Non-invasive measurement of intensive power-frequency electric field using a LiNbO$_3$-integrated optical waveguide sensor

Jiahong Zhang$^{1,2}$ | Li Yang$^3$ | Yingna Li$^{1,2}$

$^1$ Faculty of Information Engineering and Automation, Kunming University of Science and Technology, Kunming, Yunnan, China
$^2$ Yunnan Key Laboratory of Computer Technology Applications, Kunming, Yunnan, China
$^3$ Yunnan Electric Power Research Institute, Kunming, Yunnan, China

Abstract

A LiNbO$_3$-integrated optical waveguide sensor with segmented shielding electrode are designed, fabricated and experimentally investigated. The segmented shielding electrode is designed to improve the sensor response at low frequency and simultaneously to have a larger half-wave electric field. The minimum and maximum detectable power-frequency electric fields of the sensor with 10 electrode elements in the time domain are 600 V/m and 139.8 kV/m, respectively, which results in a linear dynamic range of 47.3 dB. The minimum detectable electric field of the sensor with four electrode elements is 5.7 kV/m, while the maximum electric field that can be detected is more than 240 kV/m. By applying the 1.2/50 μs lightning electromagnetic pulse, the frequency response of the sensor is calculated from DC to 200 kHz with variations of less than $\pm$2 dB. All these results investigate that such sensor has potential capability to become a portable instrument for the non-invasive measurement of intensive power-frequency electric field in high-voltage power system.

1 | INTRODUCTION

With the rapid implementation of ultra high-voltage and extra high-voltage power grid, the electromagnetic environment around the power transmission line, substation and high-voltage equipment becomes worse and more complex. It has been investigated that the power-frequency electric field can cause damages to human body [1–3]. The general public is becoming increasingly concern about potential health hazards of exposure to the electromagnetic fields. However, power workers are inevitably exposed to the electric fields in order to operate close to high-voltage facilities. To issue safety warnings in the real time, and improve the health risk assessment, it is necessary to measure the power-frequency electric field nearby power facilities with no invasion to the original field.

The capacitance-type electric field sensor based on electromagnetic induction has been developed and widely used in high-voltage power system for the electromagnetic environment measurement with advantages of convenient manufacture and higher stability [4–6]. However, disturbance to the original electric field from the sensor metallic structure cannot be ignored. In addition, the sensor size is not small enough for the portable use. To reduce disturbance to the original electric field, electro-optic (EO) sensor based on the Pockels effect of EO crystal has been designed for measurement of low-frequency electric field [7–9]. However, because discrete optical components are required, the sensor structure is complex and the alignment difficulty is increased. To solve these problems, since 1980s, integrated EO electric field sensor based on optical waveguide modulator has been widely researched and developed due to the advantages of high sensitivity, compact size and broadband width [10–17]. However, the research on integrated EO sensor is mainly focussed on how to improve the sensitivity and bandwidth in order to measure the electric field with weaker intensity ($\sim$mV/m) and higher frequency ($\sim$GHz) [10–16]. Recently, the integrated EO sensors with bow-tie antenna, log-periodic antenna or tapered antenna have been developed for the measurement of intense electromagnetic pulse (EMP) [17–19]. However, bandwidth of the sensor is from hundreds of kilohertz to several gigahertz, which is not suitable for measurement of low-frequency electric field such as the power-frequency...
electric field. Moreover, the integrated EO sensor based on a common path interferometer has been developed for measurement of the alternative current electric field as low as 20 Hz. But the maximum detectable electric field is no more than 27 kV/m [20, 21].

This paper has designed, fabricated, and experimentally investigated an LiNbO3-integrated optical waveguide sensor (IOWS) with shielding electrode for the measurement of intensive power-frequency electric field. The segmented shielding electrode is designed and coated on one arm of the asymmetric Mach–Zehnder interferometer (AMZI) to improve the low-frequency response of the sensor and simultaneously to increase its half-wave electric field. Besides, to realise a non-invasive measurement the optical waveguide AMZI is used to make it possible that the sensor can have linear response by wavelength tuning.

