Highly-accurate Measurement of Current Distribution Using Polarization-stabilized MO Probe

To achieve highly-accurate measurement of the current distribution in wireless devices, we propose an MO probe that adopts a polarization-stabilized construction and confirm the effectiveness of that construction. This research was conducted jointly with Associate Professor Masahiro Tsuchiya (currently with National Institute of Information and Communications Technology) and Research Assistant Masato Kishi, Graduate School of Engineering, The University of Tokyo.

Shin Nakamatsu, Ryo Yamaguchi and Shinji Uebayashi

1. Introduction

Remarkable advances in electronics technology of recent years have brought miniaturization and integration of wireless device circuits and great increases in the speed of electrical signals. Furthermore, it is important to evaluate the amplitude and phase of the current distribution on the chassis and antenna element with high accuracy for improving the radiation characteristics of wireless devices. With the increasing frequency and integration density of wireless device circuits, highly accurate measurement of current distribution with conventional sensors constructed solely from metal antenna elements such as a loop antenna is becoming difficult. Therefore, techniques for highly accurate measurement of current distribution are required to cope with the further miniaturization and higher frequencies that are expected in the future.

The current distribution is evaluated on the basis of magnetic field values obtained from points very close to the surface of the Device Under Test (DUT)[*1]. There are three requirements for estimating the current distribution with a high level of accuracy: very high proximity, a high degree of spatial resolution, and low invasiveness to the electromagnetic field. While magnetic sensors have mainly adopted small loop antennas, the loop antenna structure makes it difficult to satisfy the three requirements for estimating the current distribution. We therefore focused our research on a probe that adopts Magneto-Optical (MO) crystal and optical fiber and has no metal in its construction [1], and investigated techniques for more accurate evaluation of current distribution with respect to Electro Magnetic Compatibility (EMC)[*2] and antenna radiation. When compared with a probe made with a metal antenna, an MO probe creates extremely low disturbance in an electromagnetic field, even in the gigahertz band. Also, because only the light path in the crystal is the sensitive area, high proximity and high spatial resolution are easily achieved by adjusting the light and the crystal size [2]. The MO probe, however, has the issue that fluctuation in the optical polarization in optical fiber causes measurement instability. To solve this instability issue, we propose an MO probe structure that stabilizes polarization and use that probe to estimate current distribution.

2. Measuring Magnetic Fields with an MO Probe

2.1 Measurement Principle

The MO crystal generates the Faraday effect, which causes rotation of the optical polarization angle according to the magnetic field value. Applying this effect, the MO probe measures the magnetic field value by measuring the angle of the linear polarization[*3] [3]. Heretofore, magnetic field measurement using MO crystal has adopted the polarization rotation produced by the Faraday effect, which is caused by the magnetic domain

*1 DUT: The equipment that is being measured.

*2 EMC: The ability of a device or system to function satisfactorily when placed in an electromagnetic environment without producing electromagnetic interference that affects other equipment in that environment.

*3 Linear polarization: The polarization condition of electromagnetic wave in which the electric field vector or magnetic field vector is confined to a given plane along the direction of propagation.

