Highly Sensitive Electric Field Sensor Using LiNbO_3 Optical Modulator

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LETTER

Highly Sensitive Electric Field Sensor Using $LiNbO_3$ Optical Modulator

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SUMMARY This letter describes a highly sensitive broad-band electric field sensor that uses a $LiNbO_3$ optical modulator. A broad-band, low driving-power optical modulator and high-power optical source are used to achieve high sensitivity. The minimum detection level of 1 mV/m and band-width of 1 GHz are obtained.

1. Introduction

Recent progress in electromagnetic compatibility (EMC) has created a need for a small wide-band electric-field sensor to measure electromagnetic pulses and the properties of EMC test facilities. One problem for such a sensor is that metal parts, such as coaxial cables, disturb the electric field distribution.

Photonic linking systems which use Pockels-cell such as $LiNbO_3$ have been developed for use as electric field sensors, and a 1 GHz bandwidth sensor has been reported[(1)-(4)]. However, the sensitivity of the sensor is only about 1 V/m, and must be improved before it can be used for EMC study.

This paper proposes a highly sensitive broad-band electric field sensor that employs a $LiNbO_3$ optical modulator. A broad-band, low driving-power optical modulator and high-power optical source are used to achieve high sensitivity.

2. Sensor Structure

The structure of the electric field sensor is shown in Fig. 1. Two metal rods are alined with a small gap in which an optical modulator is located. When an electric field is applied to the metal elements, a voltage is induced across the gap by electromagnetic induction. The optical modulator converts the voltage to an optical signal, whose level is measured by a photodetector to obtain the electric field strength.

When the metallic rods are much shorter than the electric wavelength, the electric field sensor shown in Fig. 1 is represented by the equivalent circuit shown in Fig. 2. In Fig. 2, C_m is the input impedance of the optical modulator, and C_a is the driving point impedance of the dipole element formed by the two metal rods. C_a has mainly a capacitive factor[(5)], and C_m also has a capacitive factor because the terminal of the optical modulator is usually insulated. The voltage applied on the optical modulator V is given by

$$V = C_a Eh / (C_a + C_m), \quad (1)$$

where h is the dipole element length, and E is the electric field strength.

When a Mach-Zehnder optical modulator is used, the relation between the applied voltage on the optical modulator V and the output voltage at the photodetector V_r is given by[(6)]

$$V_r = P_{in} * CF/2 * (1 + \cos \pi (V/V_\pi)), \quad (2)$$

where P_{in} is the optical input power at the modulator, CF is a conversion factor which includes the efficiency

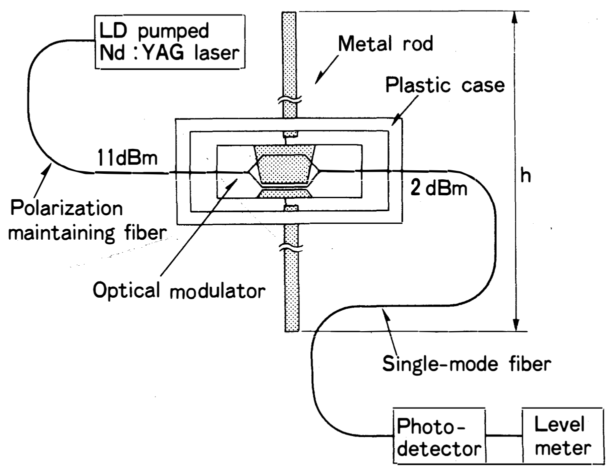

Fig. 1 Structure of the electric field sensor using $LiNbO_3$ optical modulator.

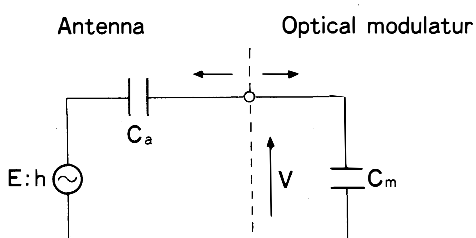

Fig. 2 Equivalent circuit of the electric field sensor.

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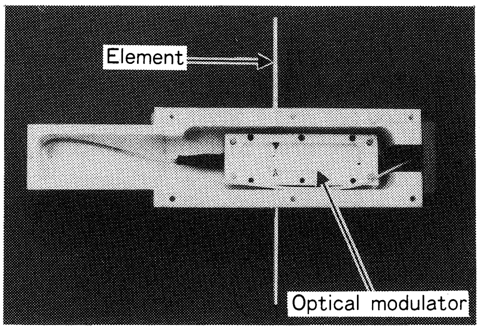

Fig. 3 External view of the electric field sensor.

of the photodetector, insertion loss of the optical modulator and the optical fiber loss, and V_π is the half-wave voltage.

Substituting Eq. (1) into Eq. (2), the relation between electric field strength and sensor output voltage is given by

$$V_r = P_{in}{*}CF/2{*}(1+\cos\pi(1/V_\pi) \cdot (C_a/(C_a+C_m))Eh). \quad (3)$$

Equation (3) shows that powerful optical source and low half-wave voltage optical modulator are needed to get high sensitivity. Therefore, a broad-band, low driving-power optical modulator whose half-wave voltage was about 4 V was used[(6)]. This modulator was a Mach-Zehnder interferometer formed from a 7 μm by 0.7 μm waveguide on a 10 mm by 40 mm Z-cut $LiNbO_3$ substrate. The electrode length and gap width were 27 mm and 15 μm, respectively. A laser-diode pumped Nd : YAG laser whose output power was 25 mW was used as a light source.