2 SENSOR PRINCIPLES AND DESIGN

2.1 System configuration

The basic schematic diagram of the sensing system is shown in Figure 1. The laser source output linear polarised optical signal is connected with the IOWS by the polarisation maintaining fibre (PMF). The light beam travelling through the IOWS is modulated by the electric field under measurement based on the Pockels effect of LiNbO3 crystal. Through the single-mode fibre (SMF), the output optical signal of the sensor is transmitted to the photo receiver to convert into electrical signal. The main attractive characteristics of this measurement system are as follows:

1. As both sensor input and output signals are transmitted by optical fibres, the measurement system has extremely good electromagnetic immunity (EMI) and low loss for long-distance transmission.

2. Because the sensor is passive and has no metallic part except for the very small electrode, disturbance to the original electric field is negligibly small, which is necessary for a non-invasive measurement.

2.2 Operation principles analysis

The sensor structure is schematically shown in Figure 2. As shown in Figure 2(a), a linear polarised light beam in the z-direction is transmitted to the annealed proton exchange (APE) optical waveguide AMZI to generate the transverse electric

FIGURE 1 Configuration of the sensing system (PMF, polarisation maintaining fibre; IOWS, integrated optical waveguide sensor; OC, optical coupler).

FIGURE 2 Schematic of the integrated optical waveguide sensor (IOWS): (a) sensor structure; (b) electric field distribution in the cross section; (c) geometry of the electrode.
The electric field is applied to the sensor along \( \zeta \)-direction, the field distribution on one arm of the AMZI is changed by the shielding electrode, which results in an unbalanced modulation. The field distribution is shown in Figure 2(b). The shield electrode is designed to improve the low-frequency response of the sensor and simultaneously to increase its half-wave electric field. This is because, for the traditional two parallel electrode, the electrode widths are greater than the gap, but for the shield electrode, there is only one electrode over the channel waveguide, and as a result the electrode width is smaller than the gap, which yields in larger capacitance. As a result, the bandwidth \( \approx (\pi R C)^{-1} \) of the sensor is reduced, that is the low-frequency response is enhanced. Moreover, for the traditional two parallel electrode, the electrode widths are greater than the gap, which results in a very high field enhancement between the internal and external electric fields. But for the shield electrode, there is almost no field enhancement in the waveguide (see the simulation results), which results in a larger half-wave electric field.

Geometry of the designed segmented electrode is shown in Figure 2(c).

According to the Pockels effect of LiNbO\(_3\) crystal and the principle of the asymmetric linear interferometric waveguide modulator [10], the phase difference of the light beams travelling through the two arms of the AMZI can then be described as

\[
\Delta \varphi = \varphi_0 + \varphi(E) + \Delta \varphi_0
\]

\[
= \frac{2\pi}{\lambda} n_{eff} \Delta L + \frac{\pi}{\lambda} n_{eff}^3 \gamma_{33} (\Delta L + N L_{eln}) \Gamma k E + \Delta \varphi_0
\]

where \( \varphi_0 \) is the static optical phase difference with no electric field; \( \Delta \varphi_0 \) is the phase variation comes from changing of the environmental conditions including temperature, humidity and stress; \( n_{eff} \Delta L \) are the effective refractive index and the length difference of the two arms; \( \lambda \) is the optical wavelength; \( \Gamma \) \( (<1) \) is the overlap factor of electric and optical field; \( k \) is the enhancement coefficient between the external and internal electric field; \( L_{eln} \) is length of the \( n \)th electrode; and \( N \) is number of the segmented electrode.

Based on the previous work [18], it is possible to ensure the static phase difference of the sensor is approximately equal to \( \pi/2 \) by wavelength tuning. However, as is known, based on the physical effects of the LiNbO\(_3\) crystal including the thermooptic, pyro-electric, EO and strain-optic effects, the operating point drift of the sensor will be occurred with changes of the external environment factors such as temperature, humidity and mechanical stress (especially the temperature). As this comes from the material properties of the LiNbO\(_3\) itself, it cannot be eliminated fundamentally. Therefore, for the proposed sensor, a bias control technology based on wavelength tuning has been used to ensure the sensor has a linear operating point and when the measuring environment changes the operating point need to be readjusted.

