antenna with the same size factor \( (ka = 2.46) \) [11]. The Half Power BeamWidth (HPBW) in horizontal (XoY) and vertical (YoZ) planes are respectively 48° and 58° in simulation and 45° and 56° in measurement. The simulated Front to Back Ratio (FBR) is 18.3 dB while the measured one is 13 dB (Fig. 5). Figure 3(d) shows the antenna radiation efficiency. It can be noticed that this efficiency rapidly decreases when approaching the design frequency. This is mainly due to the superdirectivity phenomena; where the current opposition on the different elements cancels the antenna radiation in certain directions, and hence, reduces its radiation efficiency. The antenna has a simulated radiation efficiency of 46% (a gain of 8.3 dB) and an experimental one (measured in a reverberation chamber [12]) of 47.3% (a gain of 8 dB). The antenna 3D co-polar directivity radiation pattern given in Figure 6 shows a very good agreement between the simulated and measured patterns. The maximum copolar directivity is also in the end-fire (oY) direction with a simulated value of 11.6 dBi and a measured one of 11 dBi. The antenna cross-polar 3D directivity radiation pattern is given in Figure 7. The maximum cross-polar directivity is in the broadside (oZ) direction and it has a simulated value of −4.7 dBi and a measured one of −1.2 dBi. The small difference between simulated and measured results can be attributed to the cable effect, the uncertainties in the SMD components values and measuring system and environment. This antenna is very compact compared to others presenting the same directivity. A Yagi-Uda antenna with the same directivity is around 535 × 175 × 40 mm³ [13].

4. CONCLUSION

In this letter, we presented a compact four-element parasitic-loaded superdirective array for 900 MHz frequency band for UHF RFID readers. The antenna dimensions were 231 × 122 mm² and it presented a total directivity of 11.6 dBi and a radiation efficiency of 46%. This array is significantly compact compared with antennas with the same directivity available in the market.

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RELATIONSHIP BETWEEN DIRECTIONAL PATTERNS AND THE ELECTRODE STRUCTURE OF THE LOG-PERIODIC DIPOLE ANTENNA ARRAYS FOR SENSITIVE OPTICAL ELECTRIC FIELD SENSORS

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ABSTRACT: An evaluation of the sensitivity characteristics of our improved optical electric field sensor (OEFS) that incorporates our log-periodic dipole antenna array (LPDA-type OEFS) via a detailed simulation model indicated an excellent but less than perfect outcome (Tsujino et al. PIERS Proc 2012), 1610–1614, Hidaka et al. Microwave Opt Technol Le 8th European Conference, 6–11 April 2014). However, in-depth observations of directional patterns and frequency responses with horizontally polarized microwaves indicated that the microgaps of the electrodes of the LPDA-type OEFS have a high sensitivity in the lateral direction. This behavior is closely related to the problems regarding electromagnetic compatibility. © 2016 The Authors. Microwave and Optical Technology Letters. 58:2124–2129, 2016; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29992

Key words: optical electric field sensor; log-periodic; antenna; microwave; microgap
1. INTRODUCTION

When the Internet of Things becomes mainstream, the number of wireless connections to the Internet increases significantly. To employ these wireless systems effectively, it is necessary to accurately characterize their electromagnetic field intensity. However, an optical electric field sensor (OEFS)-based instrument with fiber optics can be used to reduce the invasiveness of measuring the subject’s electromagnetic field [3]. The OEFS, which is composed of dielectric materials except for its antenna elements, has less interference on the electromagnetic field than antennas composed of metal [4].

Our improved OEFS that incorporates our log-periodic dipole antenna array (LPDA-type OEFS), shown in Figure 1, enables the accurate measurements of the Electromagnetic Field Interference (EMI), which previously could not be measured with reliable or repeatable accuracy [5,6]. In the past, signals were exceedingly difficult to detect in signal paths where measurements indicate both extraordinarily wide bandwidth and extraordinarily low level using an OEFS [4]. The minimum detectable electric field strength of an OEFS is 70 dBμV/m at a frequency of 2.0 GHz and a resolution bandwidth of 1 MHz [5].

