Three-Dimensional Broadband Electric Field Sensor Based on Integrated Lithium Niobate on Insulator

Zhao Liu, Le Qiu, Lan Zhao, Lijun Luo, Wenhao Du, Lingjie Zhang, Bao Sun, Zhiyao Zhang, Shangjian Zhang and Yong Liu

The State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

* Correspondence: sunbao@uestc.edu.cn

Abstract: A three-dimensional (3D) electric field sensing scheme is proposed and experimentally demonstrated based on an integrated lithium niobate on insulator (LNOI) platform. The 3D measurement is realized by packing three LNOI-based sensor chips in a triangular-prism-type clamp. For each sensor chip, the optical waveguide has an asymmetrical Michelson interferometer architecture, and the tapered dipole antenna is inclined to the optical waveguide. By finely placing the three sensor chips in the clamp, the three pairs of inclined tapered dipole antennas are mutually orthogonal and can be applied to measure the electric field in three orthogonal polarization directions. The volume of the packaged 3D sensor is 9.5 cm$^3$. In the experiment, a flat response in the frequency range of 10 MHz to 3 GHz is demonstrated. In addition, a 3 × 3 response calibration matrix is obtained and utilized to reduce the measurement error. After calibration, the relative measurement error of the electric field amplitude is smaller than 5.1% for every polarization direction.

Keywords: electric field sensor; lithium niobate on insulator; Michelson interferometer

1. Introduction

Electric field sensors (EFSs) are extensively used in atmospheric science, electromagnetic (EM) environment assessment of spacecraft and rocket launch, measurement of EM compatibility, and long-term monitoring of high-voltage transmission lines [1–3]. Due to the increasingly complicated EM environment, EM measurement with a large operation bandwidth, high-density large-scale distribution, and three-dimensional (3D) measurement capacity is urgently needed. Particularly, 3D measurement can provide EM information in three orthogonal polarization directions, which is beneficial for realizing comprehensive control of the space EM field. In order to realize distributed 3D measurement, EFSs are expected to have a large operation bandwidth and a small size, which is conducive to achieving high-accuracy measurement of broadband EM waves in free space.

There are various EFSs to realize 3D measurement. Thereinto, EFSs based on micro-electro-mechanical systems (MEMS) are well developed in recent years due to their small size (<1 cm × 1 cm) and high sensitivity [4–8]. However, the highest measurable frequency of the MEMS-based EFSs is limited to the level of kHz, which is attributed to the sensing implementation based on slow mechanical shape variation. Different from employing three EFSs with orthogonal polarization directions, EFSs with D-dot antennas naturally have the ability of 3D sensing due to the 3D shape construction [9–12]. The highest measurable frequency can be up to 10 GHz. However, the size of the metal antenna is generally tens of centimeters, which leads to serious distortion of the electric field under test. Moreover, D-dot sensors cannot measure the amplitudes of the electric field in different polarization directions separately. EFSs based on lithium niobate (LN) have been extensively investigated in recent years [13–20], whose theoretical operation bandwidth can reach beyond 500 GHz due to the strong linear electro-optic effect (Pockels effect) in the LN [21]. In addition, the
integrated optical waveguide fabricated on lithium niobate on insulator (LNOI) reduces the sensor size significantly. Therefore, the EFSs based on integrated LNOI waveguides have the characteristics of small size, large operation bandwidth, and undistorted measurement.

In this paper, a 3D EFS scheme is proposed and experimentally demonstrated based on an integrated LNOI platform. The optical waveguide in the EFS has an asymmetrical Michelson interferometer (MI) architecture. Due to the round-trip optical transmission in the MI, the waveguide length in the proposed EFS is reduced to half of that based on the Mach–Zehnder interferometer (MZI). In addition, the asymmetrical MI structure helps the EFS work without any electrical power supply. In the experiment, three EFSs with specially designed antennas and modulation electrodes are fixed in a triangular-prism-type clamp to realize 3D measurement. All three sensor chips have flat responses in the frequency range of 10 MHz to 3 GHz. A $3 \times 3$ response calibration matrix is obtained and utilized to reduce the measurement error. Based on the calibration matrix, the relative error between the measurement results and the theoretical values is smaller than 5.1%.

