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Ultra small magneto-optic field probe fabricated by aerosol deposition

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Abstract: The basic performance of a newly developed microscopic magneto-optic probe is described. The probe was fabricated by directly depositing a Bi-substituted yttrium iron garnet [Bi-YIG] film onto the optical fiber edge using aerosol deposition. This fabrication process is inexpensive and simple because there are no complicated procedures such as fine lithography and etching. The film is 125-μm-wide, which is the same as the diameter of a typical single mode fiber, and approximately 10-μm-thick. The 3-dB bandwidth and spatial resolution of the probe were found to be about 3 GHz and in the 10-μm order, respectively. Because the developed magneto-optic probe is very tiny and thin, it can be a powerful tool for detailed electrical characterization of densely packaged electronic circuits.

Keywords: fiber-optic magneto-optic probe, aerosol deposition, Bi-substituted yttrium iron garnet film

Classification: Photonics devices, circuits, and systems

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1 Introduction

The trend toward electronic devices of high speed and high packaging density makes circuit design more difficult. Finding appropriate solutions for electromagnetic coupling or interference problems in electronic equipment is a particularly important technical issue. One solution is to characterize packaged circuits and components in the stage of trial fabrication. Applying an electromagnetic near-field probe is considered to be a very effective way of

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solving interference and coupling problems because information so acquired can be used to make a good electrical design [1].

Electro-optic (EO)/magneto-optic (MO) probing methods have attractive features such as ultra fast response [2, 3, 4, 5], non-invasiveness, and high spatial resolution [6, 7, 8]. Applying them to near-field measurements has enabled performance and failure diagnosis of digital and microwave circuits [9, 10, 11] and antennas [6, 12].

We previously developed an ultra small EO probe [13] intended for use in electric field measurements in microscopic regions such as connection terminals between an LSI and a printed circuit board and crevices between densely packaged devices. The probe was fabricated by directly depositing EO film onto an optical fiber facet. The film was deposited using an aerosol deposition (AD) method. This method is a recently developed ceramic film formation technology that can directly deposit complex oxide films consisting of nano-particles on any kind of substrate material [14, 15, 16].

We believe that both EO and MO probes (the latter is a probe for magnetic field measurement) should be further miniaturized to create efficient tools capable of detailed electrical characterizations. It is generally recognized in transmission line theory that magnetic field intensity is strong at locations where electric field intensity is weak. Therefore, a tiny MO probe would be a powerful tool in cases where EO probe sensitivity is not sufficient to evaluate signal/power integrity in microscopic regions. Indeed, an ordinary fiber-optic MO probe was successfully used to evaluate the conduction noise characteristics of an LSI by measuring the magnetic near-field over the LSI package pins [17].

We report on the fabrication procedure and basic performance of an ultra small fiber-optic MO probe. A Bi-substituted yttrium iron garnet [Bi-YIG] film of about 10 μm thickness was successfully deposited by AD onto an optical fiber facet. After the film was processed for magnetic field sensing, we confirmed that the developed probe detected an RF magnetic field surrounding a microstrip line through the Faraday effect in an MO film. The measurable bandwidth and spatial resolution of the probe were found to be approximately 3 GHz and on the 10-μm order, respectively.

2 Probe fabrication

The AD system consists of a film deposition chamber, an aerosol chamber, and a gas bottle (all of which are connected by a tube), and a vacuum system for the deposition and aerosol chambers. The apparatus and details were reported elsewhere [14, 15, 16].

Prior to fabricating the probe, we tried to form a Bi-YIG film on a glass substrate and to investigate its magnetic anisotropy. It is known that the Faraday effect accompanying rotation magnetization in MO material is needed to detect GHz-range magnetic fields [5]. To realize this situation, a conventional fiber-optic MO probe is fabricated by attaching a cut and polished MO crystal onto an optical fiber facet so that its easy magnetization

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axis is perpendicular to the optical probe beam. Based on the relationship between the probe beam and easy magnetization axis, we thought that if the easy magnetization axis of the film on a glass substrate were parallel to the film's surface, a wideband MO probe could be fabricated by aerosol depositing a film on a fiber facet.

