DEVELOPMENT OF WIDE-BAND AND HIGHLY SENSITIVE ELECTRIC FIELD SENSOR USING $LiNbO_3$ OPTICAL MODULATOR

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Abstract

A Mach-Zehnder interferometer whose half-wave voltage is about 4V and a YAG laser pumped by a laser diode whose output power is 25mW are used to improve the sensitivity of a $LiNbO_3$ electromagnetic field sensor. The resulting frequency response is almost flat from 100Hz to 300MHz and the minimum detectable electric field strength is 1mV/m at 50MHz and 0.14mV/m at 750MHz. The frequency response of the sensor is analyzed using the moment method, and the calculated results agree with the measured results. The improved sensor can measure an electromagnetic impulse whose peak value is larger than 10V/m and width is wider than 5ns.

1. Introduction

Recent progress in Electromagnetic Compatibility (EMC) has created a need for a small wide-band electric field sensor for application to the electromagnetic interference (EMI) testing and design of information technology equipment as well as the testing of EMI measurement facilities and the measurement of the electromagnetic pulses. A serious problem for such sensors is the influence of the coaxial cable which connects the sensor to the level meter. A sensor which uses a resistive line or optical fiber in place of the coaxial cable has been developed to solve the problem.

The sensor which uses a resistive line detects an electric field by means of a diode inserted between dipole elements and transmits the detected a DC level to voltmeter over the resistive line. The sensor is so stable that it is developed for use as a standard electric field sensor[1],[2]. However, it has the fundamental problem that it cannot measure frequency and phase information.

Therefore, sensors using optical fiber have been developed. These sensors can be classified to two types: sensors which convert an electric-field strength to an optical signal by means of a laser diode or a light emitting diode[3], and those which convert an electric field strength to an optical signal by means of an optical modulator using electro-optical crystals such as $LiNbO_3$, $LiTaO_3$[4],[5],[6].

The sensor which uses electro-optical crystals has the following superior points: Influence on electromagnetic fields is reduced because most of the sensor materials are nonmetallic, the operating time of the sensor is not limited, and the operating frequency bandwidth is very wide. However, the sensitivity of the sensor should be improved because the minimum detection level is only about 0.01V/m, and the frequency response of the sensor has not been cleared.

This paper presents a highly sensitive wide-band electric field sensor, whose sensitivity is improved by a low driving voltage optical modulator and a high power light source. The measured and calculated sensor characteristics are also described.

2. Configuration

The configuration of the sensor is illustrated in Fig.1. Two metal rods are aligned and separated by a small gap, in which an optical modulator is located. When an electric field applied to the metal rods, 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 the photodetector to obtain the electric field strength.

The external view of the sensor is shown in Fig.2. The sensor is made of nonmetallic materials so as to minimize the disturbance to the electric field. Metal-rod elements that are 50mm long and 4mm in diameter are connected to each electrode of the optical modulator, so the overall length of the elements is 140mm, including the width of the modulator.

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

A Ge avalanche photo-diode (APD) is used as the detector. It is operated by a constant voltage drive so as not to saturate the output voltage with high optical input power. The APD operation level is 38V DC. The input optical power of the modulator is 11dBm, and the input optical power of the photodetector is 2dBm. However, since the polarization is tuned for the maximum sensitivity, the input power is about -6dBm in actual measurement conditions.

3. Improvement of sensitivity

The electric field sensor in Fig.1 is represented by the equivalent circuit in Fig.3, where C_m is the input impedance of the optical modulator, Z_a is the driving point impedance of the dipole element formed by the pair of metal rods[7], h_e is the effective length of the dipole element[7] and L_m is an inductance caused by the contact lead between the metal rods and the electrode of the modulator. The input impedance C_m is usually represented by a capacitance because the terminal of the optical modulator is insulated. Using this equivalent circuit, the voltage impressed on the optical modulator V_c is given by

$$V_c = E*h_e/(1+ \omega C_m(jZ_a - \omega L_m)), \qquad (1)$$

where, E is the electric field strength and ω is angular frequency.

