Optical E-field probe using $LiNbO_3$ M-Z waveguides in the electromagnetic compatibility measurements

Yongjun Yang (杨拥军), Fushen Chen (陈福深), and Bao Sun (孙 豹)

Key Laboratory of Broadband Optical Fiber Transmission and Communication Networks,
University of Electronic Science and Technology of China, Chengdu 610054

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An integrated optical E-field probe with the segmented electrode using $LiNbO_3$ Mach-Zehnder (M-Z) waveguides is proposed and an equivalent circuit of the segmented electrode is given. According to the circuit theory, the electrode structure of the probe is designed. The unpackaged size of the fabricated probe is as small as 60 × 6 × 0.5 (mm). The measured results show that the half wavelength voltage is 7.7 V, the ±5 dB baseband range is 3 GHz, and the minimum detectable field is lower than 90 dB·μV/m (bandwidth 100 Hz). Therefore it can be used in the electromagnetic compatibility (EMC) measurements.

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With the development of information communication technology, the needs for the electromagnetic compatibility (EMC) measurement are rising. To evaluate the EMC of equipment, various sensors for measuring the electric field have been developed. A serious problem for conventional electric field probe is the influence of the coaxial cable. In order to solve this problem, electric field probes which use the Pockels effect in $LiNbO_3$ are developed because of compact size, large bandwidth, and immunity to electromagnetic interference.

Many efforts have been devoted to construct the integrated optical electric field probe[1−4]. In our work, an integrated optical electric field probe using Mach-Zehnder (M-Z) interferometer structure on $LiNbO_3$ substrate with the segmented electrodes of ten sections is designed according to the new-proposed equivalent circuit theory. This device is fabricated by the proton-exchange technique. Its frequency response was measured in gigahertz transverse electromagnetic (GTEM) cell; the half wavelength voltage and the intrinsic phase mismatch are calculated by fitting the data measured in the static electric field.

The electric field probe structure with the segmented electrode using optical modulator is shown in Fig. 1. A short receiving dipole antenna drives the optical modulator directly. When the incident electromagnetic signal is a plane wave directed perpendicular to the $LiNbO_3$ substrate (normal incidence), only electric field component E_y along the y direction can result in the gap voltage V_g and $V_g = E_y L_e$. Here, L_e is the constant, related to the frequency of the incident electromagnetic wave and the electrode structure of the sensor. The gap voltage V_g can cause the Pockels effect and the light is modulated because of the index change. Figure 2 shows an equivalent circuit according to the segmented electrode structure. R and X are the radiation resistance and the radiation reactance of the dipole antenna, respectively. C_0 is the capacitance per unit length of the modulator and can be calculated with the finite element method[5]. L is the length of the electrode. V_s is the equivalent voltage source. If the number of electrode segments is n, the frequency response of the probe can be got based on the circuit theory in the form

$$H(\omega) = 1 \Bigg/ \sqrt{\left(\frac{\omega C_0 L R}{n^2}\right)^2 + \left(1 - \frac{\omega C_0 L X}{n^2}\right)^2}\,, \qquad (1)$$

where ω is the angle frequency of the incident wave, R and X can be calculated with the moment method[6,7]. When n = 1, 5, 10, 15, C_0 = 400 pF, the frequency response is shown in Fig. 3.

The longer the segmented electrode is, the higher the modulation efficiency and the detection sensitivity are. To improve sensitivity for the electric field, the antenna length is 53 mm and the segmented electrode part is 41.67 mm. Considering the frequency response of the probe and the fabrication complexity of the segmented electrode, we designed a probe with $n = 10$ from Eq. (1). By the segmentation of the modulator electrode, the effective capacitance of the electrode becomes 1/100 of that of the unsegmented electrode. The optical

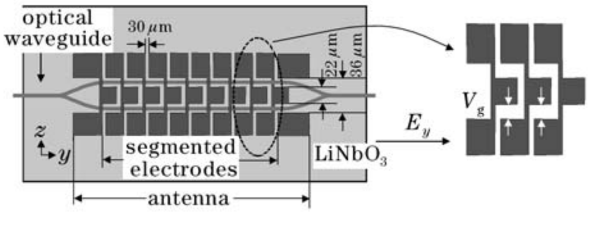

Fig. 1. Schematic diagram of the electric field sensor.