Based on theory of the integrated EO Mach–Zehnder modulator [11], the output voltage \( V(\theta) \) of the sensing system is written as (2):

\[
V_{out} = \frac{1}{2} \alpha P_{in} \cos^2 \left( \frac{\Delta \varphi}{2} \right) = \frac{1}{2} \alpha P_{in} G
\]

\[
\times \left\{ 1 + b \cos \left[ \frac{\pi}{\lambda} n_{eff}^3 \gamma_{33} (\Delta L + N L_{eln}) \Gamma k E + \frac{\pi}{2} \right] \right\}
\]

where \( P_{in} \) is the input optical power, \( \alpha \) and \( b \) stand for the optical insertion loss and extinction coefficient of the IOWS and \( G \) is voltage gain of the PD.

In (2), when \( \frac{\pi}{\lambda} n_{eff}^3 \gamma_{33} (\Delta L + N L_{eln}) \Gamma k E = \pi \), the half-wave electric field \( E_\pi \) is described as

\[
E_\pi = \frac{\lambda}{n_{eff}^3 \gamma_{33} (\Delta L + N L_{eln}) \Gamma k}
\]

Define, and substituting (3) into (2) gives

\[
V_1 = A \left[ 1 - b \sin \left( \frac{\pi}{E_\pi} E \right) \right].
\]

If the electric field under measurement and the half-wave electric field satisfy with \( \frac{\pi}{E_\pi} E \ll 1 \), then using \( \sin(\frac{\pi}{E_\pi} E) \sim \frac{\pi}{E_\pi} E \), (4) can be rewritten as

\[
V_{out} \approx A \left( 1 - b \frac{\pi}{E_\pi} E \right).
\]

From (5), the output voltage of the sensing system is linear with the detected electric field, which is necessary for a non-invasive measurement. Besides, to detect the intensive electric field, a larger half-wave electric field is required to satisfy the condition of \( \frac{\pi}{E_\pi} E \ll 1 \).

This paper designs a segmented shielding electrodes to generate lower field enhancement coefficient to acquire a larger \( E_\pi \). Using the COMSOL MULTIPHYSICS, the field enhancement coefficient \( k \) is calculated as 1.3, the simulation results are shown in Figure 3. By substituting \( \lambda = 1550 \text{ nm} \), \( N = 10 \), \( L_{eln} = 0.5 \text{ mm} \), \( n_{eff} = 2.138 \), \( r_{33} = 30.8 \text{ pm/V} \) and \( \Gamma = 0.35 \) into (3), gives \( E_\pi = 452.1 \text{ kV/m} \), and as a result the maximum detectable electric field of the sensor is approximately equal to \( E_\pi/\pi \approx 143.9 \text{ kV/m} \).

3 SENSOR FABRICATION AND ELECTRIC FIELD MEASUREMENT

With parameters shown in Figure 2(c), two IOWSs with electrode elements \( N = 10 \) (sensor 1) and \( N = 4 \) (sensor 2) are fabricated and tested. The optical waveguide AMZI with length difference of 32 \( \mu \text{m} \) in the asymmetric arm (the height and length of the \( \delta \)-type bend waveguide are 15 mm and 632 \( \mu \text{m} \)) is fabricated using the APE technology on a x-cut y-propagation
LiNbO$_3$ wafer. The proton source is benzoic acid incorporated with a small amount of lithium benzoate. The APE process last 4.5 h with the temperature kept at 250–300°C. Then the waveguide is annealed in the furnace at 350–400°C for 5 h. Because the APE process results in the extraordinary index is noticeably increased while the ordinary index is unnoticeably decreased, the APE waveguide support only TE mode (z-polarisation). An SiO$_2$ buffer layer with the thickness of $\sim$4000 Å is deposited on the surface of the waveguide by radio-frequency magnetic sputtering (RFMS) to reduce optical transmission loss caused by optical absorption of the metallic electrode. Finally, the segmented electrodes is fabricated on the surface of the straight arm of the AMZI by sputtering metals of Cr and Au and then electroplating Au. The main fabrication process is shown in Figure 4.

The sensor input/output optical waveguides are coupled with PMF and SMF, respectively. Finally, the sensor is packaged using a polypropylene case to improve stability and mechanical strength. Figure 5 is the photograph of the packaged sensor with the size of 80 mm $\times$ 15 mm $\times$ 10 mm. However, the size of the LiNbO$_3$ chip is only 50 mm $\times$ 3 mm $\times$ 1 mm, which means the sensor package size can become smaller. The tested insertion losses of sensors 1 and 2 are 18.2 and 19.0 dB, respectively.

