6 Electromagnetic Field Distribution Measurements using an Optically Scanning Probe System

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An optically scanning electromagnetic field probe system consisting of an electro-optic or magneto-optic crystal substrate and a galvano scanner has been developed for high speed and low-invasive electromagnetic field distribution measurements. In this report, we introduce some of the examples of measuring the electric field distribution using $LiNbO_3$ or CdTe crystal substrate and the probe system. Furthermore, we have developed an optical magnetic field probe array for detecting magnetic fields in the gigahertz range. Using the probe array, we also measured the magnetic field distributions above a patch antenna working at 2.49 GHz.

Keywords
Probe, Electromagnetic field, Electro-optic effect, Magneto-optic effect, Galvano scanner

1 Introduction

Recent years have seen a dramatic expansion in the use of information and communication devices such as cellular phones and PCs. Associated with this trend is increasing concern as to the adverse effects on other instruments of the inadvertent release of electromagnetic radiation (referred to as "electromagnetic field leakage") from these electronic devices, which may impair the performance of the affected devices. Furthermore, it has been noted that the performance of the communication devices themselves may also be impaired by their own leaked electromagnetic fields. A number of studies on technologies for suppressing such leakage from these electronic devices have been carried out to date, and one effective method determined as a result consists of identification of the source of the leakage based on measurement of the electromagnetic field distribution in the vicinity of the electromagnetic device, for which countermeasures are then implemented.

The operational frequencies of devices are continuing to increase from year to year as these devices become more sophisticated. Accordingly we are now seeing the need to develop technologies for measurement at higher frequencies to develop countermeasures against leakage in this range.

Electromagnetic field probes, featuring improved spatial resolution thanks to the reduction in size of dipole antennas and loop antennas, have conventionally been used for electromagnetic near-field distribution measurements of electronic devices. In these probes, metal transmission lines such as coaxial cables are used to transmit signals to the detectors, leading to the problem of disturbance of the electromagnetic field distribution under study by the metal components of the measuring instrument itself. Furthermore, since the transmission line also directly couples with the electromagnetic field when the detected signals are transmitted, the signals may be contaminated with unwanted signals. These problems have resulted in an overall reduction in the precision of measurement[1][2].

To overcome these issues, efforts have focused on the development of optical technologies for electromagnetic field measurement[3][4]. By applying these optical technologies, it should become possible to suppress the invasive effects of the measurement instrument on the target electromagnetic field to be measured.

This paper provides a summary of an optically scanning probe system for measurement of an electromagnetic field distribution; this probe conducts a high-speed scan within a plane using an optical beam. The device is currently under development within our group, with the ultimate aim of developing a system that will feature not only high precision but also high speed[5]. We will also provide examples of electromagnetic field distribution measurements made using the developed probe.

2 Optically scanning probe system

Figure 1 is a schematic diagram of the optically scanning probe system[5]. The probe mainly consists of a laser source, a galvano scanner, an fθ lens, an electro-optic thin crystal plate, a polarization analyzer, a photoreceiver, and a spectrum analyzer.

A 1,342 nm laser beam is emitted from the laser source and enters the galvano scanner via the optical circulator. The galvano scanner unit is equipped with two PC-controlled high-speed movable mirrors and controls the direction of the incident laser beam to enable scanning. This function allows for high-speed movement of the incident position of the laser beam over the optical crystal placed below the galvano unit. With this configuration, it is possible to measure the intensity of the electromagnetic field at the point of laser beam incidence, which can then be moved at high speed over the surface range of the optical crystal.

After passing through the galvano scanner, the laser beam then enters the fθ lens located beneath the unit. The fθ lens concentrates the laser beam to an extremely small spot, and at the same time, maintains the incident beam perpendicular to the plane over a large area.

