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Recent Progress in Fiber Optic Antennas for EMC Measurement

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SUMMARY Recent progress in electromagnetic compatibility (EMC) technology has created a need for small and wideband antennas that can be used to measure the quality of EMC measurement facilities and to measure electric field strength for immunity tests and human hazard studies. Antennas using fiber optics are being developed because this kind of antenna has the wideband property and can eliminate the influence of the coaxial cable. This paper first summarizes the development of fiber optic antennas for EMC measurement and the construction of practical fiber optic antennas. It then describes the recent progress that has been made in Japan. This progress includes the electromagnetic source and the electric field sensor using a spherical dipole antenna with O/E or E/O converters, and it includes a wideband electric field sensor using electro-optical crystals.

key words: EMC, EMI, fiber optic antenna, electric field sensor

1. Introduction

Antennas have been used for measuring electromagnetic compatibility (EMC), such as the strength of an electric field illuminating a piece of equipment and the strength of the field emitted from the equipment. Progress in the study of EMC requires new antennas for measuring the shielding performance, the electric field strength within a small region, and electromagnetic pulses.

The two major characteristics required of antennas used for EMC measurement are in Fig. 1. EMC measurement needs wideband and high-precision generation and measurement of electric fields, and a high-impedance detection device will be needed to get wideband performance. The FET-input type antenna[1] and the optical-modulator type antenna[2] meet this requirement. On the other hand, precise measurement of an electric field requires the elimination of disturbances due to coaxial cable. Antennas in which coaxial cable is replaced by optical fiber, such as the optical-modulator[2] and optical/electrical converter (O/E) type antenna[3], meets this requirement. Antennas using fiber optics have been developed because only this kind of antenna can satisfy the both requirements.

This paper first summarizes the development of fiber optic antennas for EMC measurement. Then it describes recent progress which has been made in Japan; the spherical dipole antenna and the electric field sensor using electro-optic crystals.

2. Recent Progress in EMC Antennas Using Fiber Optics

2.1 Antennas for EMC Measurement

The development of antennas for EMC measurement is summarized in Fig. 2, where the dotted zone represents the sensitivity required to measure an electromagnetic pulse and the dashed line indicates the antenna that cannot measure frequency information. The loop antenna is used for EMC measurement at frequencies from 10 kHz to 30 MHz, and the dipole antenna is used from 30 MHz to 1 GHz, (where biconical and log-periodic antennas are also used). For frequencies higher than 1 GHz, the double-ridged guide antenna is used. The electric field probe is used for the immunity test.

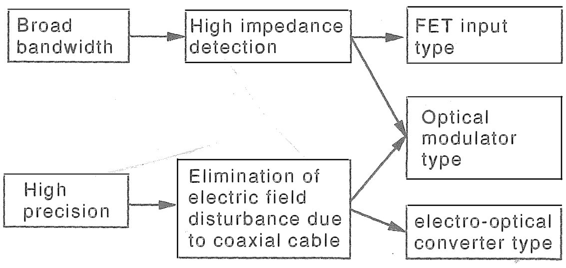

Fig. 1 Properties required of antennas used for EMC measurement.

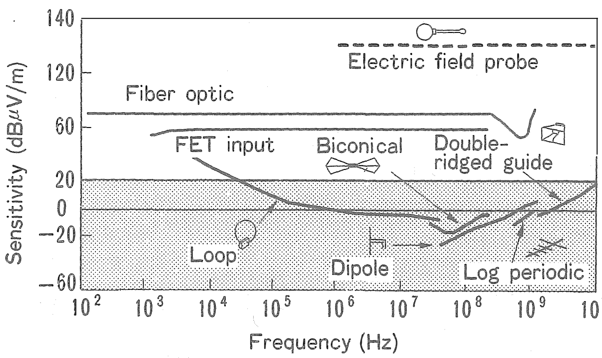

Fig. 2 Sensitivity-vs-frequency characteristics of various kinds of antennas used for EMC measurement.

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Fiber optic and FET input antennas are wideband devices, and although their sensitivity should be improved, they are useful for such EMC measurements as time domain measurement. Fiber optic antennas are expected to be especially for studying EMC because they can measure electromagnetic fields with high precision and over a broad range of frequencies.