A glass substrate was set in a film deposition chamber, and a Bi-YIG film was deposited onto a substrate at room temperature. Submicron particles of Bi-YIG were mixed with a carrier gas to form an aerosol flow in the aerosol chamber. The aerosol flow was directed through a tube to a nozzle and then accelerated and ejected from the nozzle into a vacuum-deposition chamber by the difference in pressure between the aerosol chamber and the vacuum-deposition chamber. The pressure of the vacuum-deposition chamber was lower than 20 Pa before the aerosol flow and 400 Pa during the deposition. Oxygen was used as the carrier gas.

Figure 1 shows the magnetization curves of a several-μm-thick Bi-YIG film deposited on a glass substrate as measured by a vibrating sample magnetometer. Magnetic fields were impressed in a direction parallel or perpendicular to the film's surface. It was found that the easy magnetization axis of the film is parallel to the film's surface. Based on this result, we expected to be able to fabricate a wideband MO probe that can detect GHz magnetic fields.

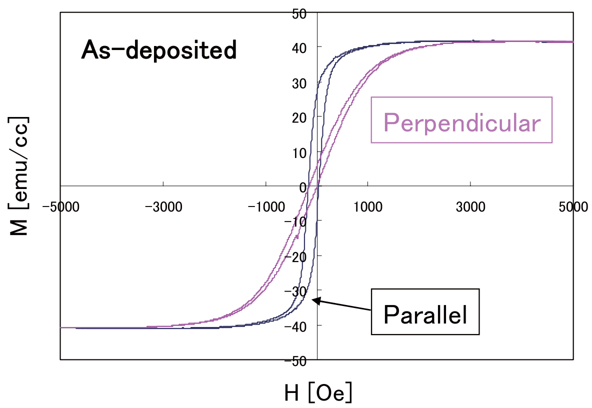

Fig. 1. Magnetization curves of a Bi-YIG film deposited on a glass substrate. Magnetic fields were impressed in a direction parallel or perpendicular to film surface.

Next, to fabricate a probe, we introduced a single mode optical fiber into a film deposition chamber and deposited a Bi-YIG film onto a fiber facet at room temperature. Using an optical microscope, we were able to confirm that a 12 – 13-μm–thick film had been formed. Its lateral size was the same as that of an optical fiber, which was similar to the EO probe [13].

After deposition, the film's surface was polished using a grinder to create a fiber facet to reduce light scattering due to surface roughness. Reflectance spectra were observed during the polishing using a white light source, an

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optical circulator, and an optical spectrum analyzer. When a reflectance spectrum showed resonator-like properties, i.e., peaks and valleys were alternatively observed in the spectrum, we stopped polishing the film.

3 Performance evaluation

The probing system consists of the fiber-optic MO probe head and its optical system. The details of the probing system were reported elsewhere [7, 8]. We used a 2-mm-wide and several-centimeter-long microstrip line to evaluate frequency response and sensitivity of the probe. Its characteristic impedance was 50 Ω and a 50-Ω terminating load was connected to its output.

The probe was positioned over the edge of a strip conductor because the detected MO signal was expected to reach a maximum at this position due to the Faraday effect [7]. The effect is brought about by a magnetic field element parallel to the probe beam, i.e., a field element perpendicular to the surface of the microstrip line in this experiment. The gap between the bottom of the probe (film's surface) and the strip conductor was several μm. We observed a sharp MO signal peak with a signal-to-noise ratio of more than 20 dB when the power and frequency of the applied RF signal to the microstrip line were 15 dBm and 100 MHz, respectively. The input optical power to the photodetector was 4.5 mW. Since the Bi-YIG film was wavelength dependent in reflectance spectra as described above, we adjusted the probing light wavelength to 1560.5 nm to maximize probe sensitivity. We confirmed that the MO signal could be observed when the Bi-YIG film was near the edge of a strip conductor and did not appear at the central position of a strip conductor.