With the present probe, it is possible to focus a perpendicular incident laser beam onto a 50 mm × 50 mm plane at focal length from the fθ lens. The beam diameter at the plane is approximately 50 μm. An optical crystal is placed at the focal length from the fθ lens, and the device under test (DUT) is placed below the crystal. Figure 2 shows a photo of a $LiNbO_3$ thin crystal plate placed directly on the DUT (referred to below as the microstrip line, or “MSL”). Here, the laser beam is transmitted from the galvano scanner to the optical crystal through air.

The polarization of the laser beam entering inside the optical crystal changes depending

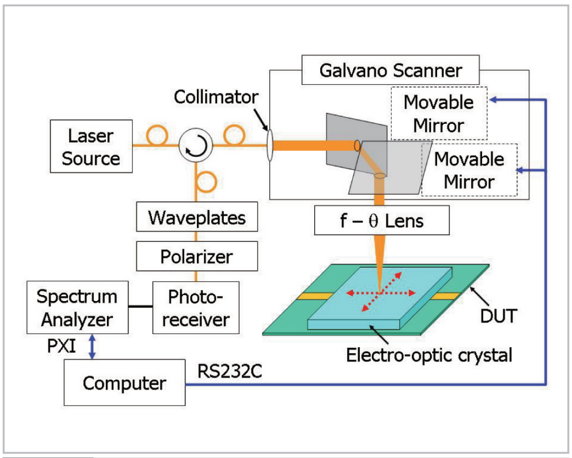


Fig.1 *Optically scanning probe system*

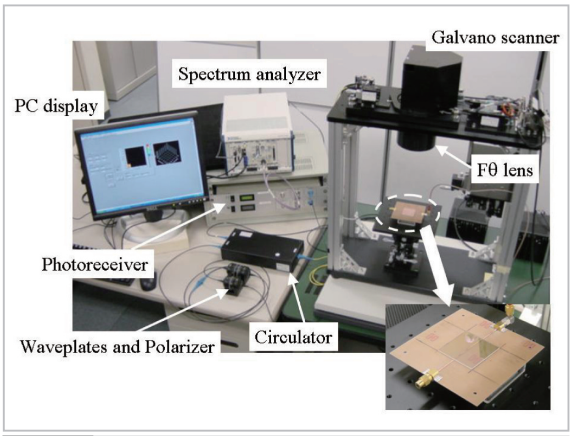


Fig.2 *Exterior view of the optically scanning probe system*

on the intensity of the electromagnetic field generated above the DUT. The bottom surface of the optical crystal is fitted with a reflector film, which returns the laser beam with the changed polarization to the polarization analyzer unit through the same path. The polarization analyzer unit is composed of the waveplates and the polarizer, and here the change in polarization of the laser beam is converted into a change in light intensity. This optical signal is then converted into electrical signals at the photoreceiver, and these signals are finally measured by the spectrum analyzer.

3 Electric field distribution measurement using an electro-optic crystal

3.1 Electric field distribution measurement on the microstrip line (MSL) filter by $LiNbO_3$ thin crystal plate

The present probe was used to measure the electric field distribution on the MSL filter. A 40 mm × 40 mm × 1 mm $LiNbO_3$ thin crystal plate was used as the electric field detector. Figure 3 shows the filter pattern for measurement. The filter was produced using a glass epoxy substrate 1.6 mm in thickness, with area dimensions of 60 mm × 60 mm. The $LiNbO_3$ thin crystal plate was placed 0.5 mm above the filter surface. Figure 4 shows the results of measurement of the transmission characteristics of this filter using a vector network analyzer. In this experiment, the field distribution was measured at a pass band of 1.2 GHz and an elimination band of 2.1 GHz. Additionally, measurements were performed by aligning the optical axis of the $LiNbO_3$ crystal in the x-direction and in the y-direction as shown in Fig. 5. For this experiment, a 17 dBm beam was output from the laser source, and a 10 dBm sinusoidal signal was input to the filter from the signal generator. The 40 mm × 40 mm area was scanned by moving the laser beam at 0.2 mm intervals and measuring the electric field intensity at each point. Approximately 3 minutes were required to measure the 40,401 points in this case, which proves that this system can perform extremely high-speed measurements of approximately 4 milliseconds per point.