2. 2 Fiber Optic Antennas for EMC Measurement

Two kinds of fiber optic antennas are shown in Fig. 3. One contains a battery and uses a laser or light emitting diode to convert electric field strength into an optical signal. The other kind inputs an unmodulated optical signal and modulates it according to the strength of an electric field.

Because antennas using light-emitting devices have attained reproducibility, most fiber optic antennas use light-emitting devices. The operation time of these antennas, however, is limited by the capacity of their batteries, and the many devices needed to construct the E/O or O/E converter make it difficult to reduce these antennas size.

On the other hand, antennas which use an optical

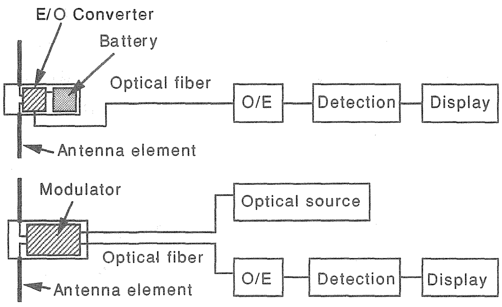

Fig. 3 Types of the sensors using fiber optics.

Table 1 Examples of the sensitivity and frequency bandwidth of fiber optic antennas.

Antenna type	Detection device	Characteristics		Reference
		Frequency bandwidth	Maximum sensitivity	
Electro-magnetic energy	Optical temper-ature sensor	1GHz-40GHz	140V/m	(6)
Electric field strength	Diode detection with E/O converter	10MHz-18GHz	1V/m	(4),(5)
	Electric discharge tube with image fiber	2.45GHz	5kV/m	(7)
	E/O converter with analog modulator	1kHz-100MHz	500V/m	(3)
	Optical modulator	100Hz-1GHz	1mV/m	(2)
Magnetic field strength	E/O converter with analog modulator	1kHz-100MHz	2A/m	(3)
Electro-magnetic field source	O/E converter with amplifier	30MHz-1GHz	——	(9)

modulator have a strong potential for achieving small and wideband antennas, but the reproducibility of these antennas should be improved; so for, only an antenna using an optical temperature sensor has been developed.

Fiber optic antennas can be classified as electric field sensors, magnetic field sensors, or electromagnetic energy sensors. Examples of the sensitivity and frequency bandwidth of these types of sensors are listed in Table 1.

Electromagnetic energy sensors that use an optical temperature sensor measure RF energy by detecting the change in the temperature of a resistive RF absorber[4]. Electric field sensors that use diodes exhibit good reproducibility and sensitivity to a broad band of frequencies; some antennas have therefore been developed[5],[6]. An electric field sensor that uses an electric discharge tube measures electric field strength by detecting the brightness of the tube[7]. This sensor is 6 mm in diameter and 18 mm long, and the minimum detectable electric field is about 5 kV/m at 2.45 GHz. Electric field sensors and magnetic field sensors can also be made by using an E/O converter[3],[8], and an electric field sensor using an optical modulator operating from 100 Hz to 1 GHz has been presented[3],[10]. An electromagnetic field source can also be created by replacing the E/O converter with an O/E converter[9].

The rest of this paper will describe the construction of the practical fiber optic sensors listed in Table 1, which are an electromagnetic energy sensor using an optical temperature sensor, an electric field sensor using diodes and resistive cable, and electric and magnetic field sensors using an E/O converter.

2. 3 Electromagnetic Energy Sensor Using Optical Temperature Sensor

Figure 4 shows the configuration of an electromagnetic energy sensor that uses an optical temperature sensor[4]. A small piece of resistive material is placed at the temperature sensing point, and RF energy absorbed by the resistor increases its temperature. The electromagnetic energy is obtained by using optical temperature sensor to measure the temperature increase.

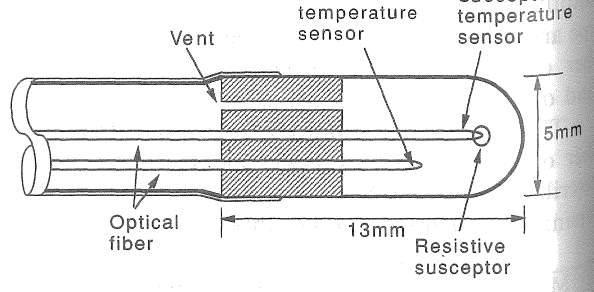

Fig. 4 Configuration of an electromagnetic energy sensor using an optical temperature sensor.