In previous reports [1,2], we demonstrated that a more accurate and reliable method of assessing the sensitivity characteristics of the improved LPDA-type OEFS can be achieved by using a detailed simulation model that prevents large errors. The frequency responses of the improved LPDA-type OEFS were calculated by a newly developed computer program using Eq. (2) in the previous paper [2] combined with an electromagnetic field simulation. The detailed simulation model for the improved LPDA-type OEFS that is covered by a case using resins is shown in Figure 2 of the previous paper [2]. Tests have shown that the calculated frequency responses of the OEFS is its sensitivity to irradiation from the lateral direction. However, the characteristics of the OEFS should be known; therefore, we must further examine the causes of the asymmetry of the directional patterns of the improved LPDA-type OEFS. Based on measurements of a conventional log-periodic antenna [7], shown in Figure 3, which do not indicate alternation of the lateral direction’s sensitivities, as shown in Figure 2, the asymmetry of the improved LPDA-type OEFS’s directional patterns is not caused by transposed excitation.

The periodicity of the calculated amplitude of the impressed voltage near the frequency of each element’s half-wavelength resonance shown in Figure 4 corresponds with the periodicity of the measured frequency responses of the improved LPDA-type OEFS at frequencies between 2.3 and 4.0 GHz shown in Figure 2. An aperture, which can be referred to as a microgap, of each electrode of each element excites a half-wavelength resonance because the detailed simulation model for the OEFS does not include the asymmetry of the electrodes of adjacent elements that are excited in opposite directions (Transposed excitation) [5]. Because the calculation time tends to infinity when the shape and size of a detailed electrode is treated using the simulation model [2,5], the influence of the asymmetry of the electrode should be analyzed using another method. Therefore, we investigated the asymmetry of the measured directional patterns through in-depth observations of the measured directional pattern and other results.

Figure 2 shows the measured frequency responses of the improved LPDA-type OEFS for irradiation angles of 0°, 90°, and 270°. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Figure 1 Photograph of the improved LPDA-type OEFS and the element numbers of the OEFS. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Figure 3 Measured frequency responses of the conventional log-periodic antenna for irradiation angles of 0°, 90°, and 270°. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]
at frequencies between 2.3 and 4.0 GHz turns to the higher sensitivity side of 90° or 270°, as shown in Figures 5 and 6 and Table 1. An antenna can alternate between transmission and reception; consequently, when an optical modulator electrode that is the same as the improved LPDA-type OEFS is driven at a frequency, radiation is likely generated from the aperture.

2. EXPERIMENTAL PROCEDURE

The frequency responses of the improved LPDA-type OEFS are measured using a system that consists of a microwave network analyzer (Agilent Technologies, PNA E8363B), a double-ridged waveguide horn antenna for a transmission (TR17206) and a device for the OEFS (in Fig. 2). The device for the OEFS consists of a light source, the OEFS and a detecting element unit, the output of which is connected to the network analyzer [5]. The distance from the OEFS to the transmitting antenna is 3 m, and the transmitting antenna is irradiated with horizontally polarized microwave energy. The reception voltage of the network analyzer is corrected by the cable loss and the antenna factor of the transmitting antenna to become a constant electric field at a position of the OEFS. All measurements are performed in an anechoic chamber with dimensions of 7.87 m (W) × 11.5 m (D) × 6.66 m (H).

The frequency responses of a conventional log-periodic antenna (SCHWARZBECK UHALP 9108A1) are measured using a system that consists of a spectrum analyzer (Agilent Technologies, E4407B) and a half-wave dipole antenna for transmission (see Fig. 3). The distance from the conventional log-periodic antenna to the transmitting antenna as well as the other measurement conditions are the same as those for the improved LPDA-type OEFS.

We can derive the phase shift, which is proportional to the sensitivity of an OEFS, of the improved LPDA-type OEFS having multiple elements by calculating the amplitude and phase of the modulation voltage of each element [6]. When the OEFS covered by a case using resins presented previously [2] receives a horizontally polarized microwave (irradiation angle of 0°), the microwave impresses modulation voltages on the electrodes of the OEFS. The modulation voltages are calculated by an electromagnetic field simulation with the detailed simulation model of the OEFS (see Fig. 4) [2].

