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Improving Design Method for Sensitivity and Frequency Response of E-Field Sensor Using a Mach-Zehnder Interferometer

Kimihiro TAJIMA[†a)], Ryuichi KOBAYASHI[††], Nobuo KUWABARA[†], *and* Masamitsu TOKUDA[†††], *Members*

SUMMARY The design method for sensitivity and frequency response of an electric field sensor using a Mach-Zehnder interferometer (an optical E-field sensor) has been developed in order to measure electromagnetic environments and the performance of measuring facilities. The designs of the optical modulator, sensor elements, and sensitivity were analyzed theoretically by using an accurate equivalent circuit of the sensor. Then an actual sensor was fabricated, and its characteristics of the sensor were evaluated experimentally. The results show that the designed sensitivity and frequency response were optimal. The optical output deviation when the temperature increased from 0 to 40°C was reduced to within 2 dB. The minimum detectable electric field strength was 17 dBμV/m (8 μV/m), and the dynamic range was more than 100 dB. The frequency response of the sensitivity was almost flat between 200 Hz and 900 MHz.

key words: *electric field sensor, antenna measurement, optical modulator, electro-optical effect, EMC*

1. Introduction

Electric field sensors are widely used in industrial, medical, and electromagnetic compatibility (EMC) technology area, and their importance is increasing with the developing of those technologies. Especially, in the EMC area, it is necessary to evaluate precisely the strength of electromagnetic fields radiated from electronic devices and existing in measuring facilities, such as anechoic chambers and transverse electromagnetic (TEM) cells.

Emission and immunity tests on electronic devices are usually performed using electric field sensors. Various types of sensors have been developed, including one with a resistively loaded element [1], one with an electrical/optical (E/O) converter [2], and one with an optical modulator (an optical E-field sensor). The optical E-field sensor has several advantages [3]-[11]:

- Its sensing part is made of non-metallic material (except for the actual sensing element), so the sensor itself has little effect on the electromagnetic field being measured.
- Its optical modulator has a wide bandwidth, from DC to several GHz.
- It operates without a battery, so measurements can be conducted over a long period.
- Its sensing part does not contain any electronic devices or circuits, so it can easily be miniaturized [8].

There are two types of optical E-field sensors from a standpoint of a optical modulator: those using E/O crystals in a bulk modulator, such as $LiNbO_3$, for optical modulation [3], [4], [11] and those using a Mach-Zehnder interferometer formed on an $LiNbO_3$ substrate [5]-[10]. The latter type can be fabricated to be highly sensitive (minimum detectable electric field strength of less than 1 mV/m) because the half-wave voltage is much less than that of bulk modulators. Their frequency range is very broad (more than 400 MHz) and they can be made very small by integrating the electrode and sensor element on the optical modulator [8].

Various optimization methods for improving the characteristics are needed to make optical E-field sensors practical. For those using a Mach-Zehnder interferometer, a method of controlling the optical bias-angle via the applied load has been studied [9]. However, it has not yet been experimentally confirmed whether the sensitivity would be made highest. And a method of suppressing resonances occurred by the piezoelectric effect of $LiNbO_3$ has been studied in part of frequency band [10]. However, it has not yet been experimentally confirmed whether the response over the whole frequency band meets the requirements of an optical E-field sensor.

On the other hand, for an optical E-field sensor using $LiNbO_3$ crystal in a bulk modulator, a method of theoretically analyzing the sensitivity [4] and a method of improving the frequency response by using resistively loaded elements [11] have been studied. However, the effectiveness of these two methods for optical E-field sensors using a Mach-Zehnder interferometer has not yet been confirmed.

In this paper, the design method for frequency and sensitivity response of an optical E-field sensor using a Mach-Zehnder interferometer is studied theoretically and experimentally. First, we theoretically analyze the sensitivity of the sensor using a new equivalent circuit and obtain the required design parameters. Then an optical E-field sensor is designed and fabricated under optimum condition. Finally, the result of measuring characteristics is evaluated, and show the effectiveness of the improving design method experimentally.

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† The authors are with NTT Lifestyle and Environmental Technology Laboratories, Musashino-shi, 180-8585 Japan.
†† The author is with NTT Technical Assistance and Support Center, Musashino-shi, 180-8585 Japan.
††† The author is with Kyushu Institute of Technology, Kitakyushu-shi, 804-8550 Japan.
a) E-mail: tajima@ntttqh.tnl.ntt.co.jp

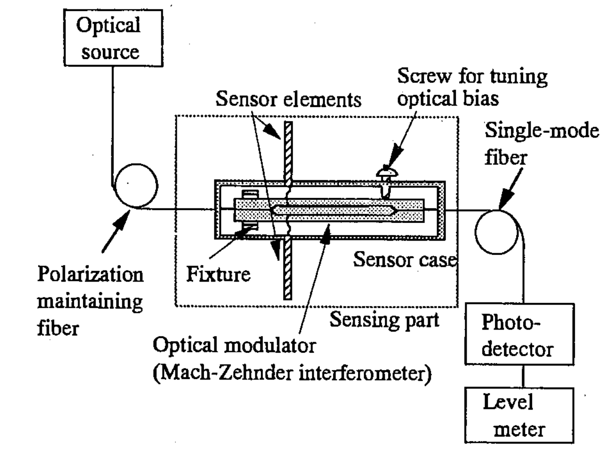

Fig. 1 Configuration of electric field sensor using Mach-Zehnder interferometer.