When a Mach-Zehnder optical modulator is used, the relation between the impressed voltage of the optical modulator and the output voltage at the photodetector V_r is given by[8]

$$V_r = C_F*P_{in}*(1+ \cos(\pi V_c/V_\pi))/2, \qquad (2)$$

where P_{in} is the optical input power of the modulator, C_F is a conversion factor which includes the efficiency of the photodetector, insertion loss of the optical modulator and optical fiber loss, and V_π is the half-wave voltage of the optical modulator.

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

$$V_r=C_F*P_{in}*(1+\cos(\pi *(E*h_e/(1 + \omega C_m(jZ_a-\omega L_m)))/V_\pi)/2 \qquad (3)$$

Equation (3) shows that a powerful optical source and low half-wave voltage optical modulator effectively improve sensitivity. Therefore, a wide-band and low driving-power optical modulator whose half-wave voltage is about 4V is used[8]. This modulator is a Mach-Zehnder interferometer formed from a 7um by 0.7μm waveguide on a 10mm by 40mm Z-cut $LiNbO_3$ plate. The electrode length is 27mm and the gap width is 15μm. A Nd:YAG laser pumped by a laser diode whose output power is 25mW is used as a light source. An 11mW optical input power of a modulator is obtained.

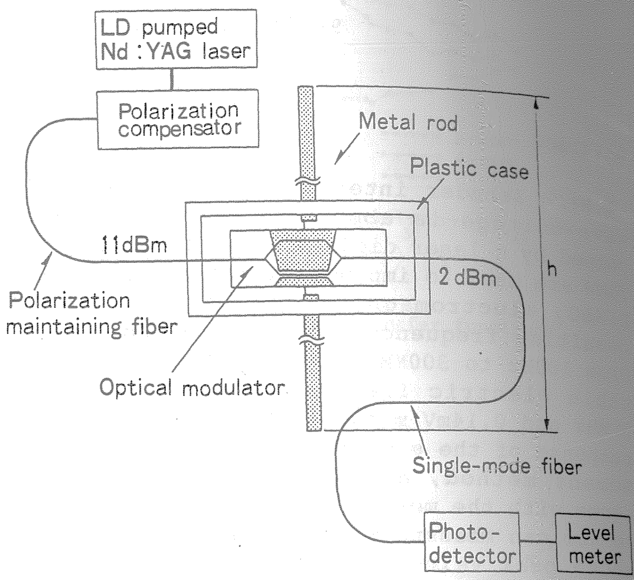

Fig.1 Configuration of electric field sensor.

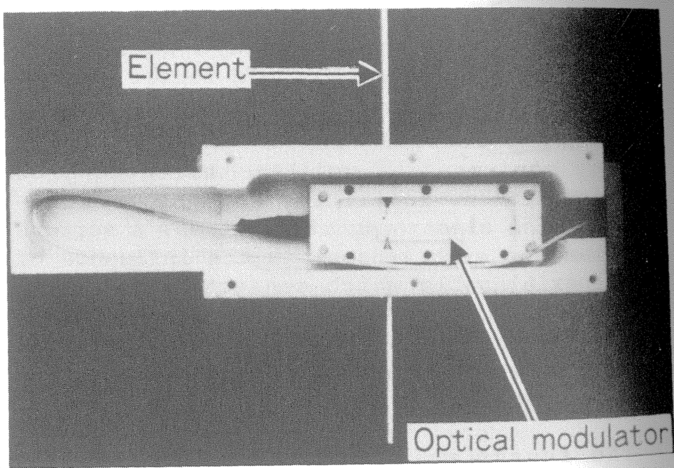

Fig.2 External view of the sensor.

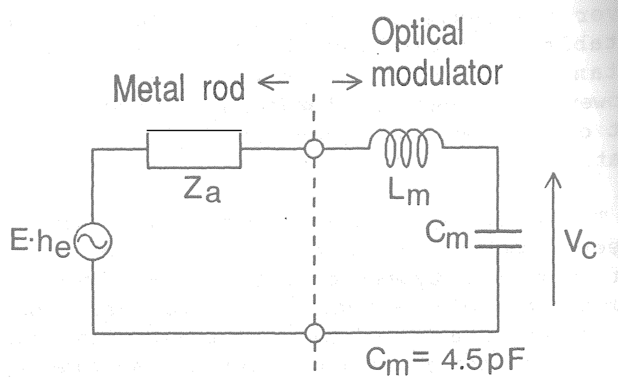

Fig.3 Equivalent circuit of the sensor.