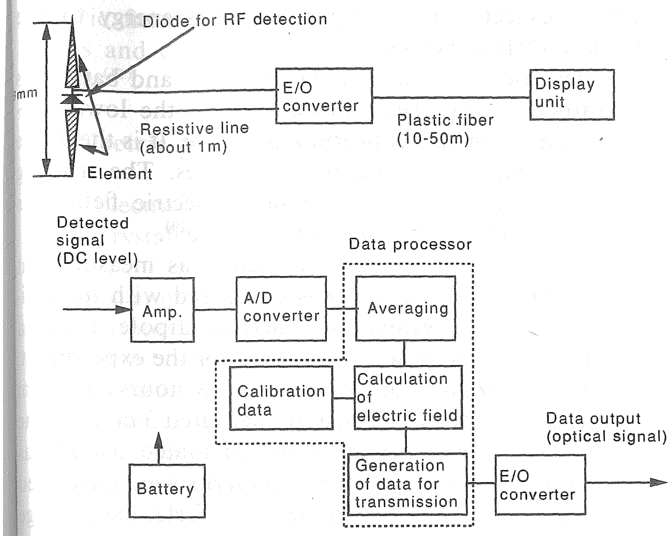

Fig. 5 Configuration of an electric field sensor using a diode.

This sensor contains two optical temperature sensors. One measures the temperature increase by RF energy, the other measures the ambient temperature, and the electromagnetic energy is calculated from the data produced by these two sensors.

This type of sensor is easily made compact: a sensor 5 mm in diameter and 13 mm long has been developed. This type of sensor is expected to be applied in the study of human hazard and hyperthermia.

2.4 Electric Field Sensor Using Diode

The configuration of an electric field sensor using a diode is illustrated in Fig. 5[5]. A diode placed at the center of an 8 mm long dipole element converts RF signal level to DC level. In the actual sensor, three orthogonal elements are used to measure the vector sum of the electric field[4]. To reduce the disturbance to the electric field distribution, a 1 m long resistive line connects the element to the E/O converter. The resistive line also reduces the RF signal component contained in the detected DC level. A plastic optical fiber 10 to 50 m long connects the E/O converter to the display unit.

The configuration of the E/O converter is also illustrated in Fig. 5. The detected electric field strength is amplified and is translated to digital data by A/D converter. The microprocessor averages the signal and calculates the electric field strength, referring to the calibration database. When the electric field is calculated, a vector sum of the data detected by the three orthogonal elements is also computed. The calculated results are converted into a data form for transmission to the E/O converter.

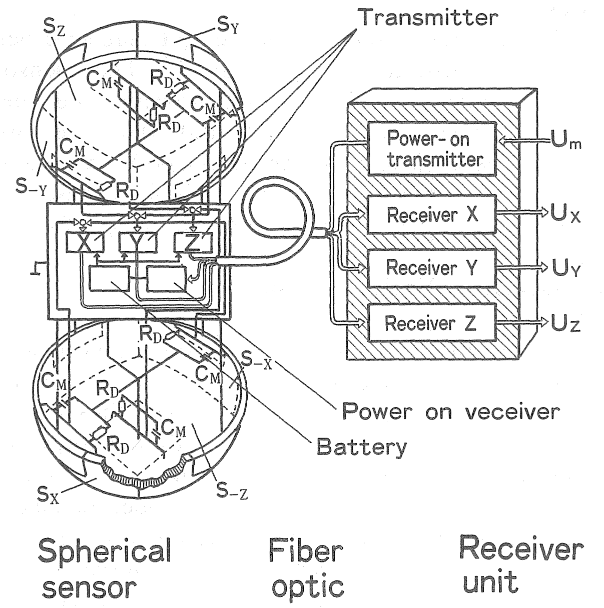

Fig. 6 Configuration of the electric field sensor using an E/O converter.

