Integrated optical electric field sensor with telescopic dipole

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

School of Communication and Information Engineering,
University of Electronic Science and Technology of China, Chengdu 610054

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An integrated optical electric field sensor based on a Mach-Zehnder interferometer with the telescopic dipole is designed and fabricated, and its electrodes are segmented and connected with a telescopic dipole. The measured results show that when the frequency response is from 10 kHz to 6 GHz with the antenna length of 55 mm, the minimum detectable electric field of 20 mV/m can be obtained, and the linear dynamics range can reach 90 dB at 250 MHz.

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In the last few years, interest in electromagnetic field (EMF) sensors has widely increased[1−4]. EMF measurement has a critical part in various scientific and technical areas, such as process control, electric field monitoring in medical apparatuses, ballistic control, electromagnetic compatibility (EMC) measurements, and microwave-integrated circuit testing[4]. The conventional EMF measurement systems currently use metallic probes which can disturb the measured EMF and make sensor very sensitive to electromagnetic noise. In order to solve this problem, electric field sensors which use Pockel's effect in $LiNbO_3$ are brought because of their compact size, large bandwidth, high sensitivity, and immunity to electromagnetic interference[4].

Great effort has been devoted to the constructing of integrated optical electric filed sensor. Different electrode structures of the sensors are proposed, such as segmented electrodes[3,5], dipole element[6], and domain inversion[7]. The sensor with domain inversion has broad bandwidth but low sensitivity. The frequency response of the sensor with dipole element is limited by the electrode capacitance of the optical modulator. By segmentation of the electrode, the effective capacitance will decrease, but the integrated antenna length is limited by the chip size. In this work, an optical electric field sensor using segmented electrodes with a telescopic dipole is designed and fabricated. It has the advantages of dipole and segmented electrode, and variable measurement range will be achieved with the telescope dipole. In addition, its frequency response, sensitivity, and linear dynamic range are measured in transverse electromagnetic (TEM) cell and gigahertz transverse electromagnetic (GTEM) cell.

Figure 1 shows the scheme of the sensing system by using optical waveguide sensor with telescopic antennas. The light source is the laser diode with the wavelength of 1.55 μm. The light source and the electric field sensor are connected by the polarization maintaining fiber. The electric field sensor and the photodetector are connected by the single mode fiber.

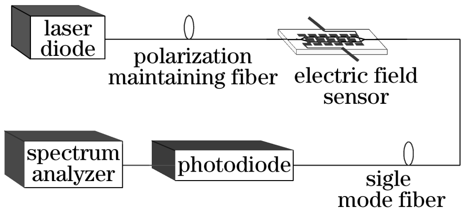

Fig. 1. Electric field sensing system based on optical waveguide sensor with telescopic antennas.

The electric field sensor with a telescopic dipole is shown in Fig. 2, which is based on a Mach-Zehnder interferometer[8,9]. The electrodes are segmented to obtain the voltage gain[5]. The dipole antenna using telescopic elements is connected to the segmented electrodes.

The electric field component E_z along the z direction can result in the gap voltage V_c, when an electromagnetic signal is a plane wave that is perpendicular to the $LiNbO_3$ substrate along the x direction.

The unmodulated optical wave from the light source passes through the polarization maintaining fiber and is given to the sensor. When the optical wave is passing the optical modulator, optical intensity is modulated by the voltage V_c. The intensity of the output wave P_{out} is

$$P_{\text{out}} = \alpha(P_{\text{in}}/2)(1 + \cos(\pi V_c/V_\pi + \varphi)), \tag{1}$$

where P_{in} is the intensity of the incident optical wave, V_π is the half-wave voltage of the sensor, V_c is the modulating voltage induced by the telescopic antennas, namely gap voltage. α is the insertion loss of the optical sensor, and φ is the optical bias angle.

Figure 3 shows the equivalent circuit of the sensor using segmented electrodes with a telescopic dipole. Suppose the segment number is N, then the capacitance between the two segmented electrodes is C_m/N and total capacitance is C_m/N^2. So the total capacitance is lower than the unsegmented electrode's capacitance[3].

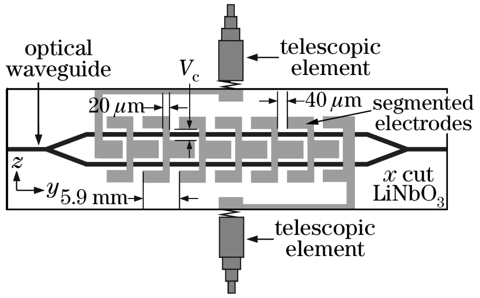

Fig. 2. Structure of the electric field sensor.