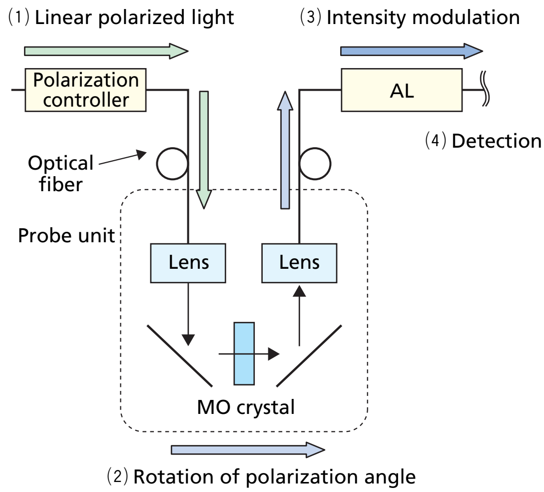

Figure 1 MO probe construction

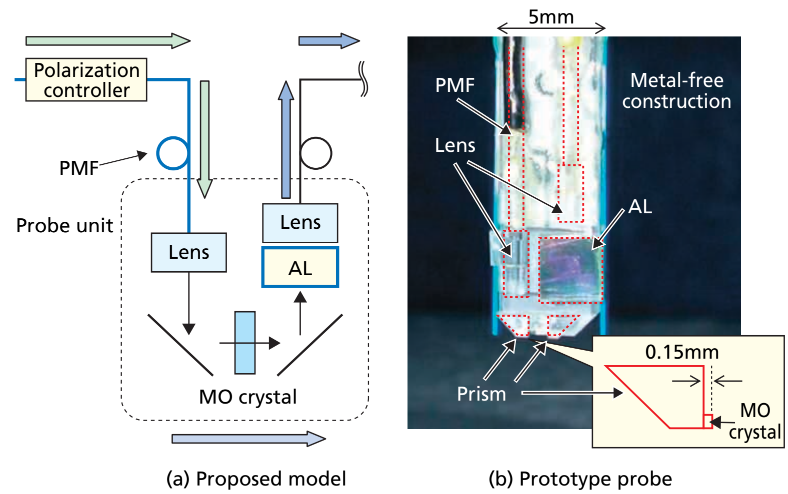

Figure 2 Proposed MO probe construction

wall displacement phenomenon*4 [2]. However, because this phenomenon is slow, the measurable frequency is limited to several megahertz at most, and it cannot measure the high-frequency magnetic fields that are generated by recent mobile communication devices such as mobile terminals. In this article, the measurement targets are devices that use RF electromagnetic waves. To measure such high-frequency magnetic fields, we adopt the rotation magnetization phenomenon to rotate the linear polarization angle. This approach can handle magnetic fields of up to approximately 10 GHz [4]. The construction of the MO probe is shown in **Figure 1**. The magnetic field is measured by the following method. Linear polarized light incident to the MO crystal is passed through a Polarization-Maintaining optical Fiber (PMF) and a prism (Fig. 1 (1)). The angle of the linear polarization is rotated according to the magnetic field value of the MO crystal (Fig. 1 (2)). An AnaLyzer (AL) comprising a deflecting plate converts the polarization angle into an optical power signal (Fig. 1 (3)). A Photo Diode (PD) converts the optical power signal into an RF signal and the resulting signal is measured using an RF Spectrum Analyzer (SA) (Fig. 1 (4)).

2.2 Polarization Stabilization Construction

In the measurement using an optical fiber, the stabilization of the polarization and the control techniques are important because fluctuation of polarization in the optical fiber causes measurement instability. The polarization condition*5 tends to fluctuate according to the fiber conditions (temperature, vibration, inflection, and so on). Even if a PMF is adopted, the polarization conditions cannot be maintained except at specific polarization angles (slow axis or fast axis). As Fig. 1 (1) shows, stabilization is possible with PMF, because the polarization state is constant at a specific polarization angle. At places where the polarization angle is arbitrarily rotated, however, as we see between Fig. 1 (2) and Fig. 1 (3), polarization cannot be maintained even with PMF, and measurement instability results.

To address this problem, we proposed a polarization stabilized MO Probe that is characterized by a small AL set at the top of the probe and next to the MO crystal to eliminate the optical fiber between the MO crystal and the AL [5]. This construction allows conversion of the polarization signal, which indicates the magnetic field level, into an amplifier signal immediately after the light passes through the MO crystal. The proposed probe construction is shown in **Figure 2** (a). The appearance of the prototype probe is shown in Fig. 2 (b).

3. Evaluation of a Probe Implementing the Proposed Construction

3.1 Measurement Configuration

With the proposed MO probe, amplitude is measured with an SA and phase is measured with an Network Analyzer (NA).