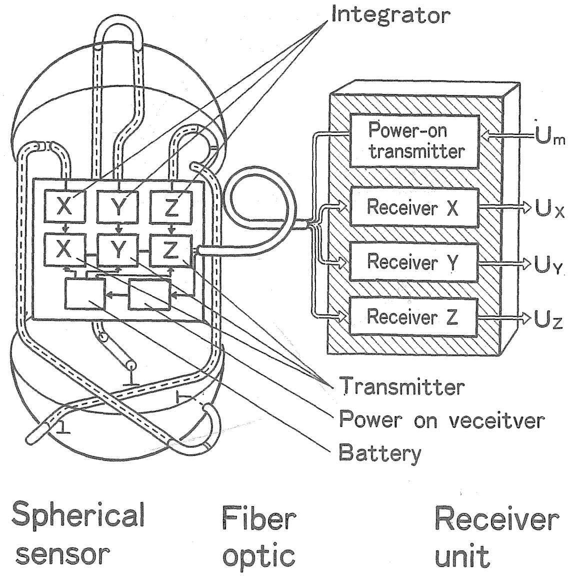

Fig. 7 Configuration of the magnetic field sensor using an E/O converter.

2.5 Electric and Magnetic Field Sensor Using an E/O Converter

The electric field strength measured by this sensor is converted into an analog optical signal that is used for modulating a light emitting device, such as a laser diode or a light emitting diode. A magnetic field sensor can be made by replacing the dipole element with a loop antenna. These sensors are being developed for measuring wideband electromagnetic fields within a small region, and for measuring electromagnetic pulses.

The configurations of electric and magnetic field sensors are illustrated in Figs. 6 and 7[8]. These sensors were developed for NEMP measurement, and their frequency range is from 1 kHz to 100 MHz. The sensitivity of the electric field sensor is 500 V/m, and its dynamic range is 46 dB. The magnetic field sensor has a sensitivity of 2 A/m, and a dynamic range of 40 dB.

3. Spherical Dipole Antenna

A spherical dipole antenna was developed to measure the shielding performance of cabinets[11] and buildings, and to test EMC measurement facilities.

The configuration of a spherical dipole antenna is illustrated in Figs. 8 and 9[9]. This antenna is divided into upper and lower elements: The upper element is an umbrella-shaped hemisphere, and the lower element is a metallic case. An electromagnetic source is made by setting an O/E converter into the lower element, and an electric field sensor is made by setting an E/O converter into the lower element as shown in Figs. 8 and 9 respectively. A battery supplies energy to the E/O or O/E converter.

Because the O/E or E/O converter and battery is contained within the metallic cases of the lower element, the boundary condition is simple. It is therefore easy to analyze the antenna properties. The driving point impedance and the radiated electric field was analyzed using mode-matching method[9].

Radiated electric field strength was measured at the open air test site and was compared with numerically calculated results. A spherical dipole antenna 150 mm in diameter was developed for the experiment, and this antenna could operate for 8 hours at room temperature. The height pattern measured 3 m from the antenna was very similar to the calculated pattern as shown in Fig. 10. When height patterns were measured at frequencies between 30 MHz and 1 GHz, the average deviations for both vertical and horizontal polarization was less than 2 dB as shown in Fig. 11. The

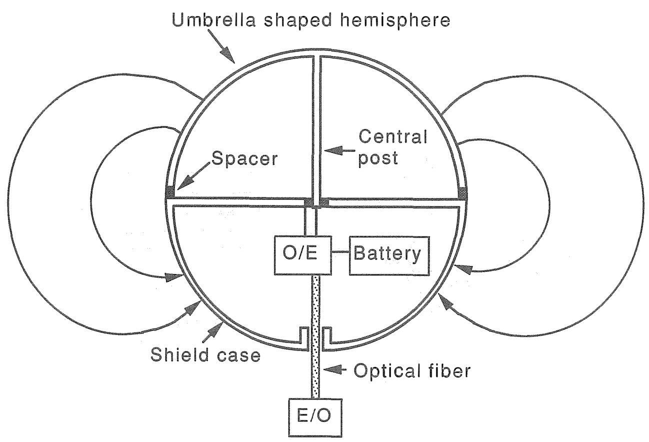

Fig. 8 Configuration of a spherical dipole antenna for an electromagnetic field source.