Figures 6(a) and (b) show the results of electric field distribution measurement at 1.2 GHz for the electric field components in the y and x directions, respectively. Here we see a region of strong electric field intensity

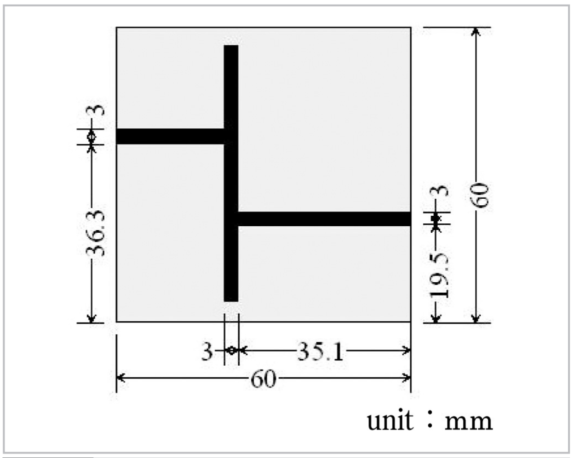


Fig.3 Microstrip line filter

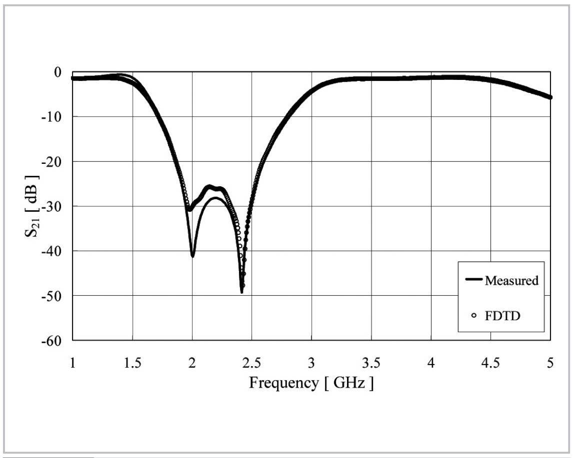


Fig.4 Transmission characteristic of filter

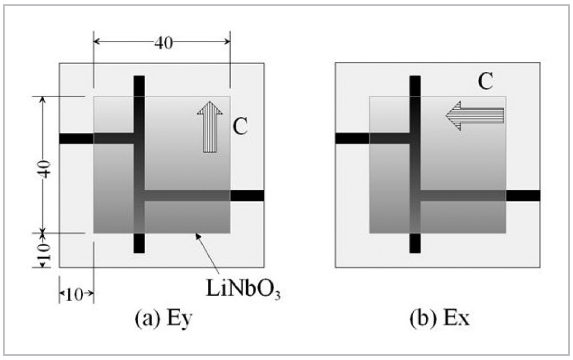


Fig.5 Alignment of the optical axis of the LiNbO3 crystal

along the edges of the filter conductor pattern. Furthermore, a region of strong electric field intensity is also present on the output side, indicating that the input signal has been transmitted to the output side.

Figures 7(a) and (b) show the results of electric field distribution measurement at 2.1 GHz for the electric field components in the y and x directions, respectively. With these results, a region of strong electric field intensity is not observed near the output side, indicating that the input signal has been stopped and that transmission to the output side has been blocked at this frequency.

In order to compare the results of measurement using this probe, the electric field distribution in the upper region of the filter was calculated using the FDTD (finite-difference time-domain) method. The results of calculation are shown in Figs. 8(a) and (b) and Figs. 9(a) and (b). Figures 8(a) and (b) show the results of calculation at 1.2 GHz, with (a) and (b) corresponding to the y- and x-components, respectively, and Figures 9(a) and (b) indicate the results of calculation at 2.1 GHz, with (a) and (b) corresponding to the y- and x-components, respectively. Here we see that the results of calculation are extremely consistent with the results of measurement using the probe.

