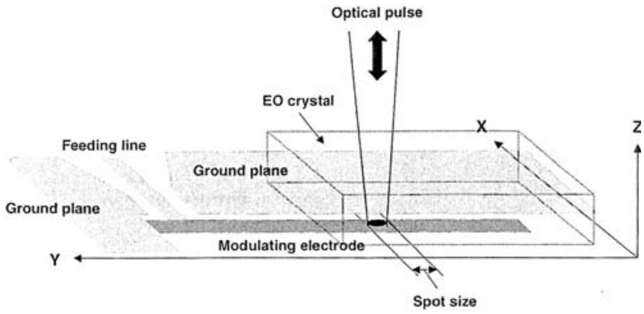

Fig. 2 Configuration of the EO crystal on the electrode.

tion. In this experiment, the optical pulse was focused on the bottom of the EO crysta1 with a spot size of approximately 50 μm by using an optical microscope lens. Although the EO crystal was moved several times in measuring the electric field distribution of a few millimeters size, the measured EO signa1 data was continuous on the boundary.

3. Results and Discussion

Figure 3 and Fig.4 show the experimental setup for measuring optical response and the frequency response sfor the asymmetric resonant electrode, respectively. In Fig.4, the dotted line is the optical response as obtained by using an electric RF-network analyzer and a photo-detector. The circles show the intensity of the electric field at the peak of the distribution on the electrode as obtained by EO sampling. The resonance frequency was 6.17 GHz. The characteristics are in good agreement with each other, except in term of the resonance frequcncy. In the EO sampling technique, to reduce the effect of the EO crystal on the asymmetric resonant electrode, we used thc EO crystal with a very small dielectric constant ε. Since the shift was still non-negligible, the difference between the resonance frequencies in the two frequency responses was measured. The resonance frequency as measured by EO sampling technique was 5.74 GHz, so the presence of the EO crystal has shifted thc resonance frequency by 430MHz. This shift in the resonance frequency is an important consideration in application of EO sampling technique. In the measurement of electric field distribution on the asymmetric resonant electrode the resonance frequency of 5 .74 GHz obtained from the frequency response using EO sampling technique was used.

In Figs.5(a) and (b) show the structure of the asymmetric resonant electrode and the measured electric field distribution on the electrode, respectively. The coordinate system is defined in Fig.5(a). The distribution is of electric field intensity in the Z direction and is normalized by the intensity of the feeding point. The electrode, with its asymmetric structure, acts as a resonant transmission line. It has two arm,s

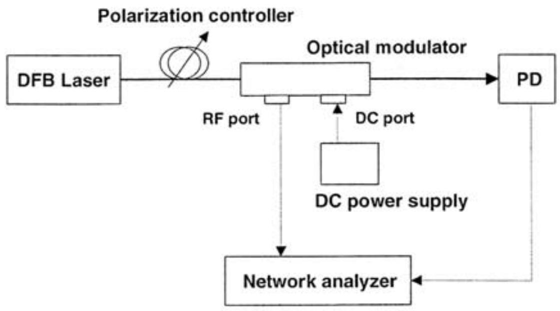

Fig. 3 Experimental setup for measuring optical response.

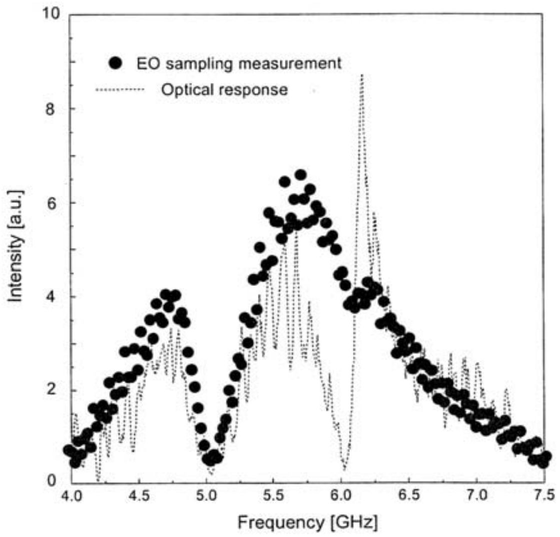

Fig. 4 Frequency response of the asymmetric resonant electrode.