2. Design and Simulation

Figure 1 expresses the diagrammatic drawing of the EFS for a single polarization direction. The sensor chip is fabricated on an x-cut LNOI, where the optical waveguide has an asymmetrical MI architecture ($\Delta L = 16 \mu m$), and the light propagates along the y direction. An optical circulator is used to inject the continuous-wave (CW) light into the sensor chip and extract the modulated light. The operation principle of the EFS is described as follows. The CW light injected into the sensor chip is divided into two branches. In the lower branch, a pair of printed inclined tapered dipole antennas are placed on both sides of the straight waveguide, whose bottom width and height are 0.5 mm and 2 mm, respectively. The EM wave is received by the antennas and is then loaded onto the CW light to achieve phase modulation via a pair of modulation electrodes with a length of 5 mm, as shown in Figure 1. The phase-modulated light is reflected by a high-reflective film at the end of the chip and experiences second-round modulation in reverse propagation. In the upper branch, the light is directly reflected by the high-reflective film at the end of the chip. Hence, the output light from the chip is intensity-modulated light, where the intensity envelope carries the information of the EM wave and can be demodulated through photoelectric detection. Benefiting from the asymmetrical MI architecture, the direct-current bias control of the sensor chip can be achieved by tuning the wavelength of the CW light from the tunable laser source, which is favorable for realizing remote sensing without an electrical power supply. By setting the sensor chip to be at its quadrature transmission point, the electric field of the EM wave can be obtained without distortion. In addition, the modulation electrodes are placed as close as possible to the high-reflective film to reduce the traveling difference and the phase mismatch between the electric wave and optical wave, which is beneficial for realizing a large operational bandwidth.

![Figure 1. Diagrammatic drawing of the EFS based on LNOI for a single polarization direction.](image-url)
In order to achieve 3D sensing, three sensor chips are placed on the three faces of a triangular-prism-type clamp, as shown in Figure 2a. Conventionally, in order to ensure the polarization orthogonality of the antennas, the three sensor chips should be distributed along the principal axes of the rectangular coordinate system, which leads to a relatively large size. The proposed triangular prism package has a volume decrease of 30% for the identical sensor chips. To guarantee that the three pairs of antennas are mutually orthogonal, the tapered dipole antennas are designed to have an incline angle of 54.7° from the horizontal plane, as shown in Figure 2b. The polarization directions of the tapered dipole antennas are strongly relative to the direction of the antennas. Figure 2b shows the orthometric direction of the antennas, where the dashed lines represent the directions of the antennas on the other two sensor chips placed on the other two faces. The details of this geometrical proof can be found in [22].

![Figure 2. (a) Lateral view and (b) perspective view of the packaged 3D sensor.](image)

The polarization simulation model of the inclined tapered dipole antennas is shown in Figure 3a, where \( \phi \) is the degree versus to z-axis and is set to be 90°. \( \theta_1 \) and \( \theta_2 \) are the degrees of the two tapered antennas versus to x-axis. The simulation result using the High-Frequency Structure Simulator (HFSS) software is shown in Figure 3b. The axial ratio at the line of the antennas is over 37.5 dB, which indicates that the inclined tapered dipole antennas have an absolute linear polarization.

![Figure 3. (a) Simulation model in the HFSS software; (b) axial ratio of each pair of antennas on a single sensor chip.](image)

Although the tapered dipole antennas are mutually orthogonal, they have an inevitable interaction due to the close distance. The effect of the electric field reflection between the sensor chips in the proposed clamp is qualitatively revealed by carrying out a simulation via HFSS. Figure 4a, b show the simulation mode of the two sensor chips with a construction of 60 degrees. The excitation source is a plane wave with an amplitude of 1 V/m at 1 GHz. The wave vector \( k \) of the plane-wave radiation is along the x-axis, and \( E_0 \) is the...
polarization direction along the z-axis. Ideally, the induced voltage between the modulation electrodes of chip 1 should only be affected by the original excitation source. However, the antennas of chip 2 will partly reflect the incident electric field to chip 1. Therefore, the induced voltage between the modulation electrodes of each chip is not only from the original source but also the reflected electric field from the antennas of other chips. Between the modulation electrodes, the simulated induced electric field on chip 1 is shown in Figure 4c. For comparison, the simulation results without chip 2 are depicted in Figure 4d. The amplitudes of the induced electric field on chip 1 under the two-chip mode and the one-chip mode are 0.4–0.9 V/m and 0.01–0.5 V/m, respectively. The reflection obviously affects the induced electric field of the two-chip mode compared with the one-chip mode. In practical terms, the unknown incident direction, amplitude, and polarization of the electric field are far more complicated than the simulation. The quantitative simulation is hard to produce.

Figure 4. (a) Perspective view and (b) lateral view of the simulation mode of the two-chip mode; (c) simulation results of the induced electric field of the two-chip mode and (d) the one-chip mode.