3.2 Electric field distribution measurement above a five-branch transmission line using a CdTe thin crystal plate

The spatial resolution of the present probe is dependent upon the beam diameter of the incident laser beam and the thickness of the optical crystal. To evaluate the spatial resolution of this probe, we measured the electric field generated above a five-branch transmission line. The substrate pattern for evaluation used in this measurement is shown in Fig. 10. Five conductors with pattern widths of 0.2 mm each were aligned on a 0.6-mm thick glass epoxy substrate. The gaps between the lines varied from 400 μm to 100 μm as shown in Fig. 10. The widths of the sloping lines passing through the transition region between the areas of different gap widths were constant. The electric field distribution was measured by applying a 1 GHz signal to the evaluation substrate. A 10 mm × 10 mm × 1 mm CdTe thin crystal was used for electric field detection in this measurement. Unlike the $LiNbO_3$ crystal, use of the CdTe crystal enables measurement of the electric field component perpendicular to the surface of the evaluation substrate.

Figure 11 shows the results of field distribution measurement in this case. For the region (or segment) with an interval of 0.4 mm between adjacent lines, regions of strong electric fields were observed above the five lines, and the observed intensities between them were small.

The narrowing down of the intervals from 0.4 mm to 0.1 mm was observable in the results, and even at intervals of 0.1 mm the five lines remained discernable.

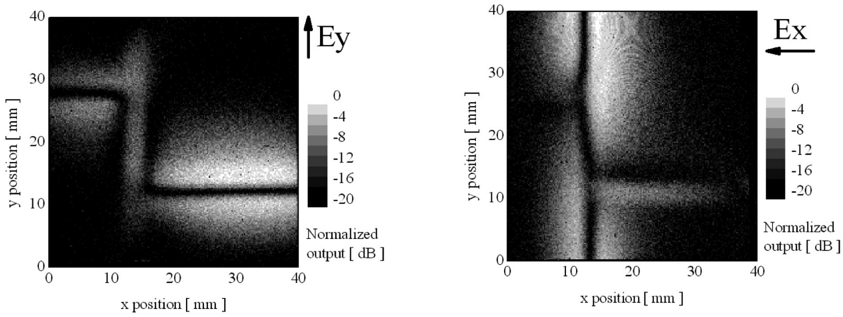
4 Magnetic field distribution measurement using an optical magnetic field probe array

4.1 Structure of the optical magnetic field probe array

The present probe may also be used for measuring the magnetic field distribution using a magneto-optic crystal. However, compared to the electro-optic crystals, magneto-crystals such as magnetic garnets generally feature reduced detection sensitivity at high frequencies in or above the GHz band.

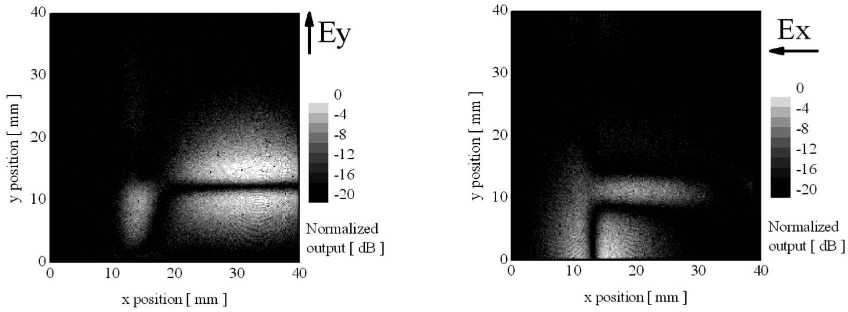
In order to measure the magnetic field distribution in the GHz band, a probe array was developed[6] with optical-magnetic field probes arranged in a two-dimensional configuration, allowing for magnetic field distributions even at high frequencies. The configuration of the probe array is shown in Fig. 12.