2. Structure and Analysis of Optical E-Field Sensor Using Mach-Zehnder Interferometer

The structure of our improved optical E-field sensor using a Mach-Zehnder interferometer is illustrated in Fig. 1. Two elements are aligned on either side of an optical modulator as forming a dipole antenna. When an electric field is applied to the sensor element, a voltage is induced across the gap between electrodes on the modulator. The modulator converts this voltage into an optical signal that is proportional to the electric field strength. The amplitude of the optical signal is measured using a photodetector and a level meter. A laser diode or high-power Nb:YAG laser pumped by a laser diode is used as the optical source, and a photodiode, such as a PIN photodiode or averanche photodiode, is used as the photodetector.

The sensing part is made primarily of nonmetallic materials to minimize its disturbance of the electrical field. A polarization-maintaining fiber connects the sensing part to the optical source, and a single-mode fiber connects the sensing part to the photodetector.

We used the equivalent circuit shown in Fig. 2 to analyze theoretically the sensitivity and frequency characteristics of the sensor. The output voltage of the level meter V_{out} is given by

$$V_{out} = Z_{in}/(Z_{in}+Z_o)V_{in} = Z_{in}/(Z_{in}+Z_o)\,\eta_d\,P_{out}, \quad (1)$$

where

$$P_{out} = \eta_s\eta_m(\eta_p\,p_{in}/2)\{1+\cos(\pi V_c/V_\pi+\phi_m)\} \quad (2)$$

$$V_c = Z_m/(Z_a+Z_l+Z_m)\,E\,h_e. \quad (3)$$

Here, Z_{in} is the internal impedance of the level meter, Z_o is the output impedance of the photodetector, V_{in} is the induced voltage by the photodiode, η_d is the conversion constant of the photodetector, P_{in} is the optical power input to the optical fiber connected to the modulator, P_{out} is the optical power output from the optical fiber connected to the modulator, η_p and η_s are the transmission loss constants of the optical fibers connected to the input and output port of the modulator, η_m is the insertion loss constant of the modulator, V_c is the voltage at the input terminal of the modulator induced by the applied electric field, V_π is the half-wave voltage of the modulator, ϕ_m is the optical bias angle, Z_a is the driving point impedance of the sensor elements, E is the applied electric field strength, h_e is the effective length of the sensor element, Z_l is the loaded impedance with the sensor element, and Z_m is the input impedance of the optical modulator.

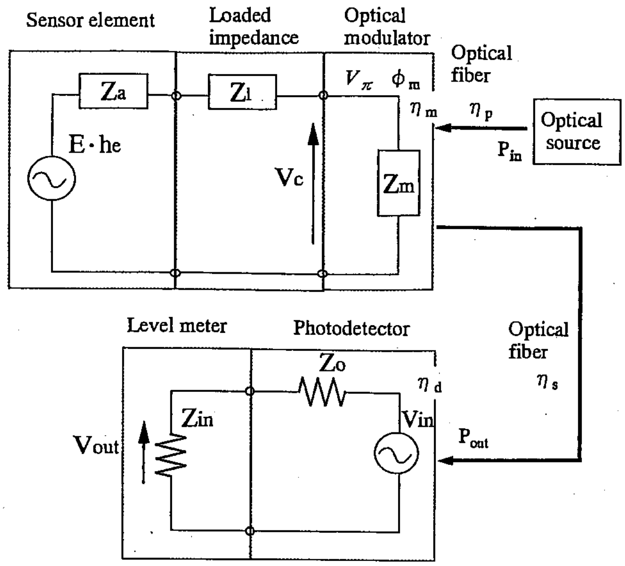

Fig. 2 Equivalent circuit of electric field sensor.

Fabrication of a practical optical E-field sensor requires appropriate values to be determined for all these parameters. In the following chapter, we describe our design method for doing this.

3. Designing an Optical E-Field Sensor

3.1 Analysis of Sensitivity

To calculate the sensitivity and frequency response of the optical E-field sensor accurately, we substitute Eqs. (2) and (3) into Eq. (1). In the frequency range where the electrodes of the modulator are much shorter than the wavelength, the input impedance of the optical modulator Z_m is expressed approximately by using the parallel connection of a resistance because of Si coating, R_m (See Sect. 3.2 in detail), and a capacitance, C_m:

$$Z_m = 1/(1/R_m + j\omega C_m). \quad (4)$$

We can thus transform Eq. (1) into

$$V_{out} = Z_{in}/(Z_{in}+Z_o)\eta_d\eta_s\eta_m\eta_p\,(p_{in}/2)\,[1+\cos\{\pi/V_\pi \times |\,1/(1+j\omega C_m R_m)\,/\,\{Z_a+Z_l+1/(1+j\omega C_m R_m)\}\,|\,E\,h_e+\phi_m\}. \quad (5)$$

In Eq. (5), the values of Z_{in}, Z_o and η_d depend on the measuring apparatus; the values of p_{in}, C_m, R_m, ϕ_m, V_π and η_m can be chosen based on the following considerations; Z_l, Z_a,

h_e can be calculated as described in Sect. 3.3; and η_p and η_s are determined by measurement, as described in Sect. 3.4.