*4 Magnetic domain wall displacement phenomenon: A phenomenon in which the boundaries of magnetic field domains move in response to changes in an external magnetic field.

*5 Polarization condition: The state of the electric field vector or magnetic field vector in light or other electromagnetic wave.

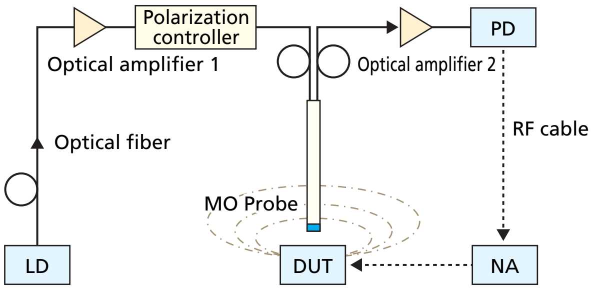

Figure 3 Experimental configuration for MO probe

A block diagram of the experimental configuration for the MO probe with NA is shown in **Figure 3**. The measurement configuration comprises the optical system from the Laser Diode (LD) to the PD. From the PD to the SA (or NA) and the DUT is the RF system. A LD is used for the Continuous Wave (CW) light source, whose wavelength is 1,550 nm. This wavelength is widely used in telecommunications. The light is first adjusted to a linear polarization by a Polarization Controller (PC) and then inserted into the MO probe. The optical signal that is output from the probe reflects the magnetic field strength. It is converted to an RF signal by the PD. The DUT is fed an RF signal by an external signal generator for the amplitude measurements and a test signal from the NA for the phase measurements. The RF signal output by the PD is measured for amplitude by the SA and measured for phase by comparison with the test signal from the NA. The investigation parameters are shown in **Table 1.**

Table 1 Investigation parameters

Optical power	4.77 dBm
Light wavelength	1,550 nm
DUT	MSL, PIFA
RF Input power	30 dBm
Frequency	2.0 GHz
RF test signal	CW
RBW (SA)	10 Hz
IF (NA)	100 Hz

IF: Intermediate Frequency
RBW: Resolution Bandwidth

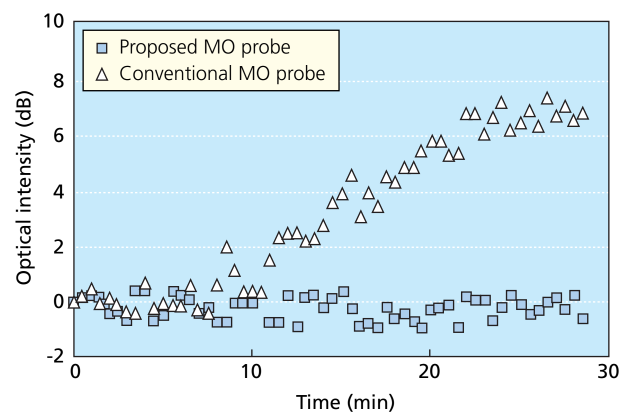

Figure 4 Comparison of polarization stabilities

3.2 Evaluation of Probe Polarization Stability

To evaluate the construction of the polarization-stabilized MO probe, we compared the received optical intensity before Erbium Doped Fiber Amplifier (EDFA) 2 in the conventional construction, which adopts an optical fiber between the MO crystal and AL, to that of the proposed construction. In this comparison, there is no magnetic field. The optical intensity after passing through the AL reflects the polarization state; if the polarization state is constant, then the optical intensity is also constant. The results are shown in **Figure 4**. The optical intensity of the conventional construction is low and constant at the beginning of the measurement, however, it increases over time. This demonstrates a change in the polarization angle over time. For the proposed construction, on the other hand, the optical intensity remains constant over time. These results confirm that the proposed construction stabilizes the polarization state.