The optical magnetic field probe array is mainly composed of three parts–a glass epoxy substrate with several loop-element patterns, minute $LiNbO_3$ crystals, and a quartz substrate to hold both of these components. The quartz



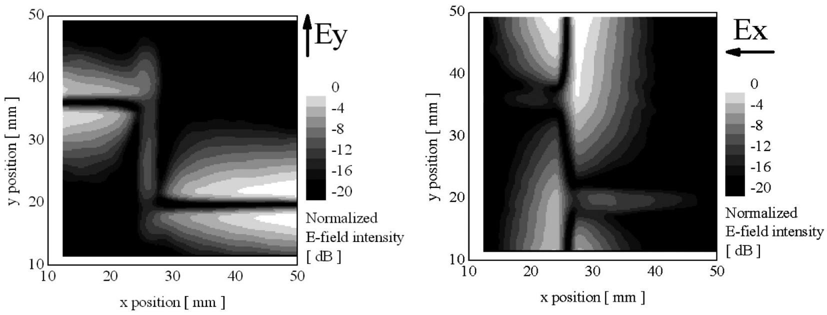
(a) Y-direction component (b) X-direction component

Fig.6 *Results of electric field distribution measurement on the MSL filter (1.2 GHz)*



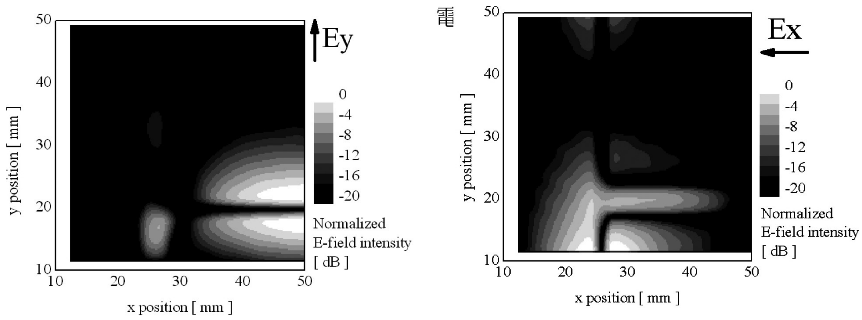
(a) Y-direction component (b) X-direction component

Fig.7 *Results of electric field distribution measurement on the MSL filter (2.1 GHz)*



(a) Y-direction component (b) X-direction component

Fig.8 *Results of calculation of electric field distribution above filter by the FDTD method (at 1.2 GHz)*



(a) Y-direction component (b) X-direction component

Fig.9 *Results of calculation of electric field distribution above filter by the FDTD method (at 2.1 GHz)* substrate is used to fix the positions of the $LiNbO_3$ crystals and the glass-epoxy substrate featuring the loop-element patterns. In the actual preparation of the array, an $LiNbO_3$ crystal substrate is affixed to a quartz substrate of equivalent dimensions; a precision cutter is then used to cut away sections of only the $LiNbO_3$ crystal substrate, leaving only the portions of the $LiNbO_3$ substrate required for the optical magnetic probe array. The effective result is the generation of numerous lines of minute $LiNbO_3$ crystals on the quartz substrate. In contrast, the tops of the loop elements on the glass epoxy substrate feature gaps for the insertion of $LiNbO_3$ crystals. The glass epoxy substrates are placed onto the quartz substrates such that the $LiNbO_3$ crystals fit into these gaps, and the $LiNbO_3$ crystals are fixed onto the respective loop elements with a conducting adhesive. On the glass epoxy substrate, there are 16 loop elements with loop conductor widths of 0.1 mm and loop openings of 1.5 mm × 1.5 mm aligned in rows at 3.2-mm intervals. The glass epoxy substrates are placed in a multiple crisscross pattern to form the probe array with 16 lines in both the x and y direction.

During actual measurements, the side with the loop element is placed toward the DUT, and the laser beam is irradiated from the quartz substrate side and into the $LiNbO_3$ crystals to measure the magnetic field distribution.