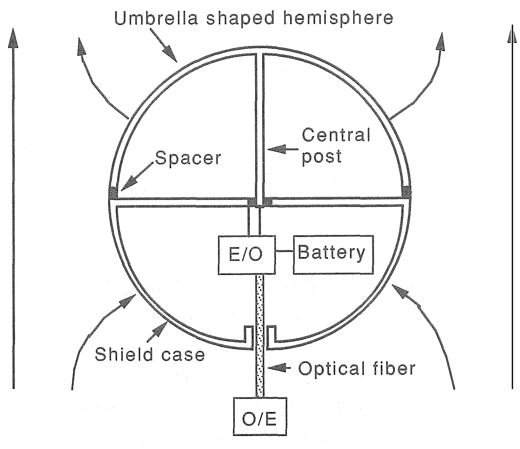

Fig. 9 Configuration of a spherical dipole antenna for an electric field sensor.

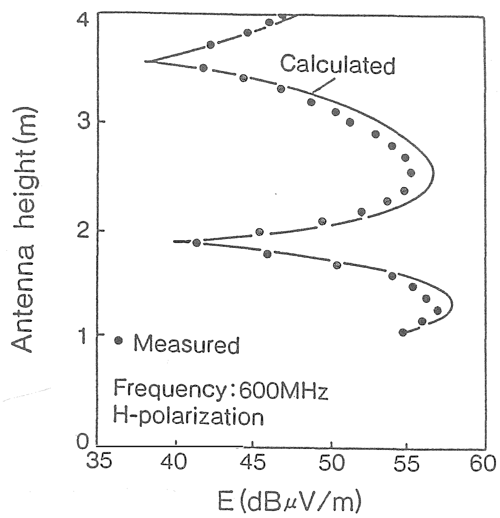

Fig. 10 Height pattern 3 m from the spherical dipole antenna.

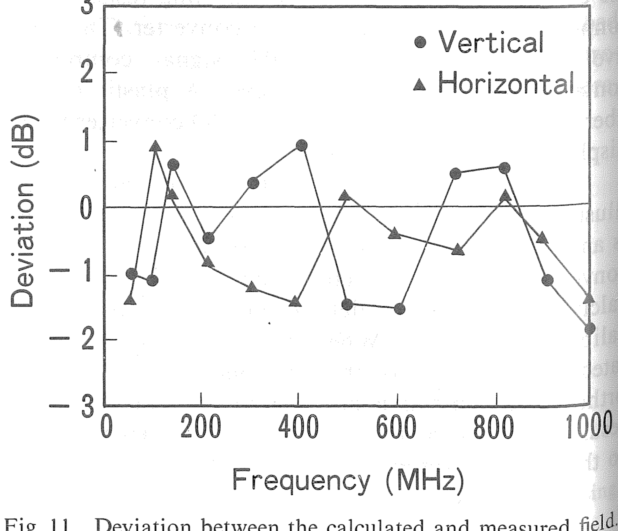

Fig. 11 Deviation between the calculated and measured field.

electric field sensor shown in Fig. 9 operated for 4 hours and could detects a signal as small as only 1 mV/m[11].

4. Electric Field Sensor Using Optical Modulator

4.1 Electric Field Sensor Using Bulk Electro-Optic Crystals

The configuration of an electric field sensor using electro-optic crystals is illustrated in Fig. 12[15]. Light from a He-Ne laser (633 nm) is focused into the 50/125 μm graded-index multimode fiber that guides the light to the sensor assembly. The beam entering the assembly is collimated so that it passes through the optical modulator containing a pair of 10 mm by 1 mm by 1 mm $LiNbO_3$ crystals, where crystals are used for temperature compensation. The light from the modulator is then refocused into the multimode fiber and guided to the photodetector.

When the sensor is set in an electric field, a voltage is induced at the electrodes of the crystals. A linealy polarized optical wave enters into the crystal at an angle of 45 degree to the crystal's z axis. When a voltage is applied, this polarization becomes elliptical because the electro-optic effect changes the traveling velocity of the z component. The analyzer, which makes an angle of 135 degree with the z axis, converts the polarization change to the amplitude change. The electric field strength can be obtained to measure the amplitude change by using the photodetector. A babinet-soleil compensator is used to tune the optical bias entering the analyzer.