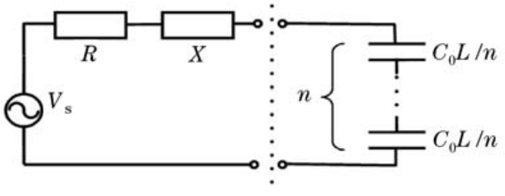

Fig. 2. Equivalent circuit of the probe.

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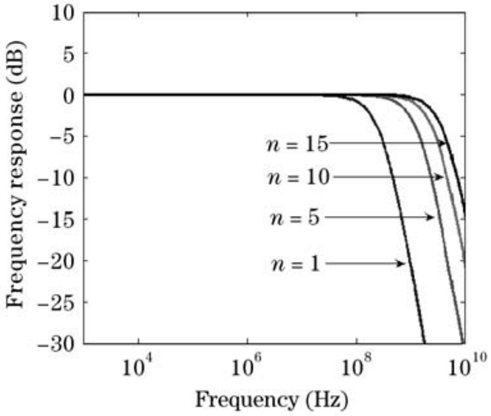

Fig. 3. Theoretical frequency response of the probe.

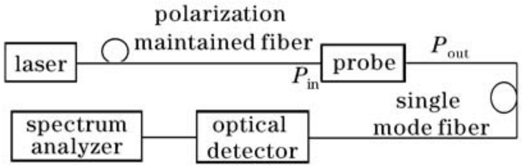

Fig. 4. Schematic diagram of the electric-field sensing system.

waveguide width is 7 μm to support a single-mode transmission at $\lambda = 1.55$ μm. In addition, in order to have a small transmission loss, the curves of two branch optical waveguides should satisfy the cosine function. The sensing system proposed is shown in Fig. 4. For the single probe, the input optical intensity $P_{\rm in}$ and the output optical intensity $P_{\rm out}$ satisfy

$$P_{\rm out} = \frac{P_{\rm in}}{2}\left\{1+\cos\left(\pi\frac{V_{\rm g}}{V_\pi}+\varphi_0\right)\right\}$$
$$= \frac{P_{\rm in}}{2}\left\{1+\cos\left(\pi\frac{E_y L_{\rm e}}{V_\pi}+\varphi_0\right)\right\}, \qquad (2)$$

where V_π is the half wavelength voltage, φ_0 is the intrinsic phase mismatch. For a given optical source and probe, the parameters $P_{\rm in}$, φ_0, $L_{\rm e}$, and V_π are constant. The output optical intensity $P_{\rm out}$ is dependent only on the electric field strength E_y of the incident electromagnetic signal. Therefore the component of the electric field strength along the y direction can be received.

M-Z type optical waveguide was fabricated by the proton exchange technique in benzoic acid at the temperature of 250 °C and the annealing technique at the temperature of 350 °C on the 0.5-mm-thick, X-cut $\rm LiNbO_3$ substrate. After coating buffer layer of $\rm SiO_2$ film, the electrodes are formed by evaporating and electroplating metals Cr and Au. A polarization-maintained fiber and a single-mode fiber are connected to probe by a silicon micro-bench with V-type groove. The unpackaged size of the fabricated probe is as small as $60\times6\times0.5$ (mm). The probe is packaged in an organic glass, and the package size is as small as $85 \times 8 \times 7$ (mm).

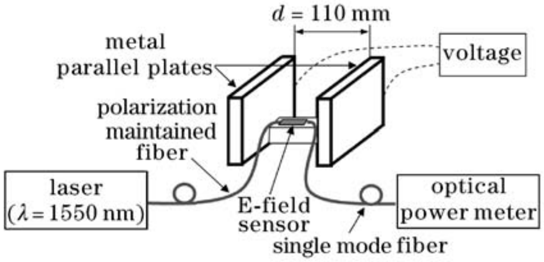

Fig. 5. Schematic diagram of the measurement setup in static electric field.