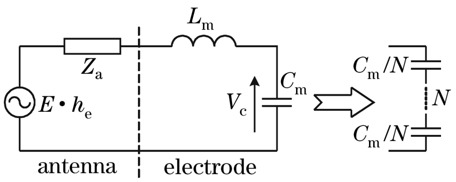

Fig. 3. Equivalent circuit of the sensor using segmented electrode with telescopic dipole.

As a result, the voltage gain is obtained through electrode segments. V_c is the voltage between the segmented electrodes, and V_c' is the voltage between the unsegmented electrodes. We can consider Z_a is pure capacitive and $Z_a = 1/j\omega C_a$, when the antenna length is far less than the wavelength of the induce electromagnetic wave and the input impedance is very small[10]. The ratio of V_c and V_c', i.e., the voltage gain is given as

$$\frac{V_c}{V_c'} = \frac{1+\frac{C_m}{C_a}-\omega^2 L_m C_m}{N+\frac{1}{N}\left(\frac{C_m}{C_a}-\omega^2 L_m C_m\right)}, \tag{2}$$

where V_c' is given[10]

$$V_c' = \frac{Z_m}{Z_a+Z_m}\left(E \cdot h_{\mathrm{e}}\right), \tag{3}$$

where Z_m is the driving point impedance, Z_a is the input impedance of the optical electric field sensor, E is the external electric field intensity, and h_{e} is the effective length of the antenna.

As shown in Fig. 4, the electrode voltage gain varies with the segment number N. The antenna length is 100 mm, the frequency of induce electromagnetic wave is 10 MHz, C_a is 0.52 pF, L_m is 7 nH, and C_m are 10, 20, 30, 40, 50 pF, respectively. From the results, we know that the voltage gain achieves maximum when the segment number is between 5 and 10. So we set $N = 7$ in our design to obtain the maximum voltage gain.

As shown in Fig. 5, the resonant frequency is different for different antenna length. We design the telescopic dipole antenna to adjust the antenna length conveniently. Figure 6 shows the architecture of the telescopic antenna. There are four segments in the telescopic antenna. The first segment length is 20 mm and the others are 10 mm. Their diameters are 4, 3, 2 and 1 mm, respectively. The thicker end is connected to the electrodes on the sensor.

Mach-Zehnder type optical waveguide is 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 LiNbO$_3$ substrate. After coating a buffer layer of SiO$_2$ film, the electrodes are formed by evaporating and electroplating metals of 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. Figure 7 gives the photograph of the integrated optical electric field sensor with telescopic antennas.

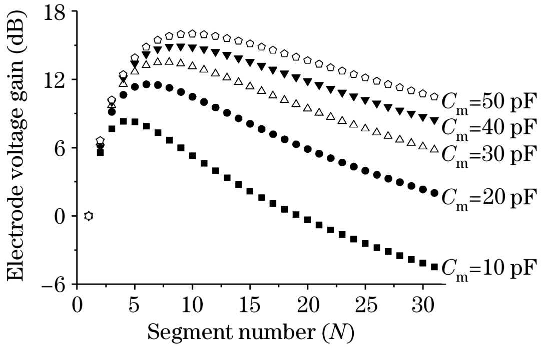

Fig. 4. Electrode voltage gain variation curve with N and C_m.

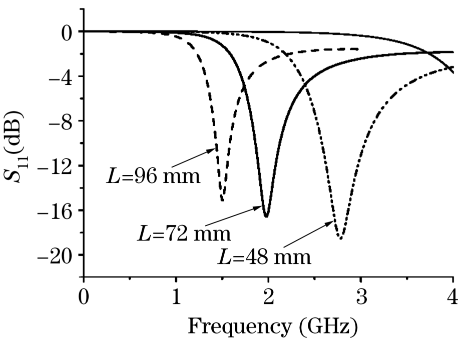

Fig. 5. S_{11} parameter of dipole antenna.

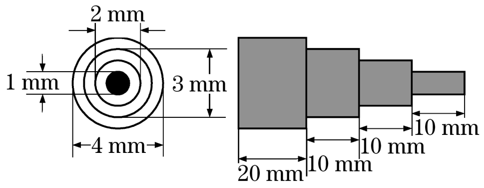

Fig. 6. Architecture of the telescopic antenna.

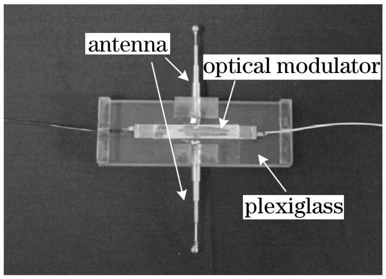

Fig. 7. Photograph of the sensor.