This sensor's sensitivity and bandwidth was measured by using a TEM cell and a semi-anechoic chamber. The minimum detectable level was 100 dB (μV/m) and the frequency response was almost flat from 100 kHz to 100 MHz.

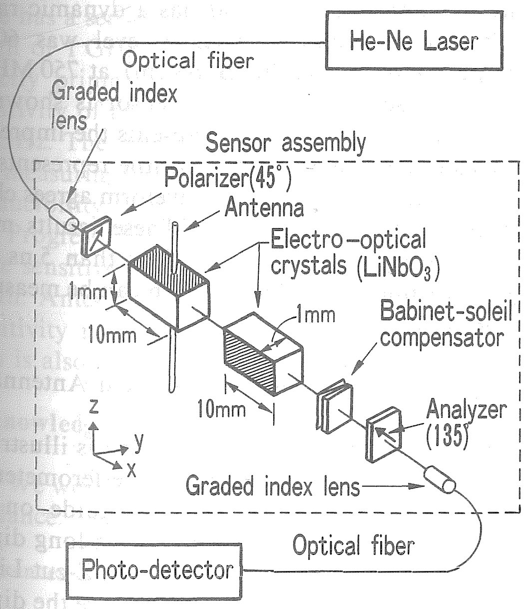

Fig. 12 Configuration of an electric field sensor using bulk $LiNbO_3$ electro-optic crystals.

4.2 Electric Filed Sensor Using Integrated Optical Circuit

An optical modulator using an integrated optical circuit operates from DC to 20 GHz, and has a high input impedance. Sensors using optical modulators were therefore developed for measuring wideband electric fields in a small regions and for measuring-electromagnetic pulses[10],[12],[13].

The configuration of such a sensor is illustrated in Fig. 13. Two metal rods are aligned and separated by a small gap in which an optical modulator is located. When an electric field is applied to the metal rods, a voltage is induced across the gap and the modulator converts this voltage to an optical signal whose level is measured by the photodetector. A Mach-Zehnder interferometer formed from a 7 μm by 0.7 μm waveguide on a 10 mm by 40 mm Z-cut $LiNbO_3$ plate is used as the optical modulator, and a pair of metal rods, 50 mm long and 4 mm in diameter, is used for sensor element.

This sensor has three superior points: its influence on the measured electromagnetic field is small because most of the sensor materials are nonmetallic, its operating time is not limited, and it operates over a very wide range of frequencies.

The frequency response, sensitivity, and the impulse response of the sensor were measured by using a TEM cell. The frequency response of the sensor is shown in Fig. 14. Its relative sensitivity, normalized to the value at 100 Hz, was almost flat from 100 Hz to 300 MHz, and rolls up above 300 MHz. The maximum

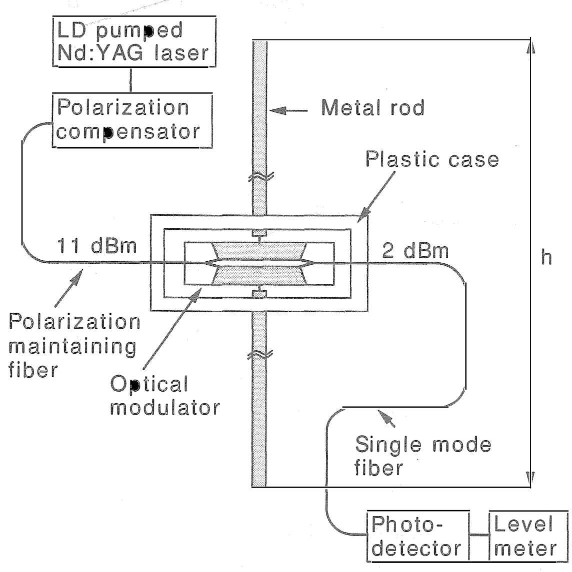

Fig. 13 Configuration of an electric field sensor using an optical modulator.