4. Frequency response and sensitivity

4.1 Experimental layout

Frequency response and sensitivity are measured using the experimental setup illustrated in Fig.4. Electric fields are generated using a 900mm by 300mm by 300mm transverse electromagnetic (TEM) cell, whose band-width is tuned to 800MHz by absorbers. A signal from 35dBm to -100dBm is supplied to the TEM cell, and its power is measured with a power meter or level meter connected to the output terminal. An electric field of from 158dB(μ V/m) to 23dB(μ V/m) is generated in the TEM cell. Output level of the photodetector is measured by a level meter whose bandwidth is 7.5kHz.

4.2 Frequency response

The frequency response of the sensitivity, which is defined by the relation between the photodetector output voltage and the TEM cell output voltage, is measured by the experimental setup shown in Fig.4. The relative sensitivity normalized to the value at 100Hz rolls up above 300MHz, and maximum sensitivity is obtained at about 750MHz.

Traditional sensors do not have sufficient bandwidth to measure electromagnetic pulses, but the frequency response of this sensor is adequate for measuring electromagnetic pulses.

4.3 Sensitivity

The sensitivity of the sensor is shown in Fig.6. The output voltage of the photodetector is measured with a level meter at 50MHz and 750MHz. The frequency of 50MHz is selected because the frequency response is flat, and 750MHz is selected because the sensor exhibits maximum sensitivity at that frequency. The band-width of the level meter is set to 7.5kHz. As shown in Fig.6, the sensor exhibits ideal linear response from 60dB (μ V/m) up to 150dB(μ V/m), and a dynamic range of 90dB. Also from Fig.6, the relation between output voltage and electric field strength is represented by

$$V_r(dB(\mu V)) = E(dB(\mu V/m)) - A_f(dB) \qquad (4)$$

where A_f is a transfer coefficient. The values of 71dB at 50MHz and 53dB at 750MHz are obtained from the figure. Since the noise level of the photodetector is -10dBμ V, the minimum detection level of the sensor is 61dB(μ V/m) (about 1mV/m) at 50MHz and 43dB (μ V/m) (about 0.14mV/m) at 750MHz.

The sensitivity of the sensor using bulk $LiNbO_3$ crystals is 1V/m(120dB(μ V/m)), so the sensitivity of the sensor is about 60dB better.

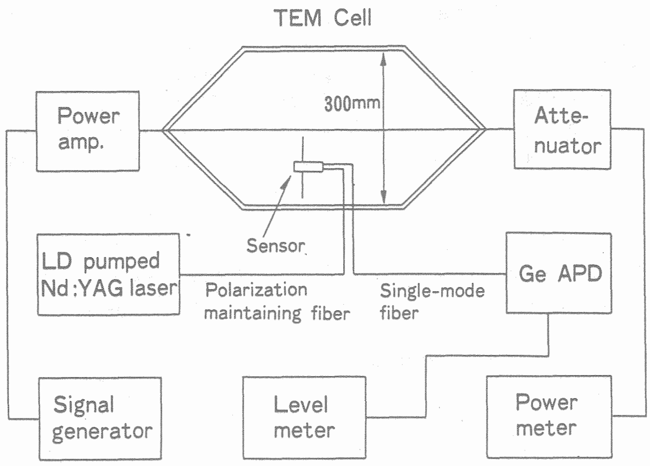

Fig.4 Experimental setup for measuring sensitivity of the sensor.