Figure 2 shows the frequency response of the probe. It can be seen that the frequency response is fairly flat until over 1 GHz. The bandwidth the signal level undulation stays within 3 dB was 3 GHz. This excellent performance is probably due to rotation magnetization-based probing. This is because the Bi-YIG film is expected to have in-plane magnetic anisotropy based on the results shown in Figure 1, and generally, the domain wall displacement phenomenon cannot be used to detect GHz fields [5]. The reason for the reduction in signal level in the range over 3 GHz is not certain at

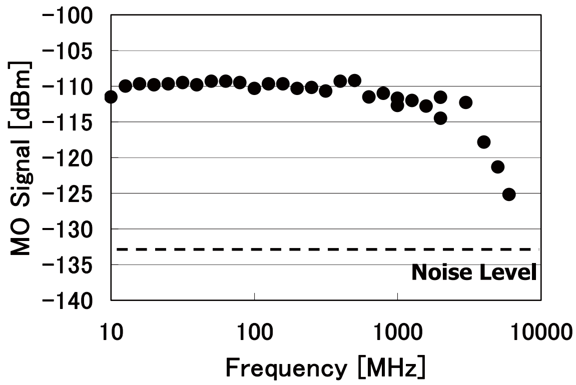

Fig. 2. Frequency response of probe.

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present, but we think that the ferromagnetic resonance in the Bi-YIG film is somehow related. Detailed studies will be done to determine why and to improve frequency characteristics.

We also evaluated the RF power response of the probe, the dependence of RF input power of the microstrip line on detected MO signal intensity. We found reasonably good linearity in the RF power range from 0 dBm to 15 dBm. The minimum detectable current estimated from the minimum signal level was approximately 4 mA (2.5 mA/Hz$^{1/2}$).

We now turn to the result of the evaluation of spatial resolution. We used a 10-μm-scale line width/space meander circuit on a glass chip for the evaluation. Figure 3 shows the measurement result of the magnetic field distribution in the direction perpendicular to the line. A 10-MHz continuous wave signal was supplied to the circuit and the probe was used to scan the circuit with a gap of several μm. We observed magnetic peaks between adjacent lines, which means that the probe has sufficient spatial resolution to separately measure the fields arising from the 10-μm-scale circuit, that is, it has 10-μm-class spatial resolution.

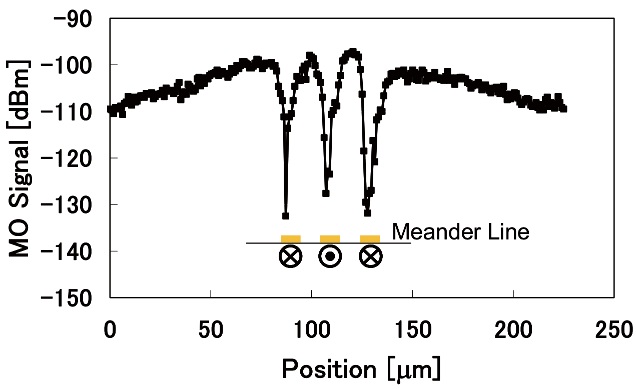

Fig. 3. Magnetic field distribution over a 10-μm-scale meander circuit. Circles indicate directions of current flow.

4 Conclusion

We developed an ultra small magneto-optic field probe by directly depositing a Bi-YIG film onto an optical fiber edge using AD. It was found that the probe had a measurable bandwidth of about 3 GHz, the capability to detect current of several mA, and 10-μm-class spatial resolution. It should be noted that both EO and MO microscopic probes were fabricated using AD.

We plan to apply the probe to densely packaged electronic circuits to improve the quality of electrical design and to improve manufacturing reliability.

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