Metal-free Electric-field Probe based on Photonics and its EMC Applications

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Abstract—To sustain electromagnetic compatibility (EMC), a metal-free electric-field probe is important because of its less invasiveness in electromagnetic field. This article describes a candidate of the metal-free electric-field probe based on photonics, its frequency response, and EMC applications. The probe consists of a 1 mm x 1 mm x 1 mm CdTe crystal mounted on the tip of an optical fiber, which theoretically possesses the potential to cover the frequency band from below megahertz to terahertz. We utilize a capacitor, GTEM-Cell, and standard gain horn antennas for applying a free-space electric field to the optical probe at frequencies from 20 kHz to 1 GHz, from 1 GHz to 18 GHz, and from 10 to 180 GHz, respectively. An electric-field measurement demonstrates its flat frequency response within a 6-dB range from 20 kHz to 50 GHz except for the resonance due to the piezo-electric effect at a frequency around 1 MHz. The sensitivity increases due to the resonance of the radio frequency wave propagating in the crystal at the frequencies higher than 50 GHz. These experimental results demonstrate that the optical electric-field probe is a superior tool for the wide-band measurement which is impossible with conventional probes such as a dipole, a loop, and a horn antenna. In transient electrostatic discharge measurements, electric-field mapping, and near-field antenna measurements, the optical electric-field probe provides the useful information for the deterioration diagnosis and the lifetime prognosis of electric circuits and devices. These applications of the optical electric-field probe are regarded as promising ways for sowing the seeds of evolution in electric-field measurements for antenna measurement, EMC, and EM1.

Keywords—Electric-field probe; Pockels effect; Photonics

I. INTRODUCTION

The new directive EC 2004/40/EC "Physical Agents Directive" will make the provisions of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) a legal requirement across Europe with respect to the exposure of workers to electromagnetic fields [1]. The basic restrictions of ICNIRP limit the specific absorption rate (SAR) of radio frequency (RF) power between 100 kHz and 10 GHz, and the incident power flux density (PFD) from 10 GHz to 300 GHz, to which the American National Standards Institute (ANSI), the Institute of Electrical and Electronics Engineers, Inc. (IEEE) standard, and the guideline of the Japan Ministry of Internal Affairs and Communication conform [2, 3]. Existing standards within Europe do not provide comprehensive coverage of SAR and PFD over this range. The joint project (T4 J07) of the European Association of National Metrology Institute (EURAMET), which started on April 1, 2008 aims to provide traceable metrology for SAR and EM field strength measurements at all frequencies that are in widespread public use [4]. Through this project, the expertise, including contribution to international documentary standards, devices and measurement techniques, is developed to make these standards widely accessible for traceable measurements regarding exposure assessment in the environment, product compliance testing, and studies into biological effects of EMF.

In these endeavors, an ideal probe will be needed for accurately detecting electric fields over the frequency ranges mentioned above. Currently, loop antennas at frequencies below 30 MHz, dipole antennas at frequencies from 30 MHz to 3 GHz, and standard-gain horn antennas at frequencies over 500 GHz are used for a RF transmission and the calibration of a magnetic-field and electric-field probe, and an electrical cable carries the detected signal to the measuring instrument. The probe and cable are made of metal, which scatters the signal emitted by the antenna being measured. This may make it difficult to know the original state of the signal. In particular, if the probe is placed near the antenna under test in SAR measurements, electrical coupling occurs and radio waves other than the free-space propagating signal arise. An ideal measurement setup requires the use of a metal-free electric-field probe and a non-metallic cable, such as an optical fiber for accurate electric-field measurements.

Electro-optic (EO) effect is a good candidate to realize an electric-field probe that contains no metal. The EO effect is a phenomenon in which the natural refractive index of a material changes when an electric field is applied. A change in the refractive index that is directly proportional to the electric field strength, which is known as the Pockels effect, theoretically provides a widely flat response in the frequency band from a few megahertz to terahertz. The potential of the optical probe for an over-terahertz measurement was demonstrated with an EO sampling system consisting of a pico-second pulse laser and free-space optics, which characterized a high-speed semiconductor circuit in the time domain [5], and free-space time-domain detection was reported [6]. The application of fiber optics improved the concept of the freely positionable probe and eliminated the inconvenience associated with free-space optical propagation [7-10]. We demonstrated the feasibility of the optical probe in a SAR measurement in 2005 [11] and improved the flexibility of the optical fiber-mounted probe for practical use [12–14].