3. RESULTS AND DISCUSSION

3.1. Asymmetry of the Measured Directional Patterns

In the case of the directional patterns with horizontally polarized microwaves, the calculated directional pattern does not always correspond well with the measured directional pattern, as shown in Figure 5 of the previous paper [2]. In fact, the measured directional patterns are asymmetrical even though the calculated directional patterns are symmetrical. Therefore, the sensitivities of the irradiation angles of 270° and 90° must be compared regarding the measured frequency responses of the improved LPDA-type OEFS. The wide solid line, narrow solid line, and dotted line in Figure 2 indicate the measured frequency responses of the irradiation angles of 90°, 270°, and 0°, respectively. The maximum value of the relative sensitivities in Figure 2 is 0 dB. The peaks and troughs of the wide solid line (irradiation angle of 90°) and the narrow solid line (irradiation angle of 270°) alternate periodically with each other at frequencies between 2.3 and 4.0 GHz, as shown in Figure 2. Because the 30-th element, which is the longest element, excites the higher order resonance near the frequency of 4.2 GHz, the peaks and troughs of the wide solid line and narrow solid line alter irregularly at frequencies over 4.2 GHz.

3.2. Influence of the Transposed Excitation

A conventional log-periodic antenna is driven via alternating antenna elements with a 180° phase shift from one another (transposed excitation) [7]. In other words, the transposed...
excitation of a dipole array indicates that adjacent dipoles in the array are excited in opposite directions. The adjacent elements of the improved LPDA-type OEFS are excited in opposite directions, as in the case of the conventional log-periodic antenna [1,2,5]. If the asymmetry of the improved LPDA-type OEFS’s sensitivities (at frequencies between 2.3 and 4.0 GHz, shown in Fig. 2) is caused by transposed excitation, then the sensitivities of the irradiation angles of 270° and 90° must be compared regarding the frequency responses of the conventional log-periodic antenna.

The measured frequency responses of a conventional log-periodic antenna (SCHWARZBECK UHALP9108A1) are shown in Figure 3 for irradiation angles of 90°, 270°, and 0°. The maximum value of the relative sensitivities in Figure 3 is 0 dB. A half-wave dipole antenna with a center frequency of 1 GHz is used for transmission because the dipole antenna does not yield an asymmetrical directional pattern. If conventional log-periodic antennas are used for both transmission and reception, the asymmetry of the directional patterns will be offset.

As shown in Figure 3, the sensitivities of the irradiation angle of 90° are different from those of the irradiation angle of 270°; in addition, the peaks and troughs of the wide solid line (irradiation angle of 90°) and the narrow solid line (irradiation angle of 270°) alter irregularly at frequencies between 200 MHz and 1 GHz. This observation is different from the measured frequency responses of the improved LPDA-type OEFS at frequencies between 2.3 and 4.0 GHz. A double-ridged guide horn antenna (DRGA) was used to measure the frequency responses of a conventional log-periodic antenna from 1 to 3 GHz. The frequency responses between 1 and 3 GHz are considered to vary in the same manner as the frequency responses in Figure 3.

Thus, the asymmetry of the improved LPDA-type OEFS’ directional patterns (Fig. 5) is not caused by transposed excitation.

3.3. Calculated Amplitude of the Voltage Impressed on the Electrode

Figure 4 shows the amplitude of the impressed voltage near the frequency of a half-wavelength resonance calculated by an electromagnetic field simulation using the detailed simulation model of the LPDA-type OEFS [2]. The figure also provides the calculated amplitude of the impressed voltage from the 19-th element to the 30-th element. Comparing Figures 2 and 4, the peaks of the narrow solid line (irradiation angle of 270°) at frequencies between 2.3 and 4.0 GHz in Figure 2 correspond to the peaks of the lines shown in the calculated amplitude of the impressed voltage of the 25-th, 23-th, and 21-th elements in Figure 4. In addition, the peaks of the wide solid line (irradiation angle of 90°) at frequencies between 2.3 and 4.0 GHz in Figure 2 correspond to the peaks of the lines shown in the calculated amplitudes of the impressed voltages of the 24-th, 22-th, and 20-th elements in Figure 4. In contrast, when each odd-numbered element operates in a half-wavelength resonance mode, the sensitivity of the irradiation angle of 90° is the trough in the measured frequency responses. In addition, when each even-numbered element operates in a half-wavelength resonance mode, the sensitivity of the irradiation angle of 270° is the trough in the measured frequency responses.