4. Experimental Results

4.1 Measurement of Magnetic Field Distribution on MSL by Proposed MO Probe

To test the feasibility of measuring magnetic fields with the proposed construction, we measured a Micro-Strip Line (MSL)[*6] for which the amplitude and phase distributions were obvious. The MSL model is shown in **Photo 1**. The measurements were made at 1 mm above a short-circuited MSL from the center of the circuit board (x = 0 mm) in the direction of the circuit power supply. The results of these measurements and the magnetic field distribution values calculated by the Finite Difference Time Domain (FDTD)[*7] method are shown in **Figure 5**. The amplitude distribution is normalized to the maxi-

*6 MSL: A line used to transmit an electrical signal in a circuit. Printed circuit boards have a three-layer structure that includes the board sandwiched between a ground plane and a signal plane.
*7 FDTD: A numerical method for analyzing electromagnetic fields.

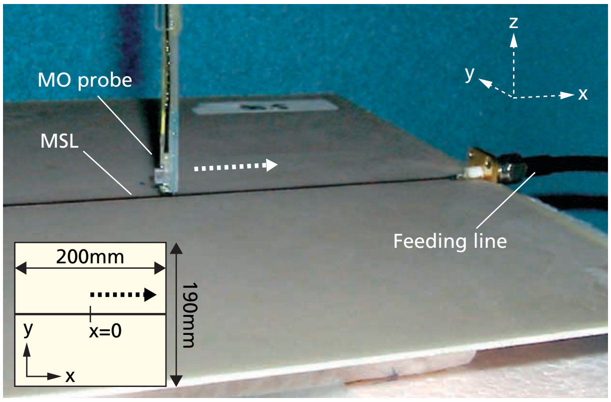

Photo 1 MSL model

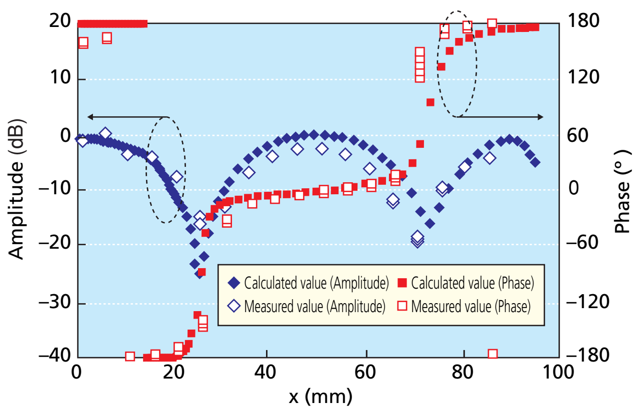

Figure 5 MSL magnetic field distribution

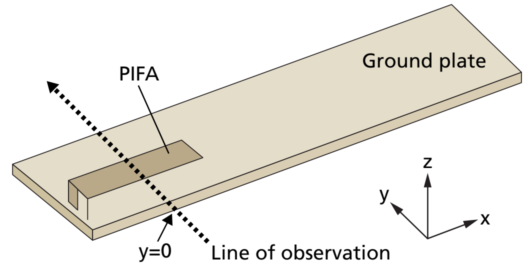

Figure 6 DUT model

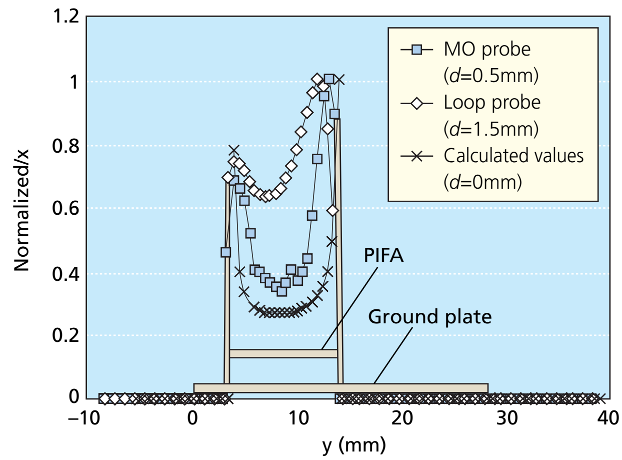

Figure 7 Current distribution measurement results

mum value of 0 dB; the phase distribution takes the value at the most stable position of x = 50 mm as the reference value (0 degrees). These results confirm that the standing wave distribution from the amplitude measurements agrees well with the calculated values. The results of the phase measurements exhibited a 180 degree change at the point of lowest current and agree well with the calculated values. We thus conclude that an MO probe that adopts the proposed construction is capable of measuring magnetic field amplitude and phase with good results.

4.2 Measurement of Current Distribution on Inverted-F Antenna

The current distribution on the DUT is estimated on the basis of magnetic field values using the proposed MO probe and a conventional magnetic field sensor, which adopts a small loop antenna. A model of the DUT, which is a mobile terminal model, is shown in **Figure 6**. A Planar Inverted-F Antenna (PIFA) is adopted in the DUT because this antenna is used in many mobile terminals and the transmission characteristics are well known. The observation line crosses over the PIFA element, which is shown in Fig. 6. The magnetic field is measured at the closest point possible for each magnetic sensor. The distance "*d*", which is the distance between the PIFA element and the