Figure 13 shows the reflected light intensity distribution obtained with the optical-magnetic field probe array. This image confirms that the reflected light is being returned from the $LiNbO_3$ crystals. Compared to the center of the probe array, the reflected light intensity falls by a maximum of nearly 6 dB at the edges. This is thought to be due to the limits in the precision of the fθ lens, and so corrections

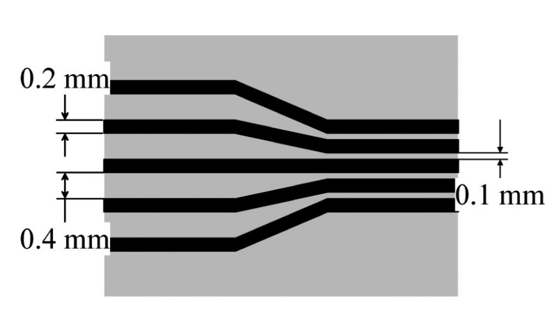


Fig.10 Five-branch transmission line

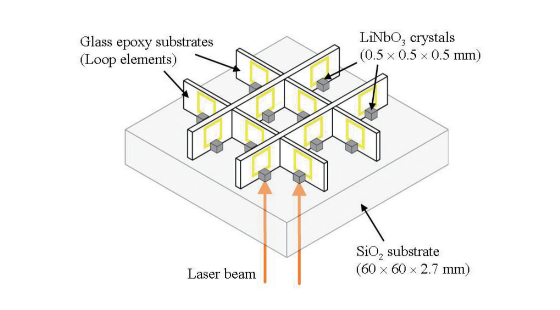


Fig.12 Structure of an optical-magnetic field probe array

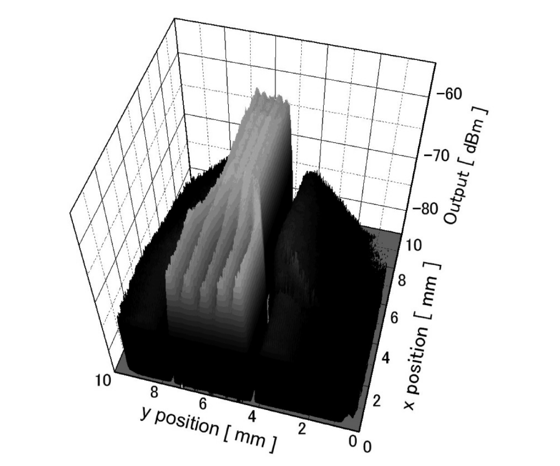


Fig.11 Electric field distribution above the five-branch transmission line (1 GHz)

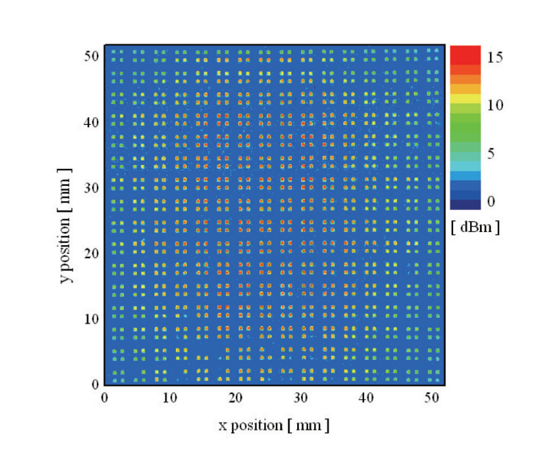


Fig.13 Reflected light intensity distribution obtained with the optical-magnetic field probe array

will be made in measurement to account for this drop in intensity.

4.2 Magnetic field distribution above a patch antenna using the optical magnetic field probe array

The optical magnetic field probe array was applied to the scanning probe system to measure the magnetic field distribution above a patch antenna. Figure 14 shows the patch antenna used in this measurement. A 2.49 GHz sinusoidal signal was input to the patch antenna, and the magnetic field distribution above the antenna was measured in the excited state. The results are shown in Figs. 15 and 16 for the y- and x-direction components, respectively. Approximately 4 seconds were required to measure a total of 512 points for the two direction components, demonstrating the system's ability to measure circuits displaying moderate variations over time.

