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 were evaluated experimentally. The results show that the designed sensitivity and frequency response were optimal. The minimum detectable electric field strength was within 2 dB. The frequency range meets the requirements of 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.

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]:

- 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 stand point 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.

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 avalanche 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

\[
V_{out} = \frac{Z_m}{(Z_m+Z_o)} V_i = \frac{Z_m}{(Z_m+Z_o)} \eta_p P_{out} \tag{1}
\]

where

\[
P_{out} = \eta_p P_{in} \left(1 + \cos \frac{\pi V_i}{V_c+\phi_m}\right) \tag{2}
\]

\[
V_c = Z_m \left(1+Z_m+Z_o\right) E h_e \tag{3}
\]

Here, \( Z_m \) is the internal impedance of the level meter, \( Z_o \) is the output impedance of the photodetector, \( V_i \) is the induced voltage by the photodiode, \( \eta_p \) 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, \( \eta_p \) and \( \eta_m \) are the transmission loss constants of the optical fibers connected to the input and output port of the modulator, \( \eta_m \) 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, \( V_c \) is the half-wave voltage of the modulator, \( \phi_m \) is the optical bias angle, \( Z_m \) 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, \( Z_o \) is the loaded impedance with the sensor element, and \( Z_m \) is the input impedance of the optical modulator.

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, \( C_m \):

\[
Z_m = \frac{1}{(1/R_m + j\omega C_m)} \tag{4}
\]

We can thus transform Eq. (1) into

\[
V_{out} = \frac{Z_m}{(Z_m+Z_o)} \eta_p \eta_m \eta_p \left(1 + \cos \frac{\pi V_i}{V_c+\phi_m}\right) \left[1+\cos \frac{\pi V_c}{V_c+Z_m} \left(1+j\omega C_m R_m\right) \right] \left(1+j\omega C_m R_m\right) \tag{5}
\]

In Eq. (5), the values of \( Z_m, Z_o \) and \( \eta_m \) depend on the measuring apparatus; the values of \( \eta_p, C_m, R_m, \phi_m, V_c \) and \( \eta_m \) can be chosen based on the following considerations; \( Z_m, Z_o \).
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 $\Omega$ and biased

---

$h_i$ can be calculated as described in Sect. 3.3; and $\eta_p$ and $\eta_s$ are determined by measurement, as described in Sect. 3.4.

As shown in Fig. 2, the parameters needed to design the optical modulator are $Z_m$, $\eta_m$, $V_m$ and $\phi_m$. The $R_m$ and $C_m$ can be measured using a impedance analyzer at low frequencies because they are independent of the frequency. The $p_m$ and the insertion loss constant of the optical modulator, $\eta_m$ can be measured without applying a voltage using an optical power meter because they are also independent of the frequency. The $\phi_m$ 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].

$V_m$ 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]

$$V_m = \frac{\lambda}{2\pi} \frac{d}{\gamma_{31}}$$

where $\lambda$ is the optical wavelength, $d$ is the electrode gap of an optical modulator, $\gamma$ is the reduction in the applied electric field, $n_2$ is the refractive index, $\gamma_{31}$ is the Pockels coefficient, and $\lambda$ 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 $\pm 2$ 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 $\phi_m$ 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...
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 \( Z(z) \) is given by [11]

\[
Z(z) = R_f \psi(z) / (h/2 - z),
\]

where

\[
\psi(z) = 4\pi A \mu_0 l(z).
\]

Here, \( R_f \) is the coefficient of distribution, \( h \) is the element length, \( A \) is the vector potential, \( l(z) \) is the current in the element, and \( \mu_0 \) is the permeability in free space. The distribution of loading resistance \( Z(z) \) was calculated using Eq. (7) for an element length of 100 mm, and this profile was used to calculate the frequency response.

The other parameters related to the design of frequency response are the effective length of the sensor elements \( h \) and the driving point impedance of the sensor elements \( Z_0 \). 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 \( R_f = 0 (Z(z) = 0) \) 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 SiO₂ coating on the LiNbO₃ substrate. Figure 6 shows the relationship between the cut-off frequency of the sensor and input impedance of the Mach-Zehnder interferometer. The cut-off frequency means the frequency at which the output 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 kΩ 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 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 $\Delta P$ [W], the extinction ratio $Fr$ [dB] is expressed as [15]

$$Fr = 10 \log \left( \frac{P_{in}}{P_{out}} - \Delta P \right).$$

Then, the relation between the extinction ratio $Fr$ and the error in sensitivity $\Delta P$ [dB] is solved as

$$\Delta P = -10 \log \left( 10^{-\frac{Fr}{10}} + 1 \right).$$

If the extinction ratio is more than 6 dB, the error in sensitivity $\Delta P$ 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 $\eta_p$ and $\eta_s$, 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 $\mu$m. 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 $\mu$m 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$^\circ$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.](image-url)
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 $V_{out}[dB(\mu V)] = E_{field}[dB(\mu V/m)] - 14$ 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.

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 response 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-
We thank the members of the EMC Group in the NTT Lifestyle and Environmental Technology Laboratories for their assistance and encouragement.

Acknowledgments

References


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.

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 committe 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.

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 committe of CISPR/A.