As shown in Fig. 2, the parameters needed to design the optical modulator are Z_m, η_m, V_π and ϕ_m. The R_m and C_m can be measured using a impedance analyzer at low frequencies because they are independent of the frequency. The p_{in} and the insertion loss constant of the optical modulator, η_m can be measured without applying a voltage using an optical power meter because they are also independent of the frequency. The ϕ_m can also be obtained by measurement using an oscilloscope while applying an AC voltage to the electrodes of the optical modulator at low frequencies [9].

V_π is the half-wave voltage and determines the sensitivity of the modulator. It takes a constant value in the frequency range in which the electrodes are much shorter than the wavelength, and it is given by [12]

$$V_\pi = \lambda\, d/(2\Gamma n_e^3\, \gamma_{33} l), \quad (6)$$

where λ is the optical wavelength, d is the electrode gap of an optical modulator, Γ is the reduction in the applied electric field, n_e is the refractive index, γ_{33} is the Pockels coefficient, and λ is the electrode length.

Accordingly, the output voltage of the optical E-field sensor can be estimated accurately by using Eq. (5). This equation is solved for the first time ever in this paper to analyze the sensitivity and frequency response of an optical E-field sensor using a Mach-Zehnder interferometer.

3.2 Improving the Performance of the Optical Modulator

The performance of the optical modulator used for the sensor should be improved in order to improve the sensor's sensitivity and frequency response. Methods of suppressing piezoelectric resonance, tuning the optical bias angle, and stabilizing the sensitivity have been studied [9], [10], [12].

The frequency response is influenced by the piezoelectric effect. Resonance generally appears between 1 and 100 MHz, with a deviation in the frequency response of more than ±2 dB. The resonance frequency depends on the shape of the substrate because the resonance occurs when the frequency of the electric signal matches the mechanical resonant frequency of the $LiNbO_3$ substrate. We previously developed a substrate with an asymmetrical shape to suppress this resonance [10].

Tuning the optical bias angle ϕ_m is very important for the sensor because the sensitivity and dynamic range are closely related to it. However, it is difficult to fabricate a Mach-Zehnder interferometer with an optimum angle because the phase difference of an actual modulator is almost zero. When a Mach-Zehnder interferometer is used to optically modulate microwave signals, the optical bias angle is usually tuned by applying a DC voltage. However, a DC voltage cannot be applied to this sensor because the electronic circuits and wires for DC power supply disturb the electromagnetic fields to be measured.

An effective way to tune the optical bias angle of this optical E-field sensor is to apply a mechanical load to the $LiNbO_3$ substrate, instead of applying a DC voltage [9].

However, it was not clarified whether the sensitivity of the sensor would be tuned in highest sensitivity. It was evaluated the relationships between sensitivity and optical bias angle. A sensor was placed in a TEM cell, and the induced electric field strength was varied for various values of optical bias angle. The optical output power was measured by an optical power meter.

Figure 3 shows a measurement result of the relationship between sensitivity and optical bias angle. It shows that the sensitivity became highest when the optical bias angle was tuned to a suitable value, in this case, 1.57 radians.

One reason it is difficult to realize the good repeatable measurements is the temperature dependence of the sensor. The sensitivity of the sensor drifts when the temperature changes, and the amount of drift is closely related to the change in the output power of the modulator when the temperature changes. This has been one of the major obstacles to fabricating Mach-Zehnder interferometers for a long time. Some studies have shown that power drift is caused by the pyroelectric effect. The mechanism of this power drift has been clarified, and a model explaining it has been proposed [12].

A configuration that prevents power drift is shown in Fig. 4. A Si (silicon) semiconductor coating is placed between the electrodes and SiO_2 layer to make the charge uniform and to discharge the charges that accumulate on the electrodes. However, the effectiveness of this technique was confirmed for an optical modulator loaded by 50 Ω and biased

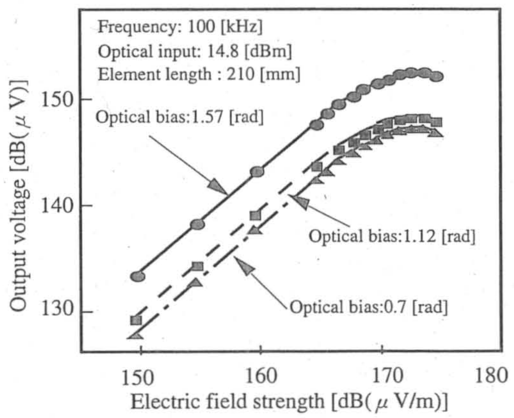

Fig. 3 Sensitivity of the electric field sensor when the optical bias angle is changed.

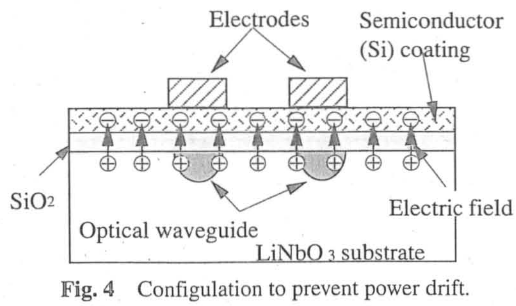

Fig. 4 Configulation to prevent power drift.