5 Concluding remarks

This paper described an optically scanning probe system developed for high-speed measurements of electromagnetic field distribution. We found that high-speed electric field distribution measurements above electric circuit substrates are possible with the combination of a laser-beam scanning mechanism and thin plates of $LiNbO_3$ or CdTe crystals. This paper also described the structure of an optical-magnetic field probe array having multiple alignments of electro-optic crystals and minute loop elements, and we also introduced an example of magnetic field distribution measurement in the GHz band above a patch antenna. In the future, we plan to devote efforts to the development of a measuring system featuring higher precision and speed relative to the system introduced in this paper, as well as to investigate production methods for systems using magneto-optic crystals aimed at high-frequency magnetic field distribution measurements.

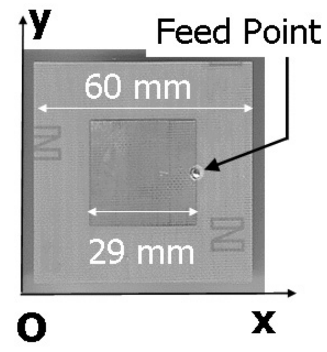


Fig.14 Photo of patch antenna

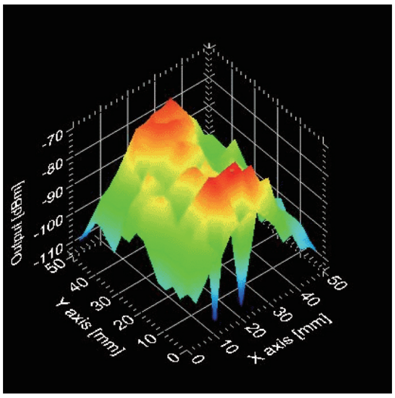


Fig.15 Magnetic field distribution above patch antenna (y-direction component)

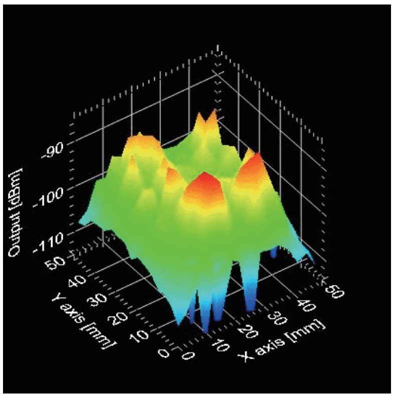


Fig.16 Magnetic field distribution above patch antenna (x-direction component)

References

1 S. Arakawa, E. Suzuki, H. Ota, K. I. Arai, and R. Sato, "Invasiveness of optical magnetic field probes with a loop antenna element", Proc. EMC'04/Sendai, Sendai, Japan, Vol. 1, pp. 149-152, June 2004.

2 M. Takahashi, H. Ota, K. I. Arai, and R. Sato, "Magnetic near-field distribution measurements above a patch antenna by using an optical waveguide probe", IEICE Trans. Commun., Vol. E88-B, No. 8, pp. 3140-3145, 2005.

3 E. Yamazaki, S. Wakana, H. Park, M. Kishi, and M. Tsuchiya, "High-frequency magneto-optic probe based on BiRIG rotation magnetization", IEICE Trans. Electron., Vol. E86-C, No. 7, pp. 1338-1344, 2003.

4 A. Sasaki and T. Nagatsuma, "Electric-field scanning system using electro-optic sensor", IEICE Trans. Electron., Vol. E86-C, No. 7, pp. 1345-1351, 2003.

5 E. Suzuki, S. Arakawa, H. Ota, K. I. Arai, and R. Sato, "Optically scanning electric field probe system", Proc. 2004 IEEE International Symposium on EMC, pp. 182-185, 2004.

6 E. Suzuki, S. Arakawa, H. Ota, K. I. Arai, and R. Sato, "Optical magnetic field probe with a loop antenna element doubly loaded with $LiNbO_3$ Crystals", IEICE Trans. Electron., Vol. E87-C, No. 11, pp. 1989-1996, 2004.

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