Fiber-Edge Electrooptic/Magnetooptic Probe for Spectral-Domain Analysis of Electromagnetic Field

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***Abstract*—We propose a new class of an electromagnetic-field probing scheme for microwave planar circuit diagnosis. The measurement principle is based on the electrooptic/magnetooptic effects of crystals glued at optical fiber facets. We have combined the concept of those fiber-edge probes with a fiber-optic RF spectrum analyzing system containing a continuous-wave semiconductor laser source, a fast photodetector, and an RF spectrum analyzer to realize a highly sensitive measurement equipment of local impedance. Electromagnetic-field intensity on a microstrip transmission line has been measured in the frequency domain, where voltage and current amplitudes have been independently investigated with sensitivities of 16 mV/Hz$^{-1/2}$ and 0.33 mA/Hz$^{-1/2}$, respectively. In addition, it has been shown that the former value can be improved to be 0.7 mV/Hz$^{-1/2}$ or smaller by the resonant cavity enhancement effect.**

***Index Terms*—Electromagnetic-field measurements, electrooptic effects, Fabry–Perot resonator, Faraday effect, local impedance measurement, magnetooptic effects, pockels effect.**

I. Introduction

RECENT progress of the monolithic-microwave integrated-circuit (MMIC) design and production technologies have realized higher performances and a resultant increase of circuit complexity. To ensure the desired performances of such sophisticated circuits, the internal node diagnosis is effective from the early design stage to the final production test. The electrooptic (EO) sampling technique based on the Pockels effect and short optical pulses has been frequently applied to such internal node tests, as well as the electric-field mapping [1]–[4], having proven its usefulness therein.

However, there are some drawbacks in the EO sampling technique as follows.

1) Since an EO crystal responds only to an electric field, characteristics related to circuit currents cannot be derived, which leads to the absence of local impedance information.
2) One has to synchronize a drive signal of a device-under-test (DUT) to an optical pulse source, which allows the diagnosis to be made only for limited discrete frequencies.
3) MMIC tests in the frequency domain are rather standard, while the EO sampling technique provides primarily temporal data. Although their numerical Fourier transform is one possible solution, relatively long waveform acquisition time is required for broad-band analyses
4) An EO crystal is generally suspended by a cantilever structure in an asymmetric manner. Such suspension leads to an asymmetrically distorted electric-field distribution and could conceal obtainable knowledge of DUT.

To overcome those obstacles, we propose in this paper a novel optical probe configuration combined with the frequency-domain measurement technique [5]–[7]. The probe configuration includes alternative use of EO and magnetooptic (MO) crystals glued at optical fiber facets, and is expected to settle the drawbacks 1) and 4). The spectrum-domain measurement is to solve the problems 2) and 3). In the following, we report our experimental trials with emphases on the proposed EO/MO probe, the measurement system configuration, and the preliminary results, together with the drastic improvement of EO-probing sensitivity provided by the Fabry–Perot enhancement effect [5].

II. Probe and System Configurations

A schematic of the novel probe structure is shown in Fig. 1. An EO or MO crystal with a high reflection coat on one surface was glued on to an optical fiber facet by UV cure adhesive. The probing light is emitted from the optical fiber facet into the crystal, responds to an electric/magnetic field through the EO/MO effect during one round trip in the crystal and goes back into the optical fiber. Note that this probe structure is symmetric to the optical axis, therefore, the field to be measured is not distorted asymmetrically. This advantageous feature was confirmed in a separate numerical simulation. We call those a fiber-edge electroopitc (FEEO) or fiber-edge magnetooptic (FEMO) probe.

In the case of electrical-field sensing, we used a ZnTe single crystal, as shown by the photograph of Fig. 1. On the other hand, an yttrium–iron–garnet (YIG) crystal was used for the magnetic-field sensing by the Faraday effect. The sizes of those crystals are 0.4 mm^2 in area $\times$ 0.1 mm in height for the ZnTe crystal and 3 mm in diameter of disk $\times$ 1 mm in height for the

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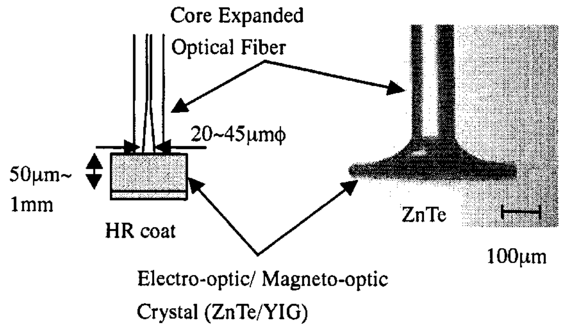

Fig. 1. Schematic of fiber-edge probe structure (left-hand side) and a photograph of a FEEO probe head.