### 3.1 Experimental set-up

As shown in Figure 6, using a high-voltage testing transformer, the input 220 V/50 Hz voltage can be amplified to 50 kV. The high voltage is connected with the two parallel electrode plates (Cu, 250 mm $\times$ 150 mm $\times$ 3 mm) to generate intensive power-frequency electric field and applied to the IOWS. Theoretically, when connecting the maximum voltage (50 kV), the intensive electric field up to 3333 kV/m can be generated between the two parallel plates (when the minimum distance of the two parallel electrodes is equal to sensor width $\sim$15 mm). However, consider the insulation safety, the maximum electric field generated in our current laboratory is no more than 240 kV/m. By changing output voltages of the transformer and distances of the two parallel plates, different intensive power-frequency electric fields are generated.

In experiment, the optical host is integrated with a micro-integrable tunable laser assembly (ITLA) (OclaroTL5000), a PD ($G = 1.6 \times 10^4$) and a bias control circuit (C8051F410). The ITLA is used to generate the linear polarised light beam covering from 1528 to 1563 nm. Based on the optical internet-working forum (OIF)-ITLA standard, the wavelength is tuned by the bias control circuit to ensure that the sensor is working in the linear region. The output linear polarised light beam from the ITLA is transmitted into the sensor using the PMF and the sensor output optical signal is connected with the PD using the SMF. The output electrical signal from the optical host is extracted and analysed using an oscilloscope. However, in experiment, length of the PMF and SMF is decided by electrical isolation and personal safety.

### 3.2 Time-domain response

Using the experimental set-up shown in Figure 6, the response characteristics of the sensor in the time domain are tested. An oscilloscope with the bandwidth of 100 MHz and sampling rate of 1 GHz is used to read out the electric field waveforms detected by the sensor. The sensor response is shown in Figure 7, when the power-frequency electric fields of 3, 50, 75 and 100 kV/m are applied to sensors 1 and 2.

From Figure 7, the sensor-detected waveforms are agreed well with the input power-frequency voltage waveform. Besides, periods of the detected electric fields are read out and analysed. The results are shown in Table 1. The average periods

---

**Figure 3** Simulation results of the sensor: (a) simulation model; (b) electric potential distribution.
of the detected electric field waveforms for sensors 1 and 2 are 20.02 and 20.03 ms, respectively, corresponding to the relative errors are 0.1% and 0.15%. Therefore, the sensor can be used for non-invasive measurement of power-frequency electric field.

3.3 Linear characteristic

In addition, the input/output characteristics of the two sensors are investigated. The results are shown in Figure 8(a) and (b), respectively. It can be seen from Figure 8(a) that the correlation coefficient between the experiment and fitting is 0.9978 when the applied electric fields varied from 1 to 140 kV/m. Accordingly, consider the noise floor of the measurement system is 10 mV, the minimum detectable electric field is 600 V/m on condition of the signal-to-noise ratio (SNR) is 3 dB. Besides, on condition of the 1 dB linear compression, the maximum detectable electric field is about 139.8 kV/m, which is in accordance with the simulation result. As a result, the linear dynamic range is 47.8 dB in the time domain.

From Figure 8(b), when the applied power-frequency electric fields varied from 10 to 240 kV/m, the linear correlation coefficient is 0.9983. Therefore, on condition of the SNR is 3 dB and the noise floor is 10 mV, the minimum detectable electric
field is 5.7 kV/m. However, as the larger electric field cannot be generated in our current laboratory, the maximum detected electric field of sensor 2 is 240 kV/m.

3.4 Frequency response

Because the sensor is designed with low sensitivity for measuring the intensive electric field, the frequency response cannot be tested using the traditional continuous wave electric field in the frequency domain. This paper evaluates the frequency response by applying the 1.2/50 μs lightning EMP (LEMP) \( X(t) \) and extracting the time-domain response \( Y(t) \) using a digital oscilloscope with bandwidth of 100 MHz and sampling rate of 1 GHz. Then the frequency spectrums \( X(\omega) \) and \( Y(\omega) \) are calculated utilizing the fast Fourier transform (FFT) algorithm. Consequently, the frequency response \( H(\omega) \) of the sensor system is obtained based on \( H(\omega) = Y(\omega)/X(\omega) \).