Table 1. Output Optical Power $P_{\rm out}$ Varied with Voltage U

U (kV)	$P_{\rm out}$ (μW)	P_0 (μW)	$P_{\rm out}/P_0$
0.3	112	112	1
0.5	113	113	1
1.0	114	115	0.991
1.5	114	116	0.983
2.0	113	117	0.966
2.5	112	119	0.941
3.0	114	120	0.950
3.2	99	106	0.934
3.4	98	106	0.925
3.5	110	120	0.917
3.6	97	106	0.915
3.8	96	104	0.914
4.0	94	104	0.904

Figure 5 is the schematic diagram of the measurement setup in the static electric field. The distance d between two parallel metal plates is 110 mm. Applying different voltages U to the parallel plates, the output optical power $P_{\rm out}$ is shown in Table 1 when the input optical power keeps steady. When $U = 0$, the output optical power is P_0. From Eq. (2), $P_{\rm out}/P_0$ satisfies

$$\frac{P_{\rm out}}{P_0} = \frac{1+\cos(\pi\frac{\alpha U}{V_\pi}+\varphi_0)}{1+\cos(\varphi_0)}, \qquad (3)$$

where $U = E_y d$, α is the constant $L_{\rm e}/d$. The relation between $P_{\rm out}/P_0$ and U is plotted in Fig. 6. V_π is 7.7 V and φ_0 is 9°.

The frequency response was measured in GTEM cell, whose measurement setup is shown in Fig. 7. Figure 8 shows the frequency response of the probe when the

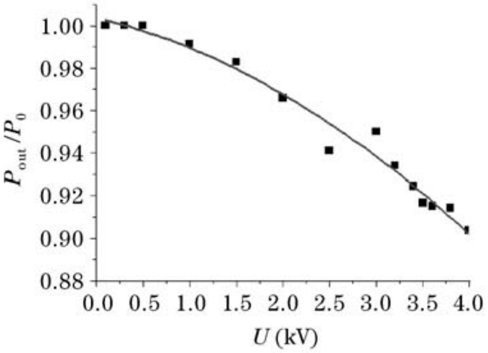

Fig. 6. Relation between $P_{\rm out}/P_0$ and applied voltage U. $V_\pi = 7.7$ V, $\varphi_0 = 9°$.

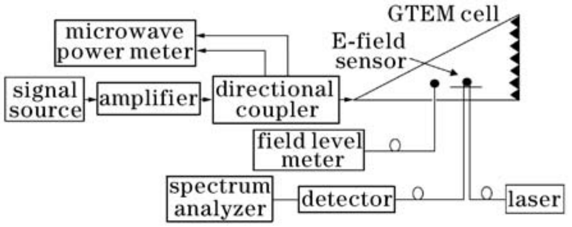

Fig. 7. Schematic diagram of the measurement setup in GTEM cell.

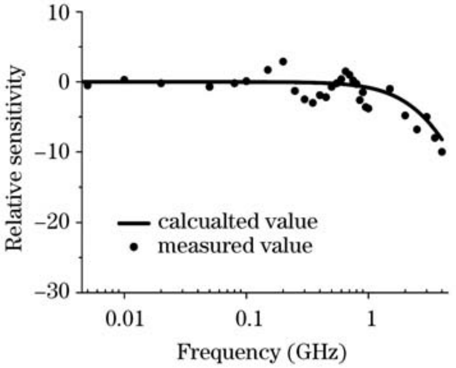

Fig. 8. Frequency response of the probe in GTEM cell.

electric field strength is 20 V/m in GTEM cell. The ±5 dB baseband can reach 3 GHz. In addition, the minimum electric field strength detected is lower than 90 dB·μV/m under the condition that relative bandwidth is 100 Hz.

In conclusion, an integrated optical electric field probe with the segmented electrode based on M-Z interferometer is proposed. According to the equivalent circuit, the frequency response of the probe is analyzed. From the results of numerical simulation and measurement, we can conclude that: 1) choosing the proper electrode segment n is beneficial to the enhancement of the frequency response and the fabrication of the segmented electrode; 2) the frequency response has reached 3 GHz within ±5 dB. The minimum detectable electric field strength of the probe is lower than 90 dB·μV/m when the relative bandwidth is 100 Hz; 3) the half wavelength voltage V_π is approximately 7.7 V, and the intrinsic phase mismatch φ_0 is approximately 9°.

Y. Yang's e-mail address is uestc_yyj@yahoo.com.cn.

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