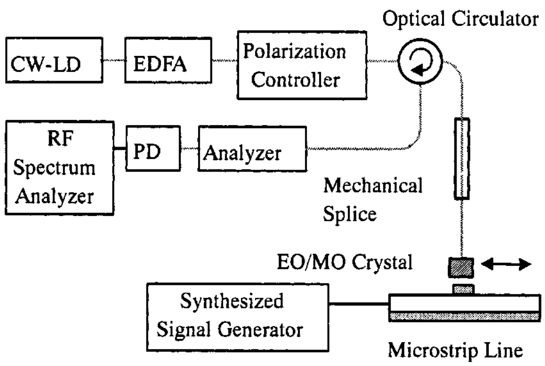

Fig. 2. Block diagram of system configuration is shown. All the optical components are connected by optical fibers.

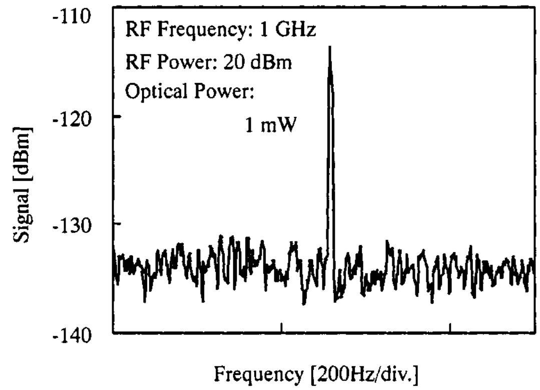

Fig. 3. Typical RF spectrum trace of detected signal.

YIG crystal, respectively. The vertical fields to the substrate are measured in both cases. We used those two probes alternatively to derive local voltage and current data independently as will be described later.

The optical fiber used here is a single-mode fiber with an expanded core region at its end. The expanded core structure provides low optical power loss in both crystals at the expense of spatial resolution. In other words, the mode field diameter is enlarged up to 25–45 μm at the facet so that the divergence of propagating optical beams in the crystals is suppressed. Therefore, about one-half of the incident light power is coupled back to the fiber. The spatial resolution given by the fiber core dimension (25–45 μm) is fine enough for most of RF circuit diagnoses.

Fig. 2 shows a block diagram of the measurement system. All the optical system contains fiber optics only, which offers some attractive features: the system is very simple, stable, and free from optical alignment. One should note here that those benefits came from the all-optical-fiber configuration provided by the introduction of the fiber-edge probe scheme. The only fault is that rather sophisticated polarization control is necessary so as to set the polarization state of probing light fixed to the optimum in the crystals. However, this issue will be solved if one uses a polarization-maintaining fiber instead of the single-mode fiber, which will be the subject of future work.

We used a semiconductor laser diode emitting 1.55-μm continuous-wave (CW) light. The laser light was amplified and launched into the FEEO and FEMO probes through a polarization controller and a circulator. The reflected light from the crystal was detected with a high-speed (>20 GHz) and high-power-allowance (>20 mW) photodetector (PD). We used Er-doped fiber amplifiers to compensate optical loss caused in all the fiber optics. The detected signal was analyzed by an RF spectrum analyzer in the frequency domain. The DUT and the probe were placed beneath a microscope for the probe position alignment. Since the microscope is not aimed for focusing an optical probe beam, one can set the magnification of microscope independently of the spatial resolution of the field measurements.