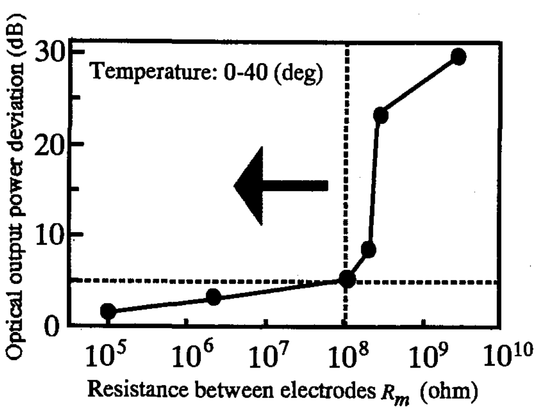

Fig. 5 Effect of reducing resistance between electrodes on optical output power deviation.

by DC voltage. It is therefore necessary to investigate the effectiveness of this configuration for the optical E-field sensor using the Mach-Zehnder interferometer with no load and DC bias.

We evaluated the effect of this coating on the power drift experimentally. A sensor was placed in a chamber, and the chamber's temperature was varied from 0 to 40°C. The resistance between the electrodes R_m was changed, and the deviation in the optical output power was measured with an optical power meter. As shown in Fig. 5, reducing R_m to less than 100 MΩ reduced the deviation of optical output power to less than 5 dB.

3.3 Design of Frequency Response

It has been reported that the resonance of an antenna element is reduced by making a traveling-wave antenna from resistive material [1], [13]. The frequency response of an optical E-field sensor using a bulk type modulator can be improved by loading resistances on a sensor element [11]. However, it has not yet been confirmed whether the resistively loaded element is also effective at improving the frequency response of an optical E-field sensor using Mach-Zehnder interferometer. The reason is that the input impedance is different from that of a bulk type modulator due to the different structure. Although the input impedance of a bulk type modulator is almost pure capacitance, that of a Mach-Zehnder interferometer consists of resistance and reactance such as capacitance and inductance.

We assume that this design method is also effective for a sensor using a Mach-Zehnder interferometer and that the distribution of the loading resistance at the point z along the element $Z_l(z)$ is given by [11]

$$Z_l(z) = R_f \psi(z) / (h/2 - z), \tag{7}$$

where

$$\psi(z) = 4\pi Az / \{\mu_0 Iz(z)\}. \tag{8}$$

Here, R_f is the coefficient of distribution, h is the element length, $Az(z)$ is the vector potential, $Iz(z)$ is the current in the element, and μ_0 is the permeability in free space. The distribution of loading resistance $Z_l(z)$ was calculated using Eq. (7) for an element length of 100 mm, and this profile was used to calculate the frequency response.

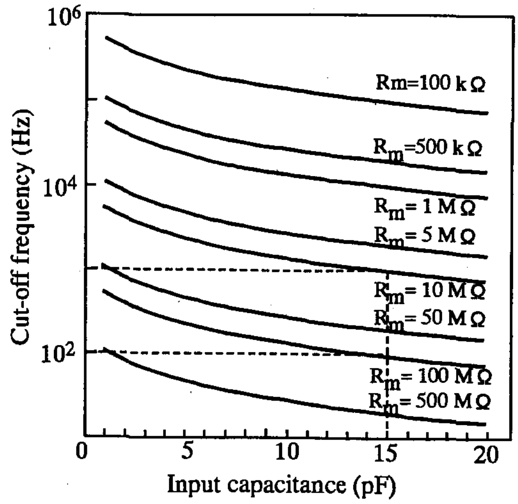

Fig. 6 Relationship between cut-off frequency of the sensor and input impedance of the Mach-Zehnder interferometer.

The other parameters related to the design of frequency response are the effective length of the sensor elements h_e and the driving point impedance of the sensor elements Z_a. Both these parameters depend on the frequency and are important in determining the frequency characteristics. They can be determined by using the method of moments in antenna theory considering the sensor element as a dipole antenna with loading resistance.

We calculated the frequency response due to changing R_f from 0 to 60 in order to search for a suitable value of R_f to make the frequency response flat, where $R_f = 0$ ($Z_l(z) = 0$) means the sensor element is perfectly conductive. As a result, the suitable value of R_f was 25 for this sensor, the same as for the sensor using a bulk type modulator, although the pattern of frequency response was obviously different. This clarifies that the resistively loaded element is also effective at improving the frequency response of an optical E-field sensor using Mach-Zehnder interferometer.

Moreover, the calculated results show that there is a reduction in frequency response at low frequencies, which is caused by the resistance of the SiO_2 coating on the $LiNbO_3$ substrate. Figure 6 shows the relationship between the cut-off frequency of the sensor and the input impedance of the Mach-Zehnder interferometer. The cut-off frequency means the frequency at which the out put level becomes 3 dB smaller than the reference level. It is shown that the cut-off frequency gradually decreases as the capacitance C_m and resistance R_m of the modulator increase.