In this paper, Section 2 describes the electric-field measurement system with our developed probe and presents measurement results and the discussion of frequency response...
in the optical electric-field probe comparing with the results of electromagnetic-field simulations. Section 3 demonstrates the applications of the optical electric-field probe to wideband measurements of transient electrostatic discharge (ESD) signal and near-field distribution around an electric circuit and an antenna, and then suggests the potential of the optical electric-field probe in electromagnetic analysis and diagnosis of electric circuits and antennas.

II. METAL-FREE ELECTRIC-FIELD PROBE

A. Configurations

The configuration of the developed optical electric-field probe is shown in Fig. 2. The probe tip comprises just dielectric components, a CdTe crystal with a dielectric reflector, a Faraday rotator (FR), a lens, a glass ferrule, and an optical fiber. The size of the crystal is 1 x 1 x 1 mm³ which is smaller than the wavelength of the RF wave at the frequency of 300 GHz. Therefore, the optical probe can detect the electric field with less invasiveness for the RF wave. The diameter of the optical beam propagating in the crystal is 200 μm which determines the spatial resolution for detecting the transversal electric field. The longitudinal resolution is determined by the interaction length between the optical beam and an RF wave propagating in the crystal, which is 1 mm in this probe. The optical electric-field probe is connected to a polarization controller through a 5-m long optical fiber, as shown in Fig. 2. Theoretically, the system should operate with stable sensitivity even if the optical fiber is extended to a length of 1 km [11].

![Metal-free electric-field probe based on phonics.](image1)

![Measured frequency responses at frequencies from 20 kHz to 1 GHz with capacitor (blue circles), from 100 MHz to 18 GHz with GTEM-Cell (red circles), and from 10 to 180 GHz (green circles), and calculated electric-field intensities in the center of CdTe crystal from 10 MHz to 300 GHz (orange solid line).](image2)

Fig. 1. Metal-free electric-field probe based on phonics.

B. Frequency Responses

We provide the frequency response of the optical electric-field probe with a capacitor, a GTEM-Cell, and a standard gain horn antenna. In order to obtain a dynamic range of sensitivity over 50 dB, electric-field intensity is set to intensity of 100 V/m at the probe tip. The GTEM-Cell has an applicable bandwidth from 10 kHz to 18 GHz and needs a high RF power source with a several tens watts. Since we don’t have such a RF power source at frequencies below 10 MHz and use a capacitor for applying electric field to the probe tip at frequencies from 9 kHz to 3 GHz with a few tens millimeter watts. At frequencies from 10 GHz to 180 GHz, standard gain horn antennas are used for the measurements.

The intensities of the output signal from the photodetector in the optical probe system are plotted with blue, red, and green closed circles for the measurements with the capacitor, GTEM-Cell, and the standard gain horn antennas in Fig. 2. The tendency of the measured intensities represents the frequency response of the optical probe. The sensitivity of the optical probe decreases due to the screen-out of the RF wave from the crystal at frequencies lower than 100 kHz. The frequency resonance due to piezo-electric effect is appeared at frequencies around 1 MHz. In the responses for the measurement with the capacitor as shown with blue circles in the figure, the intensities decrease since electric field radiates from the capacitor. The frequency response is flat within a 6-dB range at frequencies from 4 MHz to 10 GHz and the output signal and the calculated electric field increase as the frequency increases at frequencies higher than 20 GHz. The electric-field intensities at the center of the crystal are calculated with an electromagnetic simulation at frequencies from 10 MHz to 300 GHz, where the intensity of an input electric field is set to 100 V/m in a simulation model. The calculated electric-field intensities is 0 dBV/m at frequencies from 10 MHz to 10 GHz and the EO output signal intensities are around -51 dBV for the electric-field intensity of 100 V/m in the evaluation with the capacitor and the GTEM-Cell. Therefore, the calculated electric-field intensities correspond to the EO output signal intensity at the frequencies from 10 MHz to 10 GHz. The calculated intensities are plotted with an orange solid line in the figure. However, the calculated results are different from the measured ones at frequencies above 10 GHz since the simulation model does not comprise the FR, the lens and the optical fiber. Several peaks in the calculated electric-field appear at frequencies higher than 100 GHz. This is because the substantial wavelength at a frequency of 100 GHz is equal to the size of the CdTe crystal and resonances are caused inside the crystal at the frequencies higher than 100 GHz.
III. EMC APPLICATIONS

A. Transient ESD Measurements

We applied the optical electric-field probe to the transient measurement of the ESD signals transmitting on and around a microstrip line (MSL) as shown in Fig. 3. In the DUT, a 50-mm long MSL was patterned on the FR4 wafer with a size of 100 mm x 30 mm and a thickness of 1 mm. An ESD signal were generated with an ESD generator (ESS-2002/NoiseKen) and input to the DUT via an ESD gun (TC-815R/NoiseKen). The generated ESD signal was 0.7-ns duration pulse with a peak voltage of 2 kV as shown with a black solid line, which is calibrated by NoiseKen prior to shipment. The ESD signal transmitted on the MSL of the DUT and output directly to an oscilloscope through an electrical cable at the measurement for the time domain waveform of the output signal from the MSL.