In contrast with the conventional field detection systems based on the EO sampling technique, our system is unique since it contains such elements as the CW laser source, the high-speed and high-power allowance PD, and the RF spectrum analyzer, which allows the measurement to be free from the synchronization of drive signal. In other words, the DUT can be analyzed at any frequencies within the system bandwidth. In addition, we would like to point out that the spectrum-domain analysis is beneficial in the two-dimensional field-mapping application of EO-probing techniques. The details of this issue was reported in [7]. There is, however, a premature feature that the phase of the RF signal is not measurable at this point. We believe that some modification of the system could, in principle, make it possible [5], [6].

III. Measurement Results

We have preliminarily investigated the characteristics of our FEEO and FEMO probes. We used as a DUT a microstrip transmission line of a 230-μm width and a few centimeters length. Its characteristic impedance is 50 Ω and a terminating load of a 50-Ω resister was connected to its output. While the ZnTe probe head picks up the signal voltage of the DUT, the YIG probe senses the magnetic field generated by the signal current. By combining results of those measurements, local variation of transmission impedance should be clarified if it would exist.

Fig. 3 shows a typical signal acquired by the RF spectrum analyzer, where power and frequency of the applied RF signal to the DUT were 20 dBm and 1 GHz, respectively. The detected optical power was 1 mW. The gap between the transmission line and crystal was kept around 5–10 μm. The internal noise of the spectrum analyzer was a dominant noise component under such a condition of our measurements, which limited the minimum detectable level of the PD output signal to be −135 dBm.

Fig. 4(a) and (b) shows the RF power response of these probes. The horizontal axes are the RF input power of the

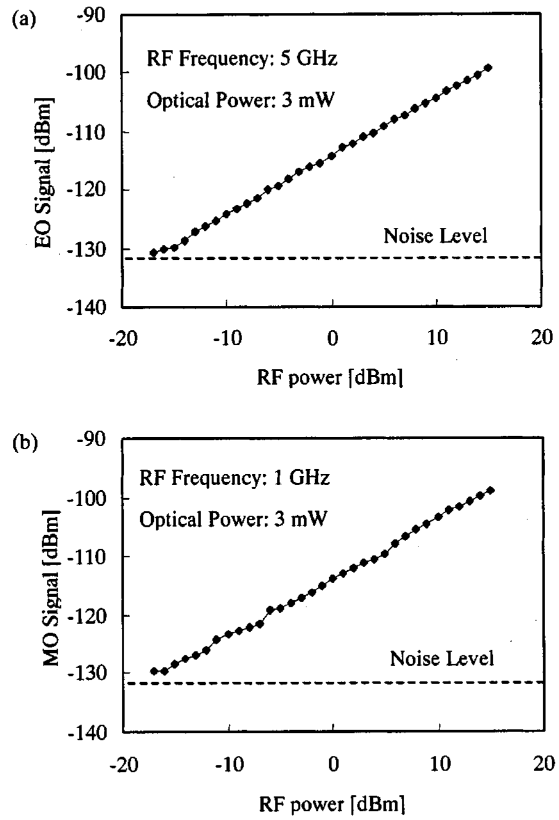

Fig. 4. Relationship between input RF power of the DUT and the signal power derived for EO and MO probing are shown in (a) and (b), respectively. Detected optical power was 3 mW in both cases.

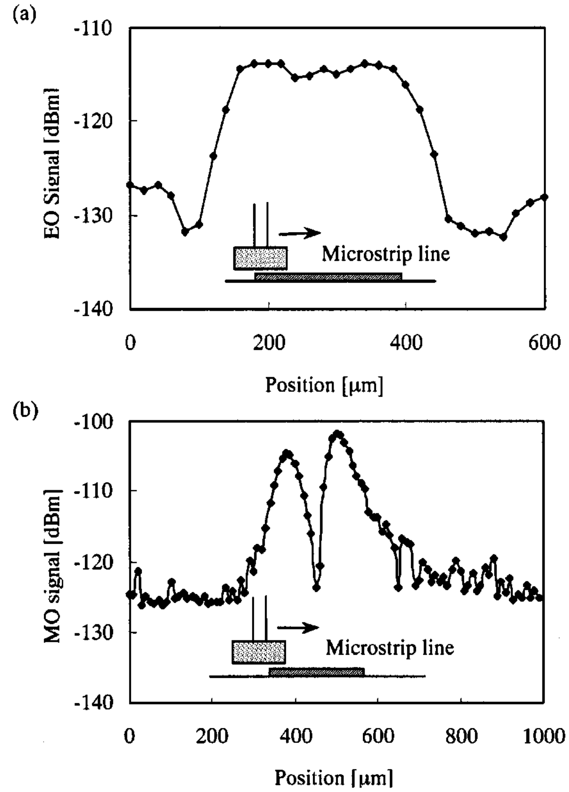

Fig. 5. Electromagnetic-field distributions near the microstrip line acquired using the: (a) EO probe and (b) MO probe.