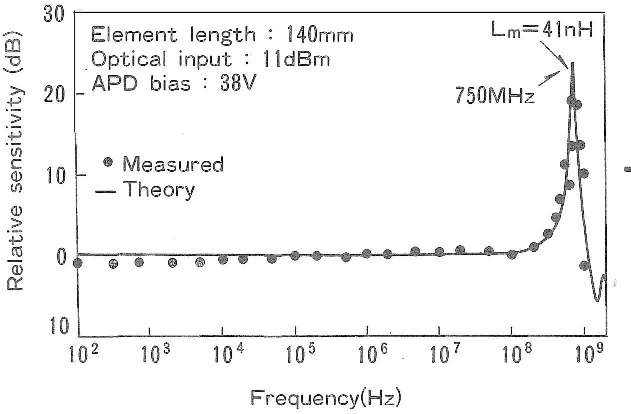

Fig. 14 Frequency response of the electric field sensor with an integrated optical circuit.

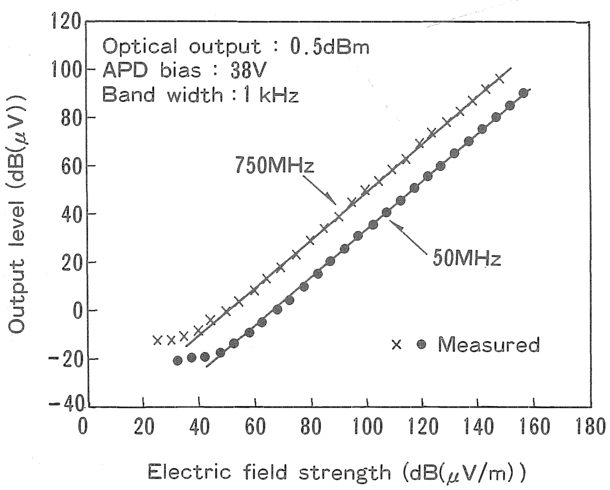

Fig. 15 Sensitivity of the electric field sensor.

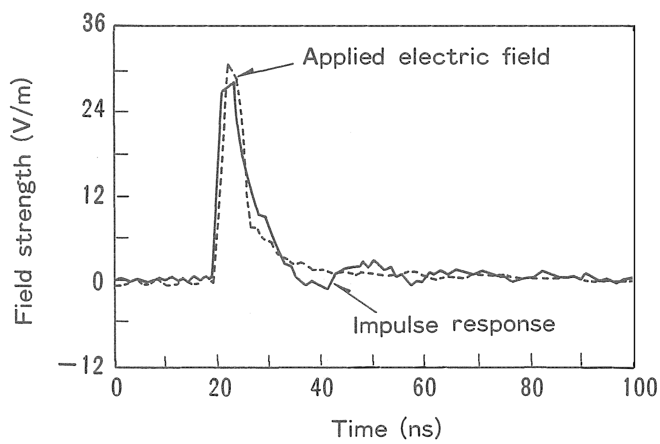

Fig. 16 Impulse response of the electric field sensor.

sensitivity was obtained at about 750 MHz. The sensitivity of the sensor at 50 MHz, where the frequency response is flat, and at 750 MHz where the sensor exhibits maximum sensitivity, is shown in Fig. 15. The bandwidth of the level meter was set to 1 kHz. The

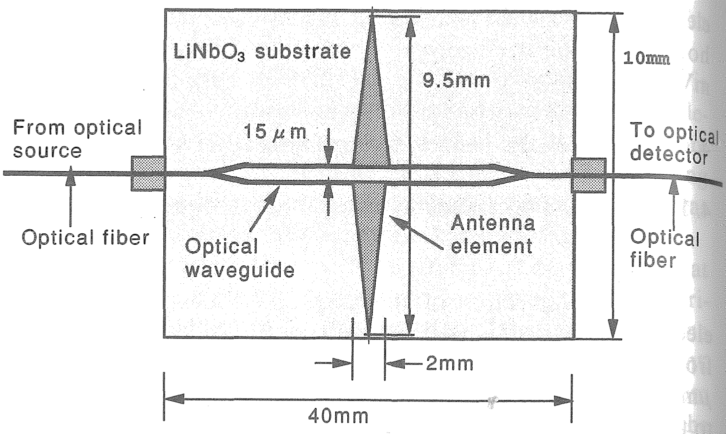

Fig. 17 Configuration of the electric field sensor using a printed antenna.