Figure 9 is the sensor response in the time domain when applying the LEMP. It can be seen that the detected waveforms agree well with the input voltage signal. From the inset of Figure 9, rise time of the sensor-detected LEMP is approximately equal to 1 μs while that of the input voltage signal is about 0.9 μs. Using the FFT algorithm, frequency spectrums of the detected LEMP and the input voltage signal are calculated.
FIGURE 9 Time-domain response of the sensor for the applied lightning intense electromagnetic pulse (LEMP)

FIGURE 10 Fast Fourier transform (FFT) results of the detected lightning intense electromagnetic pulse (LEMP) field and the input voltage signal, and the inset is the system response using $H(\omega) = Y(\omega)/X(\omega)$ and shown in Figure 10. Furthermore, the frequency response of the sensor system is obtained and shown in the inset of Figure 10. It can be seen that the input spectrum $X(\omega)$ is in accordance with the output spectrum $Y(\omega)$, and variation of the frequency response $H(\omega)$ is less than $\pm 2$ dB from DC to 200 kHz.

Consider the EO effect itself occurs on a femtosecond scale, leading to an intrinsic bandwidth exceeding 10 THz, and bandwidth of the PD such as the FINISAR-XPDV412xR can reach 100 GHz, the cut-off frequency of the sensor system is mainly decided by the sensor electrode. As a result, if a pulsed electric field with extremely short rise time is applied to the sensor, and a very high-speed PD is used, the cut-off frequency of the sensor can be obtained using $H(\omega) = Y(\omega)/X(\omega)$. Accordingly, 200 kHz is not the practical cut-off frequency of the sensor because rise time of the applied LEMP is not short enough and bandwidth of the PD is not wide enough as well. However, such frequency response can meet requirements of measuring the low-frequency electric field such as the power-frequency electric field.

Moreover, because the EO effect itself occurs on a femtosecond scale, the response time (the time delay for the induced voltage on the sensor head to be picked up by the measurement system) of the sensor system is mainly determined by the signal transmission time in the optical fibre and the response time of the PD. Consequently, consider length of the used SMF is 20 m and the conversion time of the PD is 0.35 ns, the response time of the sensor system is approximately equal to $20 \times 1.5/(3 \times 10^8) + 0.35 \text{ ns} = 1.35 \text{ ns}$.

4 CONCLUSION

Two LiNbO$_3$ segmented shielding electrode IOWS with different elements are designed, fabricated and experimentally investigated. Experiment results demonstrate that in the time domain, for sensor 1 ($N = 10$) the minimum and maximum detectable electric fields are 600 V/m and 139.8 kV/m, respectively, while for sensor 2 these are 5.7 kV/m and more than 240 kV/m. The average periods of the detected electric field waveforms for sensors 1 and 2 are 20.02 and 20.03 ms, respectively, corresponding to the relative errors are 0.25% and 0.25%. In addition, the frequency response of the sensor is calculated from DC to 200 kHz with variations of less than $\pm 2$ dB. All these results demonstrate that such IOWS has potential capability to be used for the non-invasive measurement of intensive power-frequency electric field. However, in the following work, it is necessary to design, fabricate and test segmented shielding electrode sensors with different elements and geometric dimensions to further study the relationship between the electrode and measurement sensitivity.

ACKNOWLEDGEMENTS

This work was supported in part by the National Natural Science Foundation of China (NSFC) (61765009, 61962031) and the Applied Basic Research Project of Yunnan Province, China (2018FB106).

AUTHOR CONTRIBUTIONS

Jiahong Zhang: conceptualisation and methodology; Li Yang: software and original draft; Yingna Li: validation and review and editing.

CONFLICT OF INTEREST

The authors declared that there is no conflict of interest.