3.4. Measured Directional Patterns

The measured directional patterns of the OEFS at 2.48, 2.91, and 3.44 GHz with horizontally polarized microwaves are shown in Figure 5(a), and the measured directional patterns at 2.32, 2.68, 3.17, and 3.75 GHz with horizontally polarized microwaves are shown in Figure 5(b). In Figure 6, the axis of rotation is the x-axis and the horizontal plane is the y-z plane. The maximum value of the directional patterns in Figures 5(a) and 5(b) is 0 dB, and the measured directional patterns are in increments of 2°. As shown in Figure 4 (and 2), the 2.48, 2.91, and 3.44 GHz in Figure 5(a) are the half-wavelength resonance frequencies of the odd-numbered elements, and 2.32, 2.68, 3.17, and 3.75 GHz in Figure 5(b) are the half-wavelength resonance frequencies of the even-numbered elements. Table 1 provides the maximum value of the measurement data at all azimuths, the average of the measurement data between 90° and 118° and the average of the measurement data between 242° and 270° at those frequencies in Figure 5. The sensitivity of the irradiation

![Figure 6][1] Relationship between the irradiation angles that are shown on a top view of the improved LPDA-type OEFS and the electrode’s pattern. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Thus, the asymmetry of the improved LPDA-type OEFS’ directional patterns (Fig. 5) is not caused by transposed excitation.

**Table 1** Maximum and Average Values of the Measurement Data.

| Frequency [GHz] | Maximum value in all azimuths [dBV] | Average value between 90° and 118° [dBV] | Average value between 242° and 270° [dBV] |
|-----------------|----------------------------------|----------------------------------|----------------------------------|
| 2.32            | −62.4                            | −81.4                            | −86.7                            |
| 2.48            | −63.6                            | −90.1                            | −81.7                            |
| 2.68            | −64.3                            | −91.0                            | −90.5                            |
| 2.91            | −66.4                            | −90.7                            | −81.7                            |
| 3.17            | −69.5                            | −84.9                            | −93.0                            |
| 3.44            | −70.1                            | −93.3                            | −86.0                            |
| 3.75            | −72.6                            | −85.6                            | −97.8                            |

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angle of $260^\circ$ is higher than the sensitivity of the irradiation angle of $100^\circ$ in Figure 5(a), whereas the sensitivity of the irradiation angle of $100^\circ$ is higher than the sensitivity of the irradiation angle of $260^\circ$ in Figure 5(b). These results correspond well with the results in Table 1. However, at 2.32 GHz, the sensitivity is reduced at the angle of $98^\circ$. As shown in Figure 2, although the difference between the peaks and troughs for frequencies less than 2.2 GHz is the same as the difference between the peaks and troughs for frequencies greater than 2.2 GHz, the half-wavelength resonance modes of odd-numbered elements or even-numbered elements may not always yield a relationship such as that shown in Figure 5 at frequencies less than 2.2 GHz. Adjacent elements excite a half-wavelength resonance mode.

3.5. Relationship Between the Directional Patterns and the Electrode’s Structure

Figure 6 shows a top view of the relationship between the irradiation angles and the electrode’s structure of the improved LPDA-type OEFS. One electrode in the middle of two optical waveguides is said to be the electrode of the T-side, and another electrode that surrounds the electrode of the T-side is said to be the electrode of the C-side. All of the aperture widths of the electrodes of the C-side are approximately 50 $\mu$m, and the aperture operates as a microgap, as shown below [8]. The ratio of the lengths of an electrode of the T-side to an antenna element is 2.67–49.2, and the ratio of an electrode of the C-side to the lengths of an antenna element is approximately 5.34–49.2. The apertures of the electrodes of even-numbered elements turn to the irradiation angle of $90^\circ$, and the apertures of the electrodes of odd-numbered elements turn to the irradiation angle of $270^\circ$, as shown in Figure 6. An aperture of an electrode that excites a half-wavelength resonance at frequencies between 2.3 and 4.0 GHz turns to the higher sensitivity side of $90^\circ$ or $270^\circ$, as shown in Figure 5 and Table 1.

At each frequency in Table 1, there is only a difference of approximately 16 dB between the maximum value in all azimuths and the average value of the higher sensitivity side, and the difference in the average values between the $90^\circ$-degree side and the $270^\circ$-degree side is approximately 9 dB. These differences are produced by the C-side’s electrodes, which operate as an antenna. The electrode length of the C-side exceeds 10% of the antenna element length because the electrode of the C-side surrounds the electrode of the T-side. This length of the C-side’s electrode is sufficient to detect an electric field that is at a right angle to an antenna element. The conductor that connects to an antenna element located on a central part of an aperture does not disturb the microwave radiated from the aperture via the proportion of the electrode length to the antenna element length and the difference of 16 dB mentioned above.