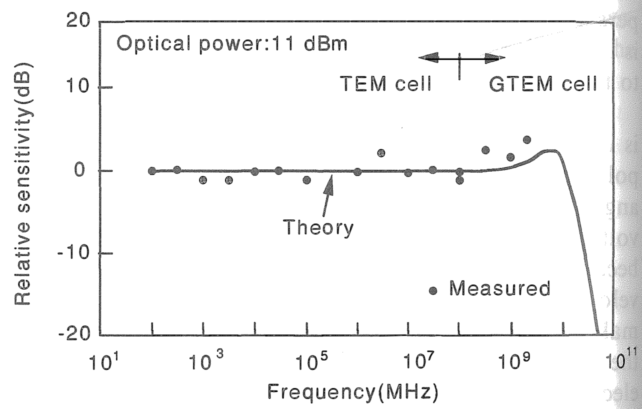

Fig. 18 Frequency response of the sensor with a printed element.

sensor exhibits an ideal linear response from 60 dB (μV/m) to 150 dB(μV/m), and has a dynamic range of 90 dB. The minimum detection level was 60 dB (μV/m) at 50 MHz, and 40 dB(μV/m) at 750 MHz.

The impulse response of the sensor is shown in Fig. 16, where the dotted line represents the impressed electromagnetic pulse and the solid line represents the measured values. The measured waveform agrees closely with the impressed waveform. These results mean that an electromagnetic impulse wider than 5 ns and having peak value larger than 10 V/m can be measured by this sensor.

4. 3 Electric Field Sensor Using Printed Antenna

The structure of the printed antenna is illustrated in Fig. 17[14]. A Mach-Zehnder interferometer is formed from a 7 μm by 0.7 μm waveguide on the substrate by titanium diffusion. A 9.5 mm long dipole element is printed on a 10 mm by 40 mm Z-cut $LiNbO_3$ substrate by vapor deposition. To reduce the dipole element resonance 0.06 μm thick Chromium is used as the element material[4]. A gap 2 mm long and 15 μm wide is created at the center of the element.

The frequency response of the sensor was measured by using a TEM cell and a GTEM cell. Figure 18 shows the relative sensitivity normalized to the value at 100 Hz. As shown in Fig. 18, the frequency response is almost flat from 100 Hz to 2.5 GHz. This means that the sensor should operate at more than 2.5 GHz.

5. Conclusion

Recent progress of antennas for EMC measurement using optical technology was described. The electromagnetic energy sensor which uses an optical temperature sensor can be used to measure the electromagnetic energy within a small region and should be valuable for evaluating the human hazard and hyperthermia. The electric field sensor which uses a diode and a resistive line exhibits good reproducibility and wideband properties, but does not provide frequency information. Electric field sensors and magnetic field sensors which use E/O converters have been developed for NEMP measurement.

A spherical dipole antenna is used to measure the shielding performance of cabinets and buildings and to test an EMC measurement facility. A transmtting antenna and receiving antenna 15 cm in diameter was developed, and the measured radiated field strength is within 2 dB of the theoretical value from 30 MHz to 1 GHz.

An electric filed sensor using electro-optic crystals was developed to measure electromagnetic pulses. The sensor using 10 mm long 1 mm by 1 mm bulk $LiNbO_3$ has a sensitivity of 0.1 V/m and can measure over a bandwidth of 100 MHz. The sensor with a Mach-Zehnder interferometer formed on a $LiNbO_3$ plate has a sensitivity of 1 mV/m and frequency bandwidth of 1 GHz. A sensor with 9.5 mm long element directly printed on $LiNbO_3$ plate is presented. The sensitivity of this sensor is almost flat from 100 Hz to 2.5 GHz. The performance of these sensors is suitable for measuring electromagnetic pulses, but their reproducibility and sensitivity should be improved.

Progress in EMC study requires sensors that are more sensitive and are responsive over a wider bandwidth. Antenna configuration must be improved and sensitivity increased. Research on new sensing materials is also needed.

Acknowledgments

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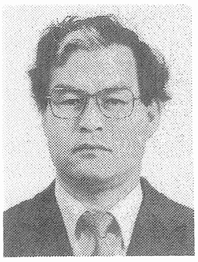

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