DUT, and the vertical axes show the detected EO/MO signal power. The measurement conditions were the same as those for the data shown in Fig. 3, except for the frequency and optical power. The minimum detectable signal level of the DUT was less than -15 dBm, which corresponded to voltage and current amplitudes of 30 mV and 0.6 mA in a 50-Ω transmission line, respectively. We believe that those values can be improved to some extent by increasing the detected optical power or inserting an electrical amplifier after the photodetection. In addition, there would be some room for improvement in the optimization of the polarization state of the probing light in the crystals. Furthermore, the Fabry–Perot resonance enhancement scheme is also effective as experimentally demonstrated later. The relationships between the applied RF power and the detected EO or MO signal power are fairly linear in the range we tested.

Fig. 5(a) and (b) shows the EO/MO profiles derived by line scans across the transmission line. One should note that reasonably precise field profiles were derived in both cases. In these measurements, the distance between the probe and sample was set to be 10–20 μm to prevent the probes from mechanical damage. We can estimate the spatial resolutions of the EO or MO probing by deconvolution of the DUT width from the data in Fig. 5. The spatial resolution in the case of EO probing is about 50 μm, whereas the MO probing resolution is more than 100 μm. Since the EO crystal we used is thin and rather small, our estimation is considerably valid in the former, where the mode field diameter at the optical fiber edge is a major limiting factor. However, the dominant parameter in the later case seems to be the dimension of the YIG crystal. This is because the MO crystal, which was available at the point of experiment, is rather big in its height and area. Thus, we have to take into consideration the possibility of field deformation caused by the YIG crystal insertion, as well as the too long MO interaction distance. Detailed analysis will be reported elsewhere.

The measurement bandwidths of the probes were also examined. Fig. 6(a) and (b) shows the measured EO/MO signal power plotted as functions of RF signal frequencies. Note that the EO probing bandwidth is as broad as 20 GHz, which is restricted either by the DUT bandwidth or the measurement system bandwidth (given by the PD or RF spectrum analyzer bandwidths), as expected. On the other hand, the practical bandwidth of the FEMO probe was about 5 GHz. The limiting factor of the MO probing bandwidth is not clear at present. In addition, one could see some resonantly degraded structures around 2 GHz in the MO probe response. Also, there are many miniature structures below 1 GHz. One could claim that the dynamic behavior of magnetic-domain boundaries might cause those structures, whereas more extended studies are definitely necessary to reach a clearer answer. Some of the origins of those behaviors have been clarified, which will be reported elsewhere.

IV. Sensitivity Improvement

Finally, we report on our trial to enhance the sensitivity of our probes by using two methods as described below; the Fabry–Perot enhancement effect and an introduction of new kind of MO crystal.

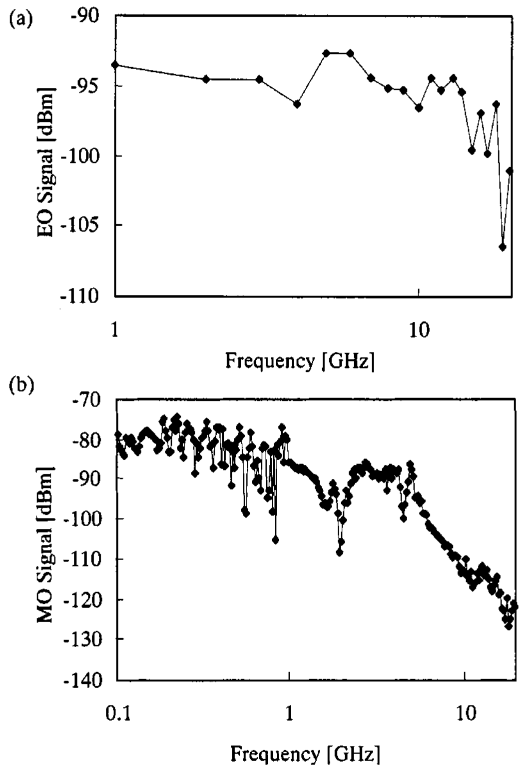

Fig. 6. Frequency response of: (a) EO and (b) MO probes, respectively.