An antenna has reversibility between transmission and reception; thus, when an optical modulator with an electrode that is the same as the improved LPDA-type OEFS is driven at a frequency, radiation is likely generated from the aperture. A previous paper [8] discussed a transient because of microgap discharge; the length of the microgap is near the aperture width of our OEFS electrode. However, our experiments suggest that a regular electromagnetic wave radiates from a microgap; consequently, this electromagnetic wave radiation is closely related to problems regarding electromagnetic compatibility (EMC).

4. CONCLUSION

This paper demonstrated that the peaks and troughs of the irradiation angles of $90^\circ$ and $270^\circ$ alternate periodically with each other via observation of the measured frequency responses of the improved LPDA-type OEFS, as shown in Figure 2. The periodicity of the calculated amplitude of the impressed voltage at the frequency of each element’s half-wavelength resonance in Figure 4 corresponds with the periodicity of the measured frequency responses of the OEFS at frequencies between 2.3 and 4.0 GHz in Figure 2. Furthermore, the OEFS has asymmetrical electrodes with an aperture, as shown in Figure 6. Therefore, the asymmetry of the directional patterns shown in Figures 2 and 5 occurs because the OEFS has apertures operating as a microgap, which has a high sensitivity in the lateral direction. If we consider that an antenna has reversibility between transmission and reception, our experiments suggest that regular electromagnetic waves radiate from the microgap; thus, this electromagnetic wave radiation is closely related to problems regarding EMC.

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APPENDIX

The following essay is a digest of the document: The Optical Electric Field Sensor Works in High Sensitivity in the Microwave Band [5]. Herein, the numbers of the figures are the same as those within the document [5]. WE WANT REVIEWERS TO MAKE ACCESSIBLE USE OF THE FOLLOWING ESSAY FOR ACQUIRING AN IN-DEPTH EVALUATION OF OUR RESEARCH.

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The Optical Electric Field Sensor Works in High Sensitivity in the Microwave Band

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1. INTRODUCTION

Using an Optical Electric Field Sensor (OEFS)-based instrument with fiber optics reduces the invasiveness of measuring the subject’s electromagnetic field. We found that the conventional OEFS lacks
the sensitivity to use for Electro-Magnetic Interference (EMI) measurements in which measuring a very small level of electromagnetic field strength is imposed upon a sensor in the microwave band. In this paper, we propose an OEFS employing a Log-Periodic Dipole antenna Array (LPDA) that works with high sensitivity and wide bandwidth in the microwave band. The LPDA-type OEFS was developed by using an electromagnetic field simulation combined with a newly developed computer program [2], and the resultant frequency responses of the simulated results are compared with frequency responses of the measured results. We have also developed an LPDA-type OEFS that makes it possible to achieve EMI measurements as shown in Chapter 4.

2. STRUCTURES AND IMPROVEMENT POINTS OF THE LPDA-TYPE OEFS

2.1. The LPDA-Type OEFS In an Early Stage
A schematic of an LPDA-type OEFS in an early stage is shown in Figure 1(a). At first, the LPDA including antenna elements was put on a substrate that was constructed from a Lithium Niobate (LN), whereby the number of antenna elements was 54 pairs, and electrodes of antenna elements did not have a phase reversal structure. A single optical waveguide that was used for an optical modulator having multiple electrodes was put on the substrate [2], so we called it a SW-LPDA-type OEFS. An electro-optical coefficient $r_{22}$ of LN crystal affected the phase shift. The minimum detectable electric field strength of the SW-LPDA-type OEFS at 2 GHz was approximately 70 dB/$\mu$V/m at 1 kHz resolution bandwidth (RBW). However, the sensitivity of the SW-LPDA-type OEFS was not high enough to use it for the EMI measurements.

2.2. Improvement of the LPDA-Type OEFS
A schematic of an improved LPDA-type OEFS is shown in Figure 1(b). An optical waveguide Mach-Zehnder interferometer is used for the optical modulator of the improved LPDA-type OEFS that we call an MZ-LPDA-type OEFS. In this case, an electro-optical coefficient $r_{13}$ that is approximately 9 times the electro-optical coefficient $r_{22}$ affects the phase shift. Because there is a reflector in one side of the optical waveguide, the product of $\tau$ and $\omega_m$ must be approximately $2\pi$ ($\omega_m \tau \approx 2\pi$). Herein, $\tau$ is a travelling time of a light, and $\omega_m$ is a frequency of the half wavelength resonance. When a light makes a round trip to a nearby resonating element and the reflector, $\tau$ is the round trip time of the light. Antenna elements, except electrodes of the improved LPDA, are put on an AD-1000 board (AD1000 materials are used in stripline or microstrip applications.), the number of antenna elements is 30 pairs, and the electrodes of the antenna elements are driven via alternating elements with 180° ($\pi$ radians) of phase shift from one another; these are different from the SW-LPDA-type OEFS.