From the standpoint of sensitivity stability, the resistance should be less than 100 MΩ to realize the stability of output power deviation within 5 dB, as shown in Fig. 5. Therefore, the cut-off frequency is at most 100 Hz when the capacitance of the modulator is 15 pF.

3.4 Case and Optical Fibers

Materials that do not disturb the electromagnetic field should be used for the sensor case. However, only a few kinds of materials are suitable for the case to protect optical parts: acrylic resin or ceramic composite is normally used for this type of sensor. The effect of these materials on the electromagnetic field should be analyzed theoretically by using simulation techniques as future work.

The optical fiber between the optical source and sensing part should be of the polarization-maintaining type to protect the polarization of the optical waves against outside disturbances, such as weighting, bending, and pulling. The optical fiber between the sensing part and photodetector can be of the single-mode type because it is not necessary to maintain the polarization after the optical intensity modulation.

The wave input to the fiber should be linearly polarized, but since it is generally difficult to input a perfectly linearly polarized optical wave, we used an elliptically polarized one instead. To investigate the allowance in the elliptically polarized wave, we estimated the extinction ratio. Denoting the error in sensitivity as ΔP [W], the extinction ratio Fr [dB] is expressed as [15]

$$Fr = 10 \log \Delta P / (P_{in} - \Delta P). \quad (9)$$

Then, the relation between the extinction ratio Fr and the error in sensitivity Δp [dB] is solved as

$$\Delta p = -10 \log (10^{(-Fr/10)} + 1). \quad (10)$$

If the extinction ratio is more than 6 dB, the error in sensitivity Δp is less than 1 dB.

An optical connector is used to connect the LD optical source with the optical fiber. The extinction ratio of the light source (LD source) is expected to remain above 15 dB because the extinction ratios of the optical connector and the polarization-maintaining fiber are more than 30 dB/km[16]. Therefore, it is unnecessary to consider the effect of the polarization characteristics of the light source.

Moreover, it can be considered that the parameters η_p and η_s, the transmission loss constants of the optical fibers, are almost 1 because their loss is less than 1 dB/km [4].

4. Measured Characteristics

4.1 Structure of Fabricated Optical E-Field Sensor

To verify the design methods described in Sect. 3, we fabricated an optical E-field sensor. The characteristics of the sensor were measured and compared with those estimated by our theoretical analysis.

A photograph of our fabricated sensor is shown in Fig. 7. The Mach-Zehnder interferometer had a half-wave voltage of less than 2 V and an operating bandwidth ranging from DC to more than 10 GHz. It was formed by Ti diffusion on a 55-mm-long, 1-mm-wide, 0.5-mm-thick, Z-cut $LiNbO_3$ substrate. The waveguides, which were divided into two path, were 40-mm-long, and the separation between them was 26 μm. The sensor case was 150-mm-long, 20-mm-wide, and 26-mm-thick; it was made of acrylic resin. The part supporting the modulator was made of a ceramic composite with a low thermal expansion coefficient to prevent it from being affected by temperature changes. The insertion loss of the optical modulator was 8.8 dB, and the optical bias angle was tuned to 1.57 radian by tuning a screw located on the side of the sensor case. The light source was a LD-pumped YAG laser with a wavelength of 1.3 μm and an output power of 30 mW (14.8 dBm). The photodetector was a PIN photodiode (HP11982) with a frequency range of DC to 15 GHz. The constants used for estimation are given in Table 1.

4.2 Stabilized Temperature Characteristics

To determine the effect of the Si coating on the $LiNbO_3$ substrate, we placed the sensor in a chamber and varied the temperature of the chamber from 0 to 40°C during a 500-minute cycle. The optical output power of the modulator was measured with an optical power meter. Its temperature dependence of the optical output in the case of no coating had a deviation of more than 20 dB, and the changes in output power was remarkable when the temperature was changed. This deviation was apparently caused by pyroelectricity because the changes usually appeared when the temperature changed. The

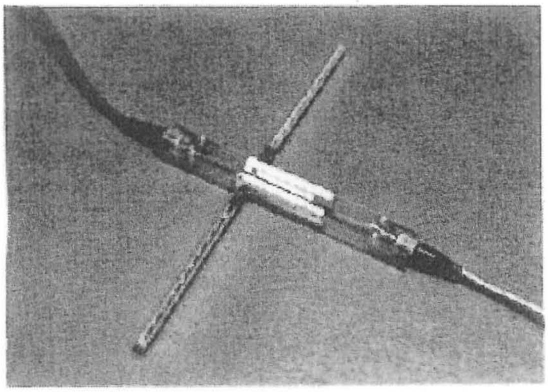

Fig. 7 Photograph of fabricated electric field sensor.

Table 1 Parameters for estimating sensitivity.

Element radius a	2 mm
Element length h	210 mm
Capacitance of modulator C_m	15 pF
Resistance of Si buffer R_m	14 MΩ
Optical bias angle ϕ_m	1.57 rad
Half-wave voltage V_π	2.0 V
Optical input power p_{in}	30 mW
Insertion loss constant of the modulator η_m	0.25
Transmission loss constants of optical fibers η_n , η_s	1.0
Conversion constant of photo-detector η_d	250 V/W
Internal impedance of level meter Z_{in}	50 Ω
Output impedance of level meter Z_n	50 Ω

improved sensor with the Si coating had a deviation of less than 2 dB, as shown in Fig. 8. This means that a sensor with a Si-coated modulator can operate stably in an indoor environment.