For the sensitivity enhancement of the FEEO probe, we applied the Fabry–Perot resonant cavity scheme to the crystal. This is a well-known technique to enhance the modulation efficiency of optical modulators [9]. On the other hand, it has been scarcely applied to an EO crystal used in the external EO-probing schemes as far as we know [8]. This is probably because of the following three reasons.

1) The resonant nature is not fully advantageous for the EO-sampling scheme since the broad-band optical spectrum of sampling pulses is not suitable to the narrowed spectral window of resonance.
2) A light source having the fine wavelength tunability is necessary to hit a resonant mode, which would lead to an increase in system complexity and cost.
3) An EO crystal with the Fabry–Perot enhancement is not commercially available at present.

   While the first issue does not matter in our case, we prepared a wavelength tunable external cavity diode laser for the second.

In addition, we made a resonant cavity FEEO probe using a ZnTe crystal. Two pairs of TiO_2/SiO_2 stacks were deposited on its top surface by the electron beam evaporation technique. The reflectance of the top mirror was designed to be about 80%.

To confirm the sensitivity enhancement, we measured the same signal on the microstrip line using the two kinds of FEEO probes; with and without the resonant cavity structure. The presence of the top mirror made the optical reflectance spectra of EO crystals different from each other drastically, as shown in Fig. 7(a). The FEEO probe without the top mirror possesses a slight wavelength dependence of reflectance because of residual

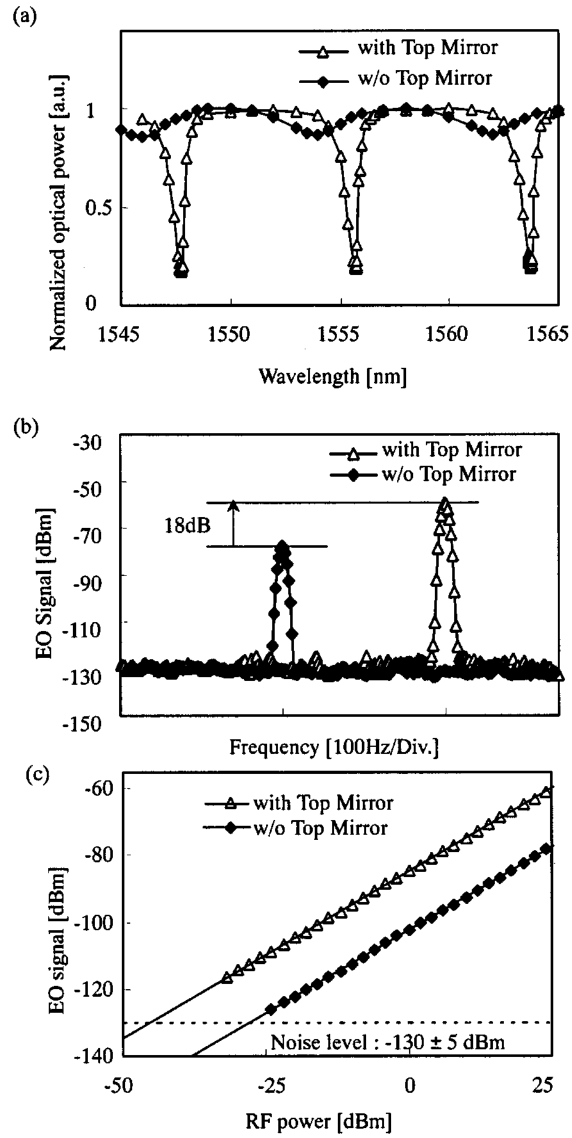

Fig. 7. Sensitivity enhancement derived by a Fabry–Perot resonator structure made on a sensor crystal. Open triangles and solid diamonds in each plot are the data acquired by the EO probes with and without the top mirror, respectively. (a) Reflectance spectra of the crystals. (b) RF spectrum analyzer traces. The spectra are shifted from each other for clarity. (c) RF power response of two probes. (In this measurement, the data without a top mirror is already improved a little compared with those in Fig. 4(a). This is probably due to fine wavelength adjustment to the spectral valley given by the residual reflectance.)