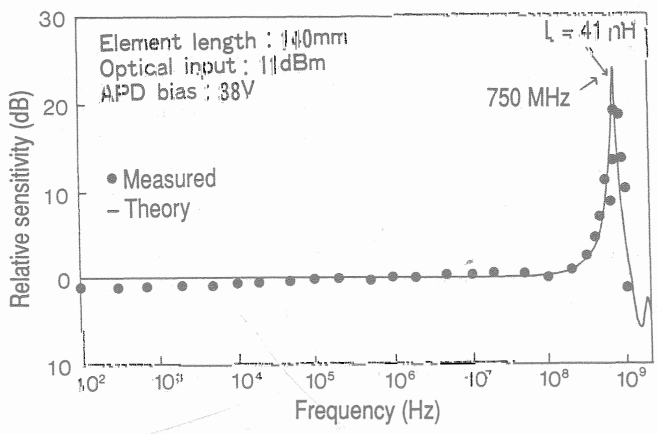

Fig.5 Frequency response of the sensor.

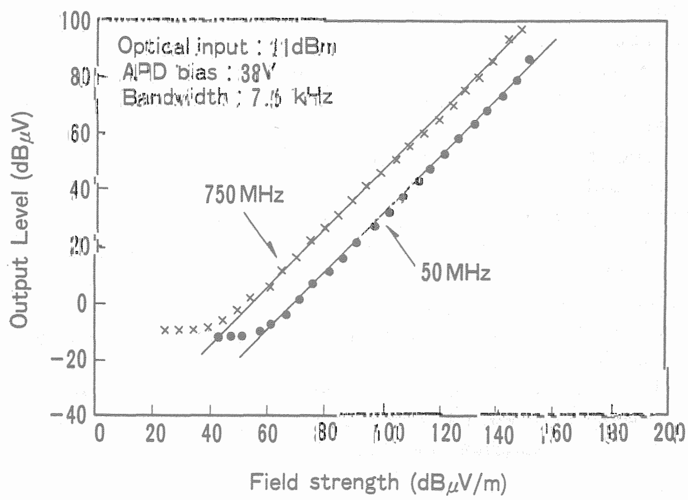

Fig.6 Sensitivity of the sensor.

5. Theoretical consideration of frequency response

The sensitivity of the sensor rolls up above 300MHz as shown in Fig.5. Since the frequency response of the optical modulator is almost flat from DC to 1GHz[8], the frequency response is determined by the dipole element of the sensor and the contact lead between the dipole element and the electrode of the modulator. Therefore, the frequency response of the sensor is studied on the basis of the equivalent circuit shown in Fig.3.

The dipole element of the sensor is equivalent to a dipole antenna. Therefore, if the dipole element is divided into segments of length Δh, the effective length h_e and the driving point impedance Z_a in Fig.3 are given by[7]

$$h_e = \sum_{i=1}^{N} \{I_i \cdot \Delta h / I_{N/2}\}, \qquad (5)$$

$$Z_a = V_{N/2} / I_{N/2}. \qquad (6)$$

where I_i is the current in each segment, and $V_{N/2}$ and $I_{N/2}$ are respectively the segment voltage and current at the driving point of the dipole element. These vales can be calculated using the moment method[9].

The input impedance of the optical modulator C_m is obtained by measuring the capacitance between the electrodes at 1kHz, and this value is presented in Fig.3.

The relation between the input voltage of the optical modulator V_c and the electric field E is calculated on the basis of the equivalent circuit in Fig.3. Since the sensitivity of the optical modulator is almost flat from DC to 1GHz[8], the value represents the frequency response of the sensor. The calculated results are shown in Fig.7, where the inductance of the lead wire is changed from 0nH to 200nH. As shown in Fig.8, the sensitivity of the sensor increases in proportion to increase in the inductance. On the other hand, the frequency showing the maximum sensitivity is decreased in proportion to the increase in inductance. When L_m is 0nH, the sensitivity is also increased at 1GHz. The sensitivity increase is considered to be caused by the increase of effective length alone. When L_m is not 0nH, the sensitivity increase is caused by the resonance in the lead-wire inductance and the increase in the effective length.

The L_m of 41nH is obtained to fit the maximum sensitive frequency in Fig.8 to the measured results in Fig.5. The calculated values are also shown in Fig.5. The figure shows that the calculation results at L_m of 41nH almost agree with the measurements. This means that the frequency response of the sensor can be calculated from the equivalent circuit in Fig.3, and that the sensitivity increase at 750MHz is due to the increase in the effective length and the resonance of the lead wire inductance.