4.3 Estimation of Sensitivity

We measured the sensitivity of the sensor by using a transverse electromagnetic (TEM) cell with a bandwidth of 150 MHz. An electric field ranging from 10 to 120 dB (μV/m) was generated in the cell, and the output level of the photodetector was measured with a level meter, whose minimum bandwidth was 1 kHz. The sensitivity measured at a frequency of 100 MHz is shown in Fig. 9. The sensor exhibited an ideal linear response from 17 to 120 dB (μV/m), indicating that it has a dynamic range of more than 100 dB. The minimum detectable electric field strength was 17 dBμV/m (8 μV/m). The sensitivity of the sensor with a metallic element was almost the same as that of the sensor with an element loading resistance. This shows that the effect of the element loading resistance is just to suppress the resonance.

The solid line in Fig. 9 represents the results calculated using Eq. (5). The constants for the actual sensor in Table 1 were used for the calculation. These calculated results agree closely with the measured ones. Since the numerical expression 'V [dB(μV)] = E [dB(μV/m)] – 14' presents the relationship between the induced E-field strength and the output voltage of the level meter, the intersection '14 ' means an antenna factor [17] . The deviation between the calculated and measured results was within 3 dB. This means that, using the method presented in Sect. 3.1, we succeeded in accurately designing the sensitivity of an optical E-field sensor with a Mach-Zehnder interferometer.

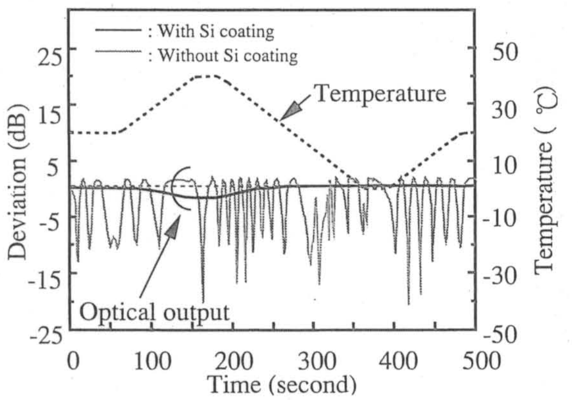

Fig. 8 Optical output power deviation with changing temperature.

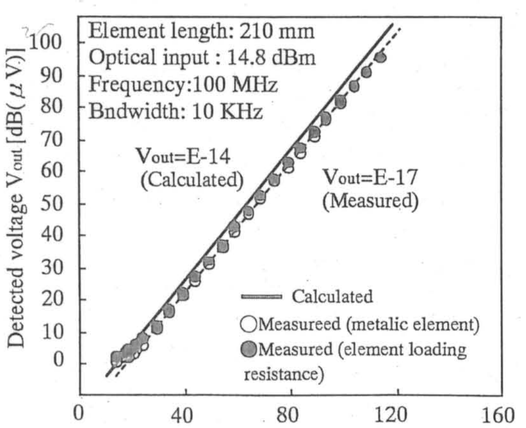

Fig. 9 Sensitivity responce of the sensor.

4.4 Estimation of Frequency Response

The configuration of the proposed element loading resistance is shown in Fig. 10. It was constructed of ten resistors that can operate at high frequencies. The value of each resistor was fitted to the resistance distribution calculated by Eq. (7).

The measured frequency response is shown in Fig. 11. The maximum frequency bandwidth, when the deviation of sensitivity was within 3 dB, was obtained when R_f was 25. It increased from 10 MHz to 900 MHz in ±3 dB deviations, compared with the response in the case of a metallic element when R_f was 0. The solid and dotted line in Fig. 11 are the results calculated by the moments method in Sect. 3.3. The constants for an actual sensor in Table 1 were used for the calculation. The calculated results agree closely with the measured ones. This means that the optimal distribution of loading resistance can be also designed for the sensor with a Mach-Zehnder interferometer using the method in Sect. 3.3.

Figure 12 shows the responce at low frequencies. The resistance of Si coating R_m was 14 MΩ and the input capacitance C_m of the optical modulator was 15 pF. The calculated values agree well with the measured ones.

We measured the frequency response of the sensor across a broad bandwidth, DC- 1 GHz, by using a calibrated electrical field supplied by a TEM or GTEM (GHz Transverse Elec-

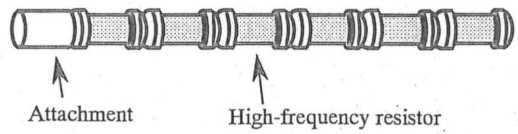

Fig. 10 Configuration of resistive element.