An external view of the sensor is shown in Fig. 3. The sensor was made of nonmetallic materials except for the elements and electrodes so as to minimize the electric field disturbance. Elements that were 50 mm long and 4 mm diameter were connected to each electrode of the optical modulator, so the overall length of the dipole element was 140 mm including the width of the modulator.

A 30 m polarization maintaining fiber connected the sensor to the optical source, and a 30 m single-mode fiber connected the sensor to the photodetector.

A Ge avalanche photodiode served as the detector. It was operated by a constant voltage drive so as not to saturate the output voltage with high optical input power. The input optical power of the modulator was 11 dBm, and the input optical power of the photodetector was 2 dBm.

3. Experimental Results and Discussion

The frequency response and sensitivity of the sensor were measured under a controlled electromagnetic field from 100 Hz to 1 GHz. The fields were

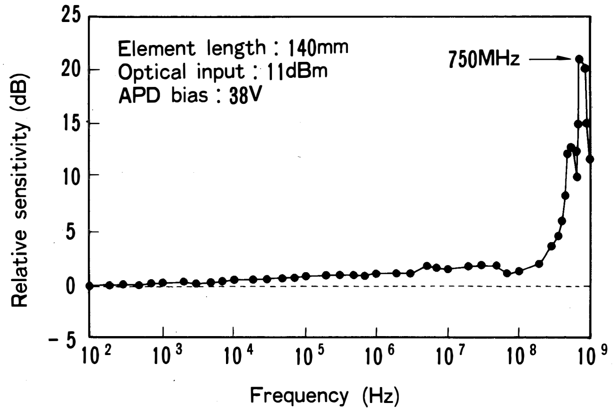

Fig. 4 Frequency response of the electric field sensor.

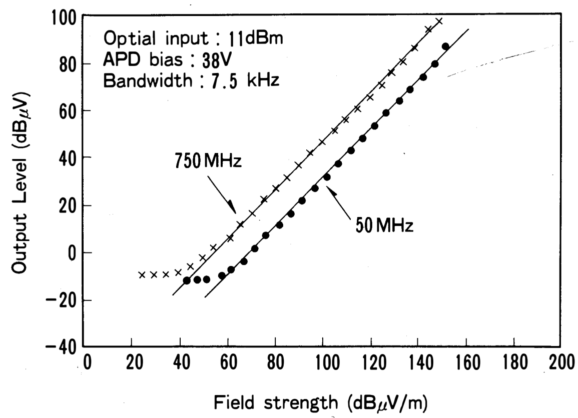

Fig. 5 Linearity of the sensitivity of the electric field sensor.

generated by a 900 mm by 300 mm by 300 mm transverse electromagnetic (TEM) cell.

The frequency response of the sensor is shown in Fig. 4. The relation between the photodetector output voltage and the TEM cell output voltage was measured with a network analyzer. The field strength was calculated from the TEM cell output voltage. The relative sensitivity A_{rf} is defined by

$$A_{rf}(\mathrm{dB}) = (E(\mathrm{dB}(\mu\mathrm{V/m})) - Vr(\mathrm{dB}(\mu\mathrm{V}))) - A_{f100}(\mathrm{dB}), \quad (5)$$

where A_{f100} is the sensitivity $(E - Vr)$ at 100 Hz. As shown in Fig. 4, the frequency response was almost flat from 100 Hz to 300 MHz. Using this property, it is possible to measur electromagnetic pulses. The sensitivity rolled up above 300 MHz, and maximum sensitivity was obtained at about 750 MHz. The reason was probably that the driving point impedance of the dipole element was decreased at that frequency by element resonance.

The linearity of the sensitivity of the sensor is shown in Fig. 5. The output voltage of the photodetector was measured with a level meter at 50 MHz and 750 MHz. The frequency of 50 MHz corresponds to a flat part of the frequency response and the frequency of 750 MHz corresponds to the maximum sensitivity of the sensor. The bandwidth of the level meter was set to 7.5 kHz. As shown in Fig. 5, the sensor exhibited ideal linear response from 60 dB(μV/m) up to 150 dB(μV/m), and a dynamic range of up to 90 dB. From Fig. 5, the relation between output voltage and electric field strength is represented by

$$V_r(\text{dB}(\mu\text{V})) = E(\text{dB}(\mu\text{V/m})) - A_f(\text{dB}), \quad (6)$$

where A_f is a transfer coefficient[7]. The values of 71 dB at 50 MHz and 53 dB at 750 MHz were obtained from the figure. Since the noise level of the photodetector was −10 dBuV, the minimum detection level of the sensor was 61 dB(μV/m) (about 1 mV/m) at 50 MHz and 43 dB(μV/m) (about 0.14 mV/m) at 750 MHz. The sensitivity of traditional sensors using bulk crystal was 1 V/m (120 dB(μV/m)), so the sensitivity of this new sensor was improved by about 60 dB.

4. Conclusion

The sensitivity of the electric field sensor was improved by using a low driving-power optical modulator and a high-power optical source. The frequency response of the sensor was almost flat from 100 Hz to 300 MHz. The minimum detection level was 1 mV/m at 50 MHz and 0.14 mV/m at 750 MHz.

This sensor can be used to measure electromagnetic pulses and the properties of EMC test facilities.

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