The output signal of the MSL is deteriorated since its high frequency components are filtered out with the degradation of the electrical connector soldered in the output port on the wafer. The first peak of the output signal decreases comparing with that of the input signal. The output port of the MSL was terminated at the transient measurement with the optical electric-field probe. The optical system for the optical electric-field probe was the same with the evaluation system with the capacitor as described in Sec. 2. The tip of the optical electric-field probe was located at a height of 0.5 mm apart from the surface of the wafer. The measurement points were positioned at a distance of 0, 5, 10 mm along the perpendicular line to the MSL. The time domain waveforms of the electric field on the MSL were provided with a single-shot measurement of the sampling oscilloscope.

Fig. 4 shows the time domain waveform of electric field along x axis measured with the optical electric-field probe at a distance of 0 (blue line), 5 (pink line), and 10 (yellow line) from the MSL. At the distance of 0, the time domain waveform of the electric field agrees well with that the input signal. This indicates that the optical electric-field probe can measure the electric field with less deterioration. The electric field is almost zero at a distance of 5 and 10 mm. This indicates that a substrate radiation mode of the electric field along x axis is below the measurement limit of the probe at the side of the MSL above the wafer. From these results, we obtained a lot of transient information about electric field transmitting and radiating above and around the MSL and the wafer, and can effectively utilize them in the diagnosis of the electric circuits damaged with ESD and the design process for defeating an ESD noise.

B. Near-field Measurements

We scanned an area of 150 mm x 50 mm at a distance of 1 mm above a planar circuit with a CPW, a radial balun and a Vivaldi antenna. The CPW and the radial balun were fabricated with a 20-μm-thick Cu film on a 0.8-mm-thick glass-epoxy wafer. The planar circuit was attached to the adapter transiting the CPW from a coaxial cable to which the sine-wave signal was supplied at 8 GHz. For comparison, a commercially available electromagnetic simulator (MW-Studio/ CST GmbH) calculated the electric field with the model. The measured and calculated near-field intensity distributions are shown in Figs. 5.

The electric-field components parallel to the x, y and z-axes are shown in (a), (b) and (c), respectively. The intensity and phase distributions measured with the optical electric-field probe agreed with the calculated distributions very well, except for the intensity distribution of the electric field parallel to the z-axis and the phase distribution of the electric field parallel to the y-axis. In the intensity of the electric field parallel to the z-axis, asymmetric distributions were measured over the Vivaldi antenna and the radial balun, which was not observed in the simulation. The phase parallel to the y-axis could not be measured out of the circuit because the intensity of the electric-field radiating for the -x direction is too small to be detected with the calculated with the electric-field components parallel to optical electric-field probe, whereas the results fairly agree well on the planar circuit. These results indicate that near-field measurement using the metal-free electric-field probe is useful for intuitively diagnosing the radiation performance when designing antenna circuits.
IV. CONCLUSIONS

We evaluated the frequency response of our optical-fiber-mounted electric-field probe at frequencies from 20 kHz to 180 GHz. The frequency response is flat within a 6-dB range at frequencies from 100 kHz to 10 GHz except for the frequency response due to the piezo-electric effect and the sensitivity increases at frequencies higher than 20 GHz. In the calculation, the electric field at the center of the CdTe crystal increased because of the RF resonance inside the crystal at frequencies higher than 100 GHz. Reducing the crystal thickness should improve the flat frequency response. The resonance frequency of 300 GHz corresponds to crystal thickness of around 0.2 mm, which decreases the sensitivity to a fifth. The organic crystal, 4-dimethylamino-N-methyl-4-stilbazolium tosylate (DAST), is promising for overcoming these drawbacks because of its high EO coefficient and low permittivity [15]. In transient electrostatic discharge measurements, electric-field mapping, and near-field antenna measurements, the optical electric-field probe provides the useful information for the deterioration diagnosis and the lifetime prognosis of electric circuits, devices, and antennas. These applications of the optical electric-field probe are regarded as promising ways for sowing the seeds of evolution in electric-field measurements for antenna measurement, EMC, and EMI.

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