center of the loop antenna or the center of the area through which light passes in the MO crystal, is 1.5 mm for the loop probe and 0.5 mm for the MO probe. The current values estimated using each sensor and the numerical simulation values are shown in **Figure 7**. Because the MO probe can measure the magnetic field at a point closer than the conventional small loop antenna, the estimation results from the MO probe are closer to the current distribution obtained from the numerical simulation than the results from the loop antenna.

5. Conclusion

To achieve highly accurate and stable measurement of current distribution, we have proposed a polarization stabilized MO probe that achieves high spatial resolution with low-invasiveness. We constructed a prototype probe and compared its performance to that of the conventional MO probe and magnetic sensor which comprises a small loop antenna. The comparison results show that the measurements obtained with the prototype can be more stable than those obtained with a conventional MO probe and more accurate than those obtained with a small loop antenna. In the future work, we plan to continue investigating the use of this construction in high-performance antenna design and highly accurate evaluation of electromagnetic compatibility.

References

[1] E. Yamazaki, H. Park, S. Wakana, M. Kishi and M. Tsuchiya: "Fabrication of broad-band fiber-optic magnetic field probe and its application to intensity and phase distribution measurements of GHz-frequency magnetic field," International Topical Meeting Microwave Photonics, MWP2002, pp. 77-80, Awaji, Nov. 2002.

[2] E. Yamazaki, S. Wakana, M. Kishi, M. Iwanami, S. Hoshino and M. Tsuchiya "Three-dimensional magneto-optic near-field mapping over 10-50μm-scale line and space circuit patterns," Conference Proceedings-Lasers and Electro-Optics Society Annual Meeting-LEOS, Vol. 1, pp. 318-319, 2001.

[3] N. Itoh, H. Minemoto, D. Ishiko and S Ishizuka: "Optical magnetic field sensors with high linearity using Bi-substituted rare earth iron garnets," IEEE Transactions, Vol. 31, issue 6, pp. 3191-3193, Nov. 1995.

[4] E. Yamazaki, S. Wakana, M. Kishi and M. Tsuchiya: "10GHz-class magneto-optic field sensing with bi-substituted rare-earth ion garnet rotation magnetization employed," Japanese Journal of Applied Physics, Vol. 41, No. 2A, pp. 904-907, 2002.

[5] S. Nakamatsu, R. Yamaguchi, S. Uebayashi, M. Kishi and M. Tsuchiya: " Measurement of Current Distribution Using Polarization Stabilized MO Probe," IEICE Journal, Vol. J89-B, No. 9, pp. 1797-1805, 2006.