A 3 × 3 matrix is used to calibrate the measured electric field amplitude from each sensor chip. Ideally, each sensor chip is mutually orthometric without interaction. Thus, all the elements of the matrix are zero except for the diagonal elements. Mathematically, the response of the 3D sensor under an electric field is expressed as

$$
\begin{pmatrix}
  a_{11} & 0 & 0 \\
  0 & a_{22} & 0 \\
  0 & 0 & a_{33}
\end{pmatrix}
\begin{pmatrix}
  b_1 \\
  b_2 \\
  b_3
\end{pmatrix}
=
\begin{pmatrix}
  c_1 \\
  c_2 \\
  c_3
\end{pmatrix}
$$

(1)
where the vector \( B \) is the original electric field. The vector \( C \) is the output voltage of the 3D sensor. The matrix \( A \) is the response matrix of the 3D sensor. In practice, the nondiagonal elements are nonzero due to the interaction among sensor chips. Therefore, the 3D sensor can be calibrated by solving all the unknown elements of the matrix \( A \), where \( A \) is indicated as

\[
A = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}
\]  

(2)

As expressed in Equation (1), the measurement result of one sensor chip is the product of the corresponding row of \( A \) and the vector \( B \). Hence, to solve the unknown elements of \( A \) in Equation (2), three linearly independent vectors \( B \) should be realized in the experiment to build a linearly independent equation set.

3. Experimental Results

Figure 5a presents the photograph of the fabricated 3D sensor and the measurement system. The packaged sensor has a volume of 9.5 cm³ and is placed into a transverse electromagnetic (TEM) cell. In the TEM cell, a standard and known electric field is produced to achieve measurement and calibration. Three tunable laser sources (Santec TSL-510, Aichi, Japan) are used to guarantee that each sensor chip is biased at its quadrature transmission point. Each modulated light from the sensor chip is detected by using photodetectors (PD, Finisar, XPDV2120R, Sunnyvale, CA, USA). Each electrical signal from the PD is then amplified by using a low-noise amplifier (LNA, Qotana, DBLNA300011800A, Chengdu, China), and is measured by using an electrical spectrum analyzer (ESA, R&S FSU50, Darmstadt, Germany). For the next measurements, the tunable laser wavelength is fixed to 1546 nm to guarantee that the sensor chip is biased at its quadrature transmission point.

Figure 5. (a) Photograph of the packaged 3D sensor and the electric field measurement system; (b) measurement and simulation transmission optical spectrums of the sensor chip. ESA: electrical spectrum analyzer; PD: photodetector; HPA: high-power amplifier; MS: microwave source; LNA: low-noise amplifier; MPM: microwave power meter.
Firstly, a standard electric field is generated in the TEM cell, which is used to obtain the $3 \times 3$ response calibration matrix. Linearly independent amplitudes in three polarization directions measured by using a single sensor chip in the 3D sensor are expressed as

\[
\begin{align*}
A_1 &= \begin{pmatrix} B_1 \end{pmatrix} = \begin{pmatrix} 20.22 \text{ V/m} \\ 28.27 \text{ V/m} \\ 20 \text{ V/m} \end{pmatrix} = c_1, \\
(a_{11}, a_{12}, a_{13}) &= \begin{pmatrix} a_{11} \\ a_{12} \\ a_{13} \end{pmatrix} \\
A_2 &= \begin{pmatrix} B_2 \end{pmatrix} = \begin{pmatrix} 0 \text{ V/m} \\ 0 \text{ V/m} \\ 40 \text{ V/m} \end{pmatrix} = c_2, \\
(a_{11}, a_{12}, a_{13}) &= \begin{pmatrix} a_{11} \\ a_{12} \\ a_{13} \end{pmatrix} \\
A_3 &= \begin{pmatrix} B_3 \end{pmatrix} = \begin{pmatrix} 23.15 \text{ V/m} \\ 32.65 \text{ V/m} \\ 0 \text{ V/m} \end{pmatrix} = c_3 (3)
\end{align*}
\]

where the three vectors $B_1$, $B_2$, and $B_3$ are the preset amplitudes of the electric field in the TEM cell. $A_1$ is the first row of the matrix $A$, i.e., the response of a single sensor chip. Thus, the measured experimental results are expressed as

\[
\begin{pmatrix} (a_{11}, a_{12}, a_{13}) \end{pmatrix} = \begin{pmatrix} b_{11} \\ b_{21} \\ b_{31} \end{pmatrix} \begin{pmatrix} b_{12} \\ b_{22} \\ b_{32} \end{pmatrix} \begin{pmatrix} b_{13} \\ b_{23} \\ b_{33} \end{pmatrix} = \begin{pmatrix} 0.1588 \text{ mV} \\ 0.0073 \text{ mV} \\ 0.2056 \text{ mV} \end{pmatrix} (4)
\]

where the matrix $B$ is composed of the vectors $B_1$, $B_2$, and $B_3$. The vector $C$ is the measured amplitude of the electric field corresponding to $B$. The solution to Equation (4) is given by

\[
(a_{11}, a_{12}, a_{13}) = (-439.9197, 311.4868, 0) (5)
\]