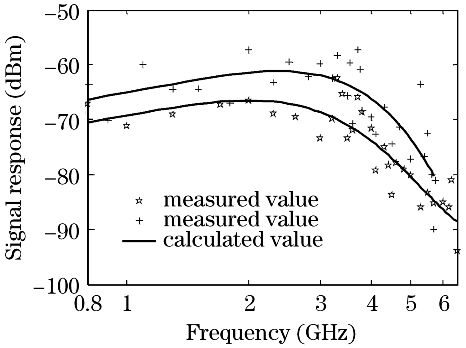

Fig. 8. Frequency response of different antenna lengths.

The measurements of the sensor's performance are carried out in TEM cell and GTEM cell. As shown in Fig. 8, the frequency response of the sensor is obtained in GTEM cell when the electric field strength is 10 V/m. The cross marks are the measured results with antenna length of 70 mm, and the star marks are the measured results with antenna length of 55 mm. The solid line is the frequency response of the antenna which is calculated by the microwave studio software from computer simulation technology (CST). The results show that the signal response is greater at the same frequency when the antenna length is longer. But the frequency response will be expanded if the antenna length is shorter. From the Fig. 9, we obtain the frequency response from 10 kHz to 6 GHz when the length of the antenna is 55 mm.

From Figs. 8 and 9, the measured and calculated results are not consistent well in high frequency range. There is an oscillation phenomenon of measured data at the high frequency. In $LiNbO_3$ electro-optic modulators, an elastic wave at acoustic frequency can appear in the substrate[11] when a voltage is applied to the electrode. This wave changes the optical waveguide refractive index due to the piezoelectric effect. In the electric field sensors exploiting a $LiNbO_3$ modulator, this refractive index change affects the device sensitivity that is not uniform in whole operating frequency range. To overcome this problem, it has been proposed to change the substrate width along the propagation direction[6].

In addition, a minimum detectable electric field of 20 mV/m has been obtained (resolution bandwidth (RBW) = 1 Hz, video bandwidth (VBW) = 1 Hz, Span = 100 Hz). The detail results are listed in Table 1, and the antenna lengthes are 55 and 102 mm, respectively. The results show that the sensitivity is improved when the length is shorter, for example, the sensitivity at 400 MHz.

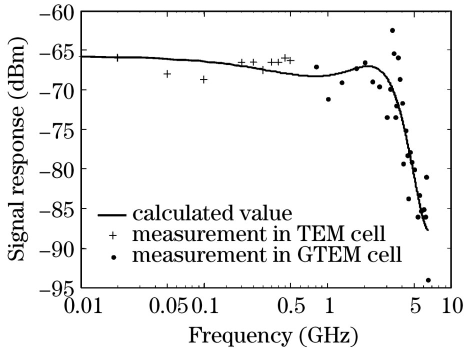

Fig. 9. Frequency response with antenna length of 55 mm.

Table 1. Sensitivity of the Sensor

Frequency (MHz)	Minimum Detectable Electric Field (mV/m)		S/N (dB)
	55 mm	102 mm	
400	60	30	6
250	10	20	6
200	20	20	6
1	60	100	6

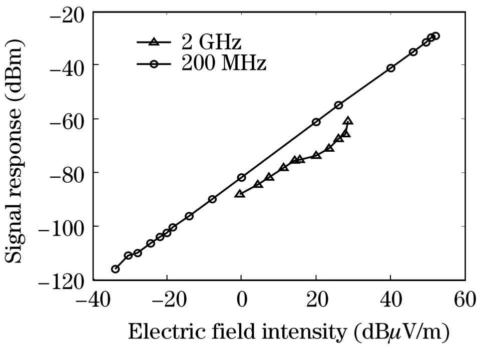

Fig. 10. Linear dynamic range of the sensor.

Furthermore, the sensitivity can be enhanced by decreasing the sensing system noise.

As shown in Fig. 10, the linear dynamic range of the sensor can reach 90 dB at 200 MHz, with the length of 115 mm. In addition, the linear dynamic range is only more than 30 dB at 2 GHz with the antenna length of 78 mm due to the measurement conditions.

We have designed an integrated optical electric field sensor with a telescopic dipole. The frequency response of the sensor has reached from 10 kHz to 6 GHz. The minimum detectable electric field is 20 mV/m. The linear dynamic range of the sensor can reach 90 dB at 250 MHz. The results show that the frequency response can be expanded, and the sensitivity is improved by decreasing the antenna length. In future work, we plan to improve the frequency characteristics by changing the substrate width along the propagation direction.

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