6. Sensor properties

6.1 Optical power dependence

The relation between the optical input power of the sensor and output level of the photodetector is shown in Fig.8, where the output levels of the photodetector are normalized by the maximum value. The optical input power is tuned by optical attenuator, and frequency of 50MHz and field strength of 0.64V/m are selected for the experimental conditions. The measured results shows that

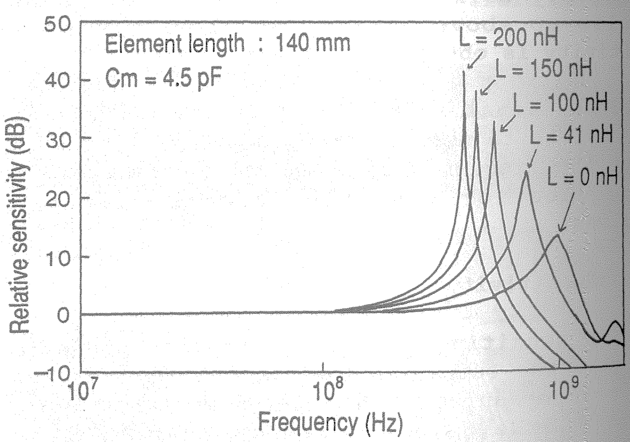

Fig.7 Calculated frequency response of the sensor.

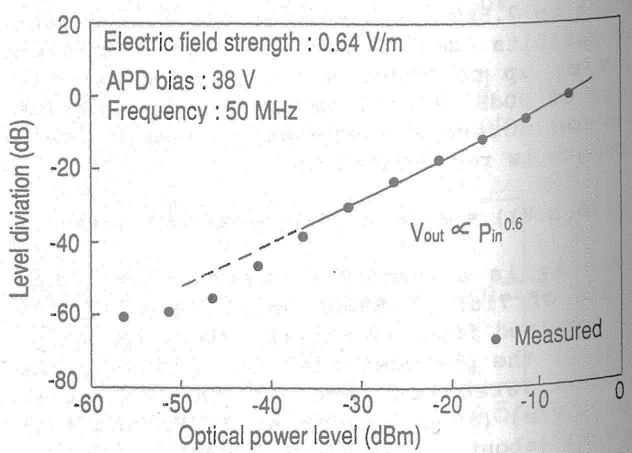

Fig.8 Optical power dependence of the sensor.

the output voltage increases proportionally with the optical power. This means that a high power optical source improves the sensitivity of the sensor.

6.2 Dipole element length dependence

The relation between the sensor output level and the dipole element length is measured in a semi-anechoic chamber. The experimental setup is shown in Fig.9. A sensor is set 10m away from the transmitting antenna. The electric field is generated by a signal generator with power amplifier and transmitting antenna. Both the transmitting antenna and sensor polarization are set to the vertical. The measurement results are shown in Fig.10, where the solid line represents the values calculated using the equivalent circuit of Fig.3, and the dots indicate measured values. The measured values almost agree with the calculated values, and the output voltage of the sensor is proportional to the dipole element length. This means that the equivalent circuit in Fig.3 is useful in explaining the properties of the sensor.

6.3 Cross-polarization

The cross-polarization characteristics of the sensor are measured with the experimental setup shown in Fig.11. The sensor is set on the antenna tower, and the polarization of the sensor is tuned from 0deg to 360deg. The level deviation is measured. The measurement results are shown in Fig.11. Cross-polarization of a half-wavelength dipole antenna is also measured for reference. Figure 11 shows that the cross-polarization of the sensor is almost the same as that of the half-wavelength dipole antenna.

7. Impulse response

The impulse response of the sensor is measured with the experimental setup shown in Fig.12. A pulse generator is connected to the input terminal of the TEM cell, and an impulse electromagnetic field is generated in the TEM cell. The waveform of the pulse is estimated from the measured waveform at the output terminal of the TEM cell. The waveform measured by the sensor is calculated from the waveform at the photodetector and the transfer coefficient A_f shown in Fig.6.