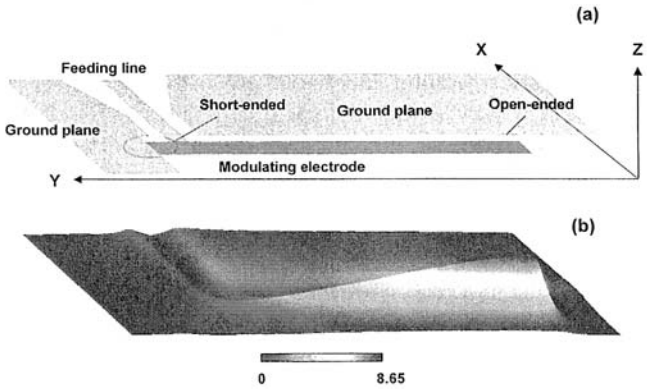

Fig. 5 (a) The asymmetric resonant structure. (b) The electric field distribution formed on the electrode structure. The frequency of the electric field is 5.74 GHz.

where one is short-ended and the other is open-ended. The electric field on the electrode is enhanced by series and parallel resonance at the electrode, and the structure of the asymmetric resonant electrode is excellent to the normalized induced phase for an optical modulating operation [3], [4]. The short-ended and open-ended arm lengths are 211 μm and 1550 μm, respectively. The

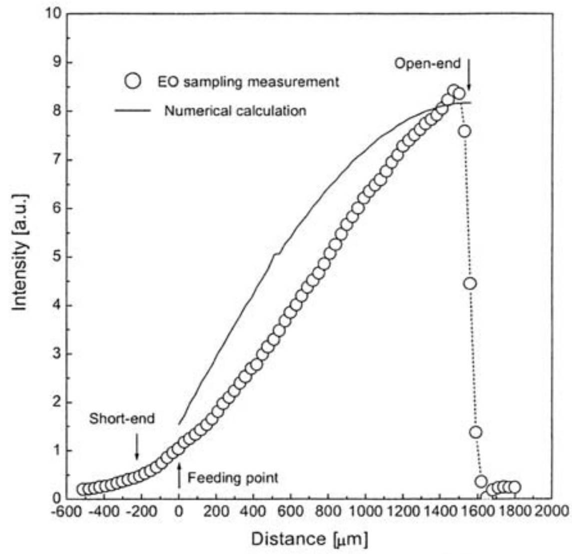

Fig. 6 A Comparison between the electric field distributions on the asymmetric resonant electrode as obtained by EO sampling technique and by numerical calculation using the equivalent circuit model.

modulating electrode width is 50 μm. The width of the gap between the ground plane and the modulating electrode is 27μm. As is shown in Fig.5(a), the modulating electrode structure is asymmetric with respect to the feeding line, while the feeding line, consisting of a coplanar waveguide, has a symmetric structure. Thus, the electric field distribution was asymmetric near the feeding point.

Figure 6 gives a comparative view of the electric field distributions on the asymmetric resonant electrode as measured by EO sampling technique and as numerically calculated by using the equivalent circuit model [3],[4] . Although the distributions have a common characteristic of convexity along the electrode is the same, the profiles of electric field are not the same. The minimum and maximum intensity of the calculated electric field are at the short-end and open-end, respectively. In the result for EO sampling technique, however, the position of the minimum electric field intensity is approximately 300 μm away from the short-end in the Y direction and the position of the maximum electric field intensity is approximately 90μm away from the open-end in the Y direction. The measured electric field distribution at the edge of the electrode is different from the results numerically calculated by the equivalent circuit model for the asymmetric resonant structure. This difference between thc actual and numerically calculated resonant states on the electrode as a resonant transmission line is important. We can say that the difference of the resonant state is one of the factors for the imperfection of thc circuit model.

4. Conclusions

By using the EO sampling technique, the electric field distribution on the asymmetric resonant electrode was measured with a resolution in the micrometer range. The presence of the EO crysta1, which we used in the sampling technique, shifted the resonance frequency of the asymmetric resonant electrode. The frequency response as obtained by EO sampling technique is good agreement with the optical response, except in terms of the resonance frequency. This shift in the resonance frequency is an important factor in applying EO sampling technique. We also showed for the asymmetric resonant electrode, that the measured electric field distribution at the edges of the electrode was different from the results that are numerically obtained by an equivalent circuit model. Difference between the actual resonant state and the numerically calculated resonant state on the electrode as a resonant transmission line was clearly shown.

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