ORCID

Jiahong Zhang https://orcid.org/0000-0003-1496-5770

REFERENCES

1. Ztoupis, I.N., et al: Measurement and calculation of power frequency electric fields generated by high voltage overhead power lines. Proceedings of the 2014 International Conference on High Voltage Engineering and Application (ICHVE), Poznan, Poland, pp. 8–11 (2014)
2. Korpinen, L., Paakkonen, R.: Occupational exposure to electric and magnetic fields during tasks at ground or floor level at 110 kV substations in Finland. Int. J. Occup. Saf. Ergon. 22(3), 384–388 (2016)
3. Listed, N.A.: Possible health hazards from exposure to power-frequency electric and magnetic fields—a COMAR technical information statement. IEEE Eng. Med. Biol. 19(1), 131–137 (2000)
4. Zamurovic, S.A., Lee, R.D.: A high-stability capacitance sensor system and its evaluation. IEEE Trans. Instrum. Meas. 58(4), 955–961 (2009)
5. Lin, Y.Y., et al.: Study on measurement errors of the ball type sensor in the power frequency electric field. Adv. Mater. Res. 1022, 415–418 (2014)
6. Bertain, A., et al.: Capacitive sensor interface for passive wireless sensor systems. Sensors 15(9), 21554–21566 (2015)
7. Passard, M., et al.: Design and optimization of a low-frequency electric field sensor using Pockels effect. IEEE Trans. Instrum. Meas. 50(5), 1053–1058 (2001)
8. Jarrige, P., et al.: Electrooptic probe adapted for bioelectromagnetic experimental investigations. IEEE Trans. Instrum. Meas. 61(7), 2051–2058 (2012)
9. Gaborit, G., et al.: A nonperturbative electrooptic sensor for in situ electric discharge characterization. IEEE Trans. Plasma Sci. 41(10), 2851–2857 (2013)
10. Bulmer, C.H., et al.: Linear interferometric waveguide modulator for electromagnetic-field detection. Opt. Lett. 5(5), 176–178 (1980)
11. Kawahara, N., et al.: Development and analysis of electric field sensor using LiNbO3 optical modulator. IEEE Trans. Electromagn. Compat. 34(4), 391–396 (2002)
12. Meier, T., et al.: Integrated optical E-field probes with segmented modulator electrodes. J. Lightwave Technol. 12(8), 1497–1503 (1994)
13. Schwerdt, M., et al.: Integrated optical e-field sensors with a balanced detection scheme. IEEE Trans. Electromagn. Compat. 39(4), 386–390 (1997)
14. Sun, B., et al.: Integrated optical electric field sensor from 10 kHz to 18 GHz. IEEE Photon. Technol. Lett. 24(13), 1106–1108 (2012)
15. Hong, J.: An integrated photonic electric-field sensor utilizing a 1X2 YBB Mach–Zehnder interferometric modulator with a titanium-diffused lithium niobate waveguide and a dipole patch antenna. Crystals 9(459), 1–11 (2019).
16. Gutiérrez-Martínez, C., et al.: Novel Electric Field Sensing scheme using integrated optics LiNbO3 unbalanced Mach–Zehnder interferometers and optical delay-modulation. J. Lightwave Technol. 35(1), 27–33 (2017)
17. Zhang, J., et al.: Integrated optical E-field sensor for intense nanosecond electromagnetic pulse measurement. IEEE Photon. Technol. Lett. 26(3), 275–277 (2014)
18. Zhang, J., et al.: Nanosecond transient electric field measurement system using an integrated electro-optic sensor. Opt. Eng. 53(11), 1171011–1171016 (2014)
19. Zhang, J., et al.: Study of an integrated optical waveguide sensor with a tapered antenna for measurement of intense pulsed electric field. Optik 218, 1648371–1648377 (2020)
20. Li, Z., et al.: Measurement of distorted power-frequency electric field with integrated optical sensor. IEEE Trans. Instrum. Meas. 68(4), 1132–1139 (2019)
21. Wang, H., et al.: Measuring AC/DC hybrid electric field using an integrated optical electric field sensor. Electr. Power Syst. Res. 179, 106871–1068713 (2020)

How to cite this article: Zhang J, Yang L, Li Y. Non-invasive measurement of intensive power-frequency electric field using a LiNbO3-integrated optical waveguide sensor. IET Sci Meas Technol. 2021;15:101–108. https://doi.org/10.1049/smt2.12014