reflection between the fiber and EO crystal. In contrast, strongly resonant structures were clearly provided in the Fabry–Perot cavity case. The frequency traces measured by the RF spectrum analyzer are shown in Fig. 7(b). The applied RF power was 25 dBm, and detected optical power was set around 3 mW. Those values were provided commonly for both probes, whereas the laser wavelength was tuned to fit to one of the valleys in each reflectance spectra of Fig. 7(a). One can conclude from the data that the obtained sensitivity enhancement is as much as 18 dB.

The relationships between the applied RF power and detected signal power were plotted in Fig. 7(c). The lowest input RF power of the DUT was limited to be -32 dBm in the experiment since an accurate attenuator to go down further was not available. We expected from the extrapolation of the data that the minimum detectable signal power of our measurement is as low as −45 dBm. This value corresponds to sub-millivolt sensitivity (0.7 mV/Hz$^{-1/2}$), which is the lowest in the ever-reported EO-probing sensitivity for microstrip line measurements as far as we know. Furthermore, an additional 5-dB improvement can be obtained if one increases the detected optical power to 10 mW. Thus, it has been clearly indicated that the introduction of a resonant cavity structure to an FEEO probe is quite effective in the sensitivity improvement. One can expect further sensitivity enhancement by the following improvements:

1) cavity resonance optimization;
2) polarization state optimization;
3) more precise control of probe position for closer probing.

For the FEMO probe sensitivity enhancement, we have chosen a (BiR)IG crystal (2 mm^2 in area × 0.24 mm in height) supplied by the Mitsubishi Gas Chemical Co. Inc., Tokyo, Japan, It is well known that the partial replacement of yttrium with bismuth enlarges the efficiency of Faraday rotation. However, it turned out in our experiment that the sensitivity was not improved, but even worsened as long as our examination range of frequency is concerned. The shorter length for the MO interaction than that of the YIG probe might be a dominant origin of the inferior sensitivity. A detailed investigation will be reported elsewhere. Note that one can expect the same kind of improvement to be provided by the Fabry–Perot resonant cavity method for an FEMO probe as in the FEEO probe case, although we have not applied it yet.

V. Conclusion

In this paper, we have proposed and experimentally demonstrated a new class of an electromagnetic-field measurement system based on the EO/MO effect: an EO or MO crystal is attached to a fiber facet to measure the local voltage or current amplitude on microwave planar circuits. Through the experimental investigations, the following attractive features and real performances have been confirmed.

We have pointed out some potentially advantageous features of this probing system compared with the conventional EO sampling systems. It has been also found that the symmetrical probe structure provided by the fiber-edge configuration affects the device field distribution less.

Employing a CW laser source, a fast PD, and an RF spectrum analyzer, the measurement has been performed in the frequency domain. The minimum detectable signal amplitudes were 30 mV for the voltage prober and 0.6 mA for the current prober at 1-GHz signal frequency. Measurement bandwidth was 20 GHz for the EO probe, and 5 GHz for the MO probe. Applying the Fabry–Perot resonator configuration to the EO probe, we achieved the sensitivity improvement by 18 dB, which leads to the estimated value of 0.7 mV/Hz$^{-1/2}$ or lower.

In the future, we plan to optimize the crystal sizes and apply the system to the field mapping measurement [7] of both voltage and current. Also, we have to clarify the invasiveness of our probes in their application to the electronic device and circuit analysis. Furthermore, we will confirm the usefulness of the local impedance measurement with the present system configuration or improved by measuring voltage, current, and frequency responses at specific points of RF circuits. We expect that it will provide careful comparison between theoretical and real effectiveness of impedance-varying circuit designs.

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