3. ELECTROMAGNETIC FIELD SIMULATION

3.1. An Analytical Condition
Because an LN has anisotropy in a dielectric constant and the SW-LPDA-type OEFS has many antenna elements, it has been difficult to analyze the SW-LPDA-type OEFS by an electromagnetic field simulation. However, the improvement of the antenna array in 2.2 has enabled the analysis of the MZ-LPDA-type OEFS. A conception diagram of its simulation model is shown in Figure 3.

The total amount of the phase shift is

$$\delta Tm = \frac{4r_3\phi_n}{d_{12}} \sum_{k=1}^{N} \left\{ L_k V_{mk} \sin(\omega_m t - \phi_{mk}) \cos(\omega_m T_k) \right\}$$  (8)

The amplitude $V_m$ and phase $\phi_m$ of the voltage that was applied to the electrode of each antenna element was calculated in a condition shown in Chapter 2. When $k$ is an even number or an odd number, the mark of $V_m$ is plus or minus, respectively, because electrodes of antenna elements have a phase reversal structure.

3.2. Simulation Results
The amplitude level $V_m$ at each frequency range when the larger voltage is applied to an electrode is shown in Figures 4 and 5. At lower frequency, $V_m$ of an element having a half wavelength resonance is larger than the others, as shown in Figure 4. At 6.5 GHz, $V_m$ of Ant 13 that is yielding a half wavelength resonance is larger than others, but $V_m$ of Ant 24 that is yielding a 3/2 wavelength resonance is near to $V_m$ of Ant 13, as shown in Figure 5. Because the electrode length of Ant 24 ($L_{24}$) is longer than the electrode length of Ant 13 ($L_{13}$), Ant 24 has a larger phase shift than Ant 13, as shown in Eq. (8). As shown in Figure 6, because $\phi_m$ of an element adjacent to an element yielding a half wavelength resonance is reversed with respect to each other, the phase reversal structure of electrodes described in 2.2 is needed.

3.3. Sensitivity Characteristics
Because the amplitude of $\delta Tm$ is large in proportion to the sensitivity of the MZ-LPDA-type OEFS at a frequency $\omega_m$, the frequency response (shown in Fig. 8) of the OEFS is derived by the total amount of phase shift $\delta Tm$. From 1.8 GHz to 6.0 GHz, because the product of $\tau$ and $\omega_m$ is approximately $2\pi$, the sensitivity of the OEFS is highly desirable. At the same frequency range, the frequency response of the OEFS calculated by the simulation closely corresponds to the measured result. From 6 GHz to 8 GHz, the frequency response of the OEFS calculated by the simulation falls off sharply, but the frequency response of the measured result does not fall off sharply. It is necessary to analyze the OEFS with a more detailed simulation model to make the results of simulation correspond well with the measured results.

4. EMI MEASUREMENTS
Sensitivities of various antennas compared with a Double-Rigged Guide Antenna (DRGA 3115) are shown in Figure 9. At 2 GHz, the MZ-LPDA-type OEFS is 10 dB more sensitive than a dipole antenna. At 5 GHz, the OEFS is as sensitive as a dipole antenna. Because the minimum detectable electric field strength of the OEFS is 70 dB/$\mu$V/m at 2.0 GHz (at 1 MHz RBW), the OEFS makes it possible to measure the noise that is generated from a clock signal of a personal computer.

5. CONCLUSION
Because a conventional OEFS is insensitive in the microwave band, the OEFS cannot be used for EMI measurements for which high sensitivity and wide bandwidth are imposed upon a sensor. However, because the improved LPDA-type OEFS works with high sensitivity and wide bandwidth in the microwave band, we can use the OEFS for such EMI measurements. Important issues of a future LPDA-type OEFS concern making it more sensitive with frequencies between 1.0 GHz and 1.7 GHz.

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