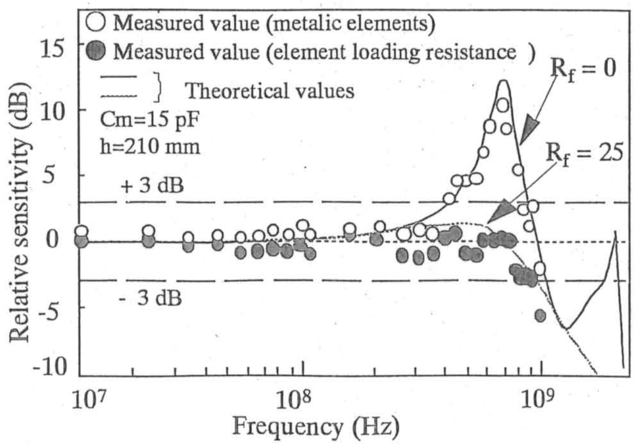

Fig. 11 Frequency response of optical E-field sensor using Mach-Zehnder interferometer with element loading resistance.

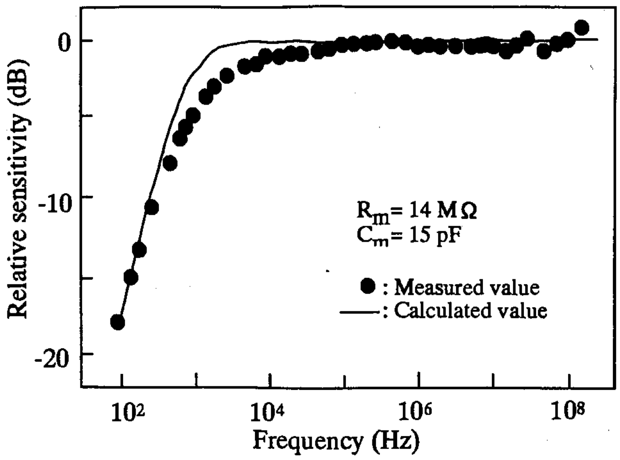

Fig. 12 Response in low-frequency band.

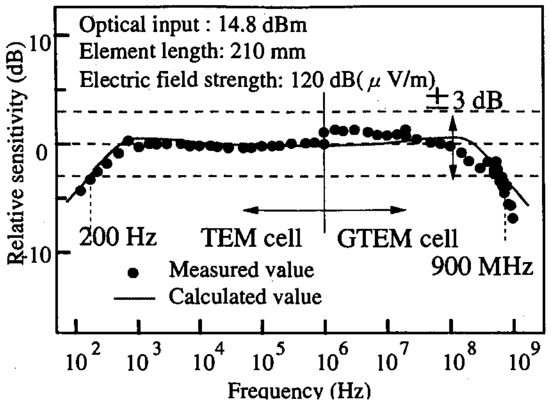

Fig. 13 Frequency response of sensor.

tromagnetic) cell. A PIN photodiode, which can operate from DC to 15 GHz, was used as the photodetector. Figure 13 shows the relative sensitivity when the induced electric field strength was 120 dBμV/m and the value at 1 MHz was put as a reference level. The cut-off frequency decreased up to 1 kHz with increasing resistance of the Si coating; the frequency bandwidth ranged from 200 Hz to 900 MHz. Therefore, this sensor is useful for broad bandwidth measurements, such as measuring electromagnetic pulses and testing EMC measurement facilities.

The dotted line in Fig. 13 is the results calculated using Eq. (5). The constants for an actual sensor in Table 1 were used for the calculation. These calculated results agree closely with the measured ones and the deviation is within ±3 dB. This means that the frequency characteristics of the sensitivity can be designed using the method presented in Sect. 3.1.

5. Conclusion

We have described our optimal method for designing the sensitivity and frequency response of an E-field sensor with a Mach-Zehnder interferometer. First, we derived the equivalent circuit of the optical E-field sensor and its parameters using a new method. Then, we theoretically analyzed them to determine the values of the parameters. Finally, we fabricated a sensor and compared its characteristics with the theoretical values.

Our study clarified the following points.

- The frequency and sensitivity response of an E-field sensor using a Mach-Zehnder interferometer have been analyzed accurately for the first time as the absolute value of output voltage. The differences from the measured values were within 3 dB.
- It has been confirmed experimentally that the sensitivity can be designed to be most sensitive by tuning the optical bias.
- It has been confirmed experimentally that the optical E-field sensor can be designed by using a modified Mach-Zehnder interferometer to suppress piezoelectric resonance.
- It has been confirmed theoretically and experimentally that the method of suppressing resonance by using resistively loading elements is also effective in a sensor using a Mach-Zehnder interferometer.
- It has been confirmed experimentally that the Si coating on a Mach-Zehnder interferometer is also effective in stabilizing the sensitivity of the optical E-field sensor against temperature changes.
- The fabricated sensor has a high sensitivity of 17 dB (μV/m) (= 8 μV/m) and a broad bandwidth of 200 Hz to 900 MHz.

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References

[1] M.Kanda and L.D.Driver, "An isotropic electric-field probe with tapered resistive dipoles for broadband use, 100 kHz to 18 GHz," IEEE Trans. Microwave Theory & Tech., vol.MTT-35, no.2, pp.124-130, Feb. 1987.

[2] K.Murakawa, N.Kuwabara, and F.Amemiya, "Receiving properties of a receiving spherical dipole antenna," IEICE Technical Report, EMCJ87-86, 1991.

[3] K.Tajima, N.Kuwabara, R.Kobayashi, and M.Tokuda, "Improved sensitivity in an electric field sensor with $LiNbO_3$ electro-optic crystals by loading inductance," IEICE Trans., vol.J76-B-II, no.6, pp.538-545, June 1993.