The results are shown in Fig.13, where the dotted line presents the impressed electromagnetic pulse and the solid line presents the measured values. An electromagnetic impulse whose width is 5ns and peak value is about 30V/m is generated in the TEM cell. From Fig.13, the measured waveform agrees closely with the impressed waveform.

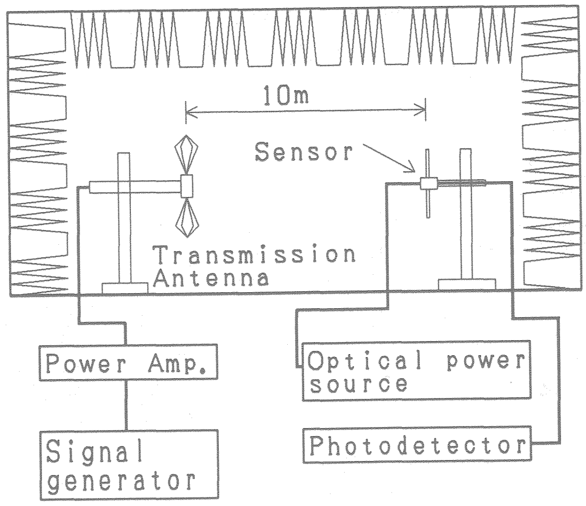

Fig.9 Experimental setup for measuring dipole element length dependence and cross-polarization.

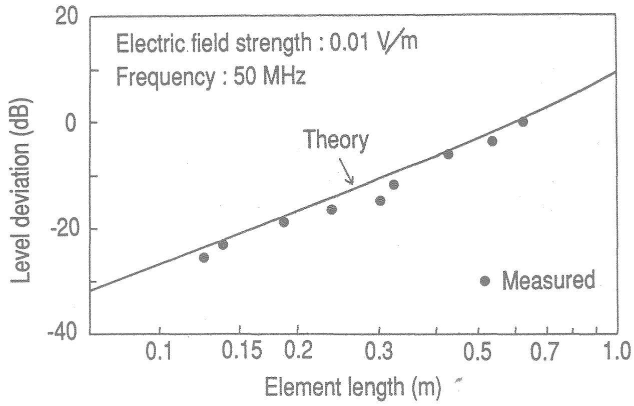

Fig.10 Dipole element length dependence of the sensor.

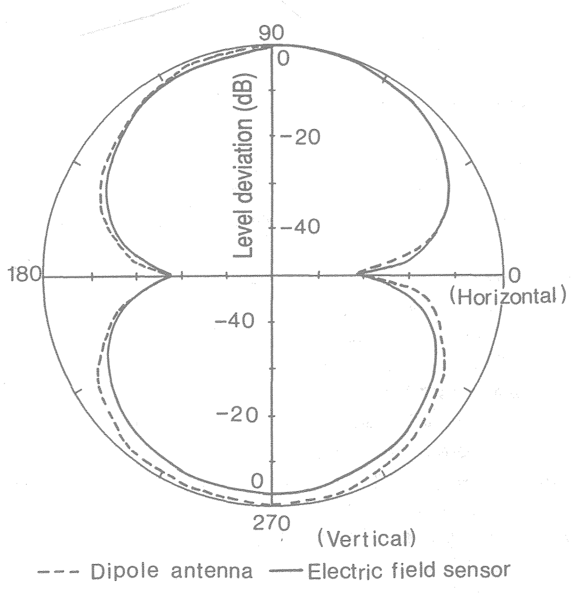

Fig.11 Cross-polarization of the sensor.

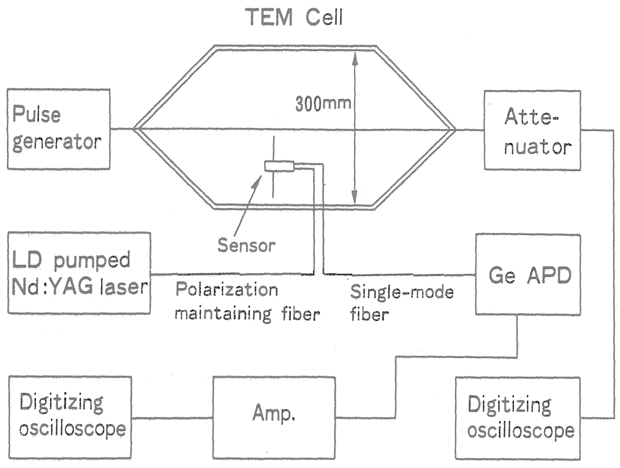

Fig.12 Experimental setup for measuring impulse response of the sensor.