In the same way, the measured results of the other two sensor chips in the electric field are given by

\[
\begin{align*}
C_2 \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} &= \begin{pmatrix} 0.3855 \text{ mV} \\ 0.0335 \text{ mV} \\ 0.4693 \text{ mV} \end{pmatrix} \\
C_3 \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} &= \begin{pmatrix} 0.3381 \text{ mV} \\ 0.0521 \text{ mV} \\ 0.4385 \text{ mV} \end{pmatrix} (6)
\end{align*}
\]

Therefore, all the elements of matrix $A$ can be solved and given by

\[
\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} = \begin{pmatrix} -439.9197 & 311.4868 & 0 \\ 0 & -726.9027 & 514.6901 \\ 924.7007 & 0 & -1305.9828 \end{pmatrix} (7)
\]

The matrix $A$ of the fabricated 3D sensor is not a diagonal matrix with nonzero elements $a_{12}$, $a_{23}$, and $a_{13}$. Placing sensor chips away from each other is an effective way to decrease the interaction due to its exponential amplitude attention versus distance. After calibration, another electric field with a different amplitude is generated in the TEM cell and is measured by using the 3D sensor. The amplitude vector $B_{\text{theo}}$ of the standard electric field is given by

\[
B_{\text{theo}} = \begin{pmatrix} 7.35 \text{ V/m} \\ 10.37 \text{ V/m} \\ 7.34 \text{ V/m} \end{pmatrix} (8)
\]
The measured amplitude vector $C_m$ is given by

$$C_m = \begin{bmatrix} 0.061 \text{mV} \\ 0.147 \text{mV} \\ 0.119 \text{mV} \end{bmatrix}$$  (9)

The measured vector $B_{mear}$ is solved by the vector $C_m$ and the matrix $A$ is given by

$$B_{mear} = \begin{bmatrix} 7.72 \text{V/m} \\ 10.82 \text{V/m} \\ 7.07 \text{V/m} \end{bmatrix}$$  (10)

Therefore, compared with the vector $B_{theo}$, the absolute error is calculated as

$$Er_{ab} = \begin{bmatrix} 0.37 \\ 0.45 \\ -0.27 \end{bmatrix}$$  (11)

The relative error is calculated as

$$Er_{re} = \begin{bmatrix} 5.1\% \\ 4.3\% \\ -3.7\% \end{bmatrix}$$  (12)

These relative errors indicate that the measurement by the proposed EFS has a high accuracy for electric field recovery.

Finally, the response of the three sensor chips in the 3D sensor is measured with the bandwidth of 10 MHz to 3 GHz. The measurement system is displayed in Figure 5a with the electric field polarization direction identical to the vector $B_1$ in Equation (3). The measurement results are shown in Figure 6. It can be seen that every sensor chip in the 3D sensor has a relatively flat frequency response up to 3 GHz. Therefore, the response matrix $A$ can be regarded as a constant in this frequency range. The tiny difference in the frequency response among the sensor chips is mainly attributed to the fabrication disorder including the coupled optical insertion loss and the deposited shape of the metal antennas, which can be further calibrated via detailed measurement.

Figure 6. Frequency response and optical insertion loss of the three sensor chips in the 3D sensor.
4. Conclusions

In conclusion, a broadband LNOI-based 3D EFS has been fabricated and demonstrated. Three-dimensional electric field sensing is realized by packing three LNOI-based sensor chips with an optical waveguide-based asymmetrical Michelson interferometer architecture in a triangular-prism-type clamp. The tapered dipole antennas on each sensor chip have an incline angle of 54.7° from the horizontal plane, which guarantees that the three pairs of antennas are mutually orthogonal. The packaged 3D sensor has a small volume of 9.5 cm³, which is beneficial for achieving high-accuracy measurements of EM waves in free space. In the experiment, a flat response in the frequency range of 10 MHz to 3 GHz is demonstrated. In addition, a $3 \times 3$ response calibration matrix is obtained and utilized to reduce the measurement error. After calibration, the relative measurement error of the electric field amplitude is smaller than 5.1% for every polarization direction. The proposed 3D EFS scheme is a promising candidate to realize distributed broadband EM measurement.

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