[4] R.Kobayashi, K.Tajima, N.Kuwabara, and M.Tokuda, "Theoretical analysis of the sensitivity on electric field sensor using $LiNbO_3$ optical modulator," IEICE Trans., vol.J79-B-II, no.11, pp.734-743, Nov. 1996.

[5] N.Kuwabara and R.Kobayashi, "Development of electric field sensor using Mach-Zehnder interferometer," Proc. 11th International Zurich Symp. on EMC, Switzerland, pp.489-494, 1995.

[6] F.Gassmann and M.Mailand, "A 9 channel photonic isotropic electric and magnetic field sensor with subnanosecond rise time," Proc. 12th International Zurich Symp. on EMC, Switzerland, pp.217-221, 1997.

[7] M.Schwerdt, J.Berger, and K.Petermann, "An integrated optical E-field sensor using a reflection scheme," Proc. 12th International Zurich Symp. on EMC, Switzerland, pp.597-602, 1997.

[8] K.Tajima, N.Kuwabara, R.Kobayashi, and M.Tokuda, "Evaluation of electric field sensor with very small elements using Mach-Zehnder interferometer," IEICE Trans., vol.J79-B-II, no.11, pp.744-753, Nov. 1996.
[9] R.Kobayashi, K.Tajima, N.Kuwabara, and M.Tokuda, "Optical bias angle control method for electric-field sensor using Mach-Zehnder interferometer," IEICE Trans., vol.J81-B-II, no.5, pp.542-549, May 1998.
[10] R.Kobayashi, K.Tajima, N.Kuwabara, and M.Tokuda, "Improvement of frequency characteristics of electric field sensor using Mach-Zehnder interferometer," IEICE Trans., vol.J81-B-II, no.7, pp.699-706, July 1998.
[11] K.Tajima, R.Kobayashi, N.Kuwabara, and M.Tokuda, "Frequency bandwidth improvement of electric field sensor using optical modulator by resistively loaded element," Trans. IEE Japan, vol.117-A, no.5, 1997.
[12] I.Sawaki, "Improvement of temperature characteristics of Z-cut $LiNbO_3$ waveguide devices by semi-insulating Si film coating in chip surface," IEICE Technical Report, OQE86-44, 1986.
[13] M.Kanda, "A relatively short cylindrical broadband antenna with tapered resistive loading for picosecond pulse measurements," IEEE Trans. Antennas & Propag., vol.AP-26, no.3, pp.439-447, May 1978.
[14] H.Nishihara, M.Haruna, and T.Suhara, ed. Optical integrated circuits, chap.10, ver.2, Ohm co., 1987.
[15] Hikarisangyoshinko Foundation, Handbook of useful optical technology, part 4, chap.2, pp.348-350, Oputoronikusu co., 1989.
[16] T.Okoshi, H.Nishihara, K.Okamoto, K.Kyuma, M.Otsu, and K.Hotate, ed. Optical fiber sensor, chap.2, sec.3, p.23, Ohm co., 1986.
[17] T.Akao, Basic of EMC, chap.4, sec.3.3, p.276, IEICE., 1991.

Kimihiro Tajima received the BE and ME degrees in Electronic Engineering from Kumamoto University, Kumamoto, Japan in 1986 and 1989 respectively. He entered NTT Telecommunication Networks Laboratories and has been engaged in the studies on the optical measuring methods for EMC. In 1991-1993, he was engaged in technical supports for EMC troubleshooting in field at NTT Technical Assistance and Support Center. Currently, he is a Senior Research Engineer of NTT Lifestyle and Environmental Technology Laboratories and he researches EMC measuring methods, indoor mobile communication systems using infrared rays and knowledge creating offices for new lifestyle with multimedia communications. Mr.Tajima is a member of IEEE, URSI, the national commitee of CISPR/A.

Ryuichi Kobayashi received the BE and ME degrees in Communication Engineering from University of Electro-Communications, Tokyo, Japan in 1991 and 1993 respectively. He entered NTT Telecommunication Networks Laboratories. He has been engaged in research and development of optical measurement technique for EMC. Currently, he is a Chief engineer of NTT Technical Assistance and Support Center. Mr.Kobayashi is a member of IEEE and URSI.

Nobuo Kuwabara received the BE and ME degrees in Electrical Engineering from Shizuoka University, Shizuoka, Japan in 1974 and 1976 respectively, and the Dr.Eng. degree from Shizuoka University in 1992. Since joining NTT in 1977, he has been engaged in research on the overvoltage protection of telecommunications system and design of the induction free optical fiber cable. He is currently involved in studies of the electromagnetic compatibility telecommunication system. He is a manager of electromagnetic environment research group in NTT Lifestyle and Environmental Technology Laboratories. Dr.Kuwabara is a member of IEEE.

Masamitsu Tokuda received the BE and ME degrees in Electronic Engineering from Hokkaido University, Hokkaido, Japan in 1967 and 1969 respectively. He joined the Electrical Communication Research Laboratory and he has been engaged in research on transmission measurement of optical cables and EMC for telecommunication networks. He is currently a Professor in Faculty of Engineering, Kyushu Institute of Technology. Dr.Tokuda is a member of IEEE.