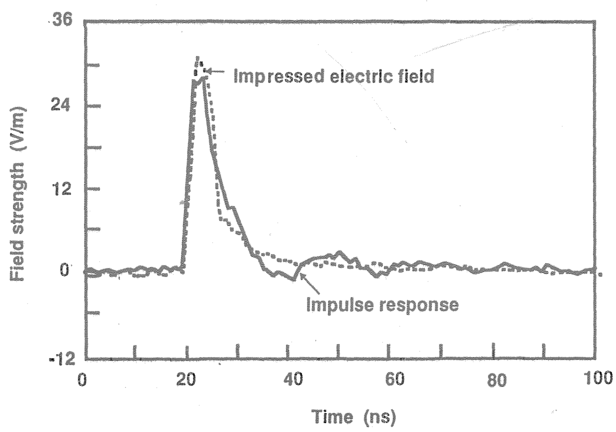

Fig.13 Impulse response of the sensor.

This results means that a electromagnetic impulse whose width is wider than 5ns and whose peak value is larger than 10V/m can be measured by this sensor.

8. Conclusion

A sensor using electro-optical crystals has been developed to support EMC studies such as the measurement of electromagnetic pulse.

The sensor features improved sensitivity obtained by using a low driving-power optical modulator whose half-wave voltage is about 4V and a YAG laser pumped by a laser diode as a high power optical source. The sensor can detected the minimum field strength of 1mV/m at 50MHz and 0.14mV/m at 750MHz. The frequency response of the sensor and the sensor rod length dependence calculated theoretically, considering the inductance due to the lead wire, almost agree with the measured values. The sensor can measure an electromagnetic impulse whose width is wider than 5ns and whose peak value is larger than 10V/m.

This sensor has sufficiently performance for use in EMC measurement. In future work, the reproducibility and precision of the measurements will be checked.

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Reference

[1]M. Kanda and F. X. Ries; "A broad-band isotropic real-time electric-field sensor using resistivity loaded dipole", IEEE Trans. Electro-magnetic Compatibility, Vol. EMC-23, No.3, pp.122-132, Aug. 1981.

[2]H. B. Berger, V. Kumara and K.Matloubi; "A broadband E-field sensing system", Proceedings of the 1988 IEEE Symposium on Electro-magnetic Compatibility, Seattle, pp.383-389, Aug. 1988.

[3]K. Murakawa, N. Kuwabara and F. Amemiya; "Radiation properties of a spherical dipole antenna", Proceedings of the 1989 IEEE Symposium on Electro-magnetic Compatibility, Nagoya, pp.572-580, Sep. 1989.

[4]N. Kuwabara, F. Amemiya and M. Tokuda; "An electric-field probe using a bulk LiNbO3 electro-optic crystal", OEC'90, 12B3-14, Japan, 1990.

[5]M. Kanda; "Photonic probes for the measuring of electro-magnetic fields over broad bandwidth", National Symp. on EMC, pp.1-6, Denver 1989.

[6]J. C. Wyss and S. T. Sheeran; "A practical optical modulator and link for antenna", IEEE Journal of Lightwave Technology, Vol. LT-3, No.2, pp.316-321.

[7]J. D. Kraus; "Antennas", McGraw Hill, 1950.

[8]K. Kawano, T. Kitoh, O. Mitomi, T. Nozawa and H. Jumonji; "A wideband and low-driving power phase modulator employing a Ti:LiNbO3 optical waveguide at 1.5μ m wavelength", IEEE Photonics Tech. Letters, Vol.1, No.2, Feb. 1989.

[9]R. F. Harrinton; "Field computation by moment method", The Macmillan Company, 1968.