Electric field sensors based on optical retarders in lithium niobate (LiNbO₃) integrated optics technology

Esquemas de sensores de campo eléctrico basados en retardadores ópticos en tecnología de óptica integrada en niobato de litio (LiNbO₃)

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ABSTRACT:

The aim of this paper is to describe the use of Lithium Niobate (LiNbO₃) electrooptic retarders as electric field sensors. There are two types of optical retarders that can be implemented on LiNbO₃ crystals: birefringent optical waveguides (BOW) and asymmetric Mach-Zehnder interferometers (AMZI). These devices can be used for configuring electric field sensing schemes, taking advantage of their potential of generating practical optical delays. An optical delay becomes practical when its equivalent optical path-difference is longer than the coherence-length of the optical source and ranges between some hundreds of micrometers and some millimeters. This goal can be achieved when using incoherent optical sources as light emitting diodes (LEDs) or super-luminiscent diodes (SLDs) whose coherence-length is around 100 micrometers. In an optical retarder-based electric field sensing scheme, an optical delay can be modulated by the sensed electric field and transmitted to an optical receiver. The demodulation of the optical delay is achieved when a second optical delay is introduced on the received light. The detection of the sensed electric field is ensured only when the sensing and demodulating delays are optically matched. The technique of modulating and demodulating optical delays for the transmission of information signal is more generally known as coherence modulation. The operating principle of the modulation-demodulation of optical delays as well as the use of BOW and AMZI as optical retarders and their use for configuring electric field sensing schemes are describe in this paper.

Key words: LiNbO₃; electrooptic sensors; optical retarders; optical waveguides; electric field sensing.

RESUMEN:

El propósito de este artículo es describir la utilización de retardadores electroópticos en niobato de litio (LiNbO₃), como sensores de campo eléctrico. Hay dos tipos básicos de retardadores ópticos que pueden realizarse en cristales de LiNbO₃: guías de onda ópticas birrefringentes (GOB) e interferómetros Mach-Zehnder asimétricos (IMZA). Estos dispositivos se utilizan para configurar esquemas sensores de campo eléctrico, aprovechando su capacidad de generar retardos ópticos prácticos. Un retardo óptico se vuelve práctico cuando la diferencia de camino óptico equivalente, es superior a la longitud de coherencia de la fuente luminosa. Los valores prácticos varían en un intervalo entre algunos cientos de micrómetros y algunos milímetros. Estos valores pueden alcanzarse cuando se utilizan diodos emisores de luz (DEL) o diodos superluminiscentes (DSL) como fuentes de luz, cuya longitud de coherencia es inferior a 100 micrómetros. En un esquema sensor de campo eléctrico basado en retardador óptico, el retardo es modulado por el campo eléctrico y transmitido hacia un receptor. La demodulación del retardo luminoso se realiza cuando la luz recibida pasa por un segundo retardador que introduce un retardo idéntico al del sensor y es la única condición que asegura la detección del campo eléctrico sensado. Esta técnica de modulación-
In the perspective of using optical retarders as electric field sensors, the optical delay, or its equivalent optical path difference, can be used as information carrier if it is longer than the coherence time of the optical source. In the perspective of using optical retarders as electric field sensors, the optical delay can be modulated by a sensed electric field and transmitted through an optical channel; at the receiver, the electric field can be recovered by introducing a second optical delay which is optically matched to the sensor's delay [1]. Electrooptic waveguides used simultaneously as optical retarders and electric filed sensors are of two types: birefringent slabs and Mach-Zehnder interferometers. A birefringent slab (straight optical waveguide) is normally used in a polarization interferometer configuration and generates an optical delay when 45° polarized light enters the optical waveguide and is projected in two transverse modes TE and TM. Such modes travel through the optical waveguide at different velocities and become delayed. The optical delay, or its equivalent optical path difference, is determined by the waveguide birefringency and its physical length. Another type of optical retarder is an integrated optics asymmetric Mach-Zehnder interferometer. In this case the optical delay or the equivalent optical path difference is not generated by the birefringence but by the differential lengths of the optical arms. Several years ago, AMZI have been proposed as temperature and electric field sensors, not as optical retarders [2, 3]. In our case, we are using AMZI acting as optical retarders and electric field sensors simultaneously.

REFERENCES AND LINKS / REFERENCIAS Y ENLACES


1. Introduction

Integrated optics waveguides on electrooptic crystals can be used as electric field sensors. An electrooptic waveguide can sense an external electric field and imprints it on the light traveling through it. The sensed electric field can modulate the optical intensity or, in an alternative approach, an optical delay. Optical retarders can be easily implemented by using Lithium Niobate (LiNbO3) electrooptic waveguides, as either birefringent waveguides or asymmetric Mach-Zehnder interferometers. An optical retarder introduces an optical delay, which can be used as information carrier if it is longer than the coherence time of the optical source. In the perspective of using optical retarders as electric field sensors, the optical delay can be modulated by a sensed electric field and transmitted through an optical channel; at the receiver, the electric field can be recovered by introducing a second optical delay which is optically matched to the sensor's delay [1]. Electrooptic waveguides used simultaneously as optical retarders and electric filed sensors are of two types: birefringent slabs and Mach-Zehnder interferometers. A birefringent slab (straight optical waveguide) is normally used in a polarization interferometer configuration and generates an optical delay when 45° polarized light enters the optical waveguide and is projected in two transverse modes TE and TM. Such modes travel through the optical waveguide at different velocities and become delayed. The optical delay, or its equivalent optical path difference, is determined by the waveguide birefringency and its physical length. Another type of optical retarder is an integrated optics asymmetric Mach-Zehnder interferometer. In this case the optical delay or the equivalent optical path difference is not generated by the birefringence but by the differential lengths of the optical arms. Several years ago, AMZI have been proposed as temperature and electric field sensors, not as optical retarders [2, 3]. In our case, we are using AMZI acting as optical retarders and electric filed sensors simultaneously.
As described in section 2 of this paper, an electric field sensing scheme based on optical delays is configured by a low-coherence optical source and two matched optical retarders, a first one acting simultaneously as retarder and sensor; the second one acting as optical demodulator. On the sensing scheme, an external electric field is imprinted on the first optical path-difference and is transmitted to an optical receiver. At the receiver, the optical demodulator is a second optical retarder that is optically matched to the electro-optic sensor. This is the only condition for recuperating the sensed electric field. The optical demodulator can be easily implemented by a passive optical retarder using polarization-maintaining optical fiber (PMF) or a second electro-optic retarder [1]. In a practical scheme, the sensor retarder introduces an optical path-difference, which should be longer than the optical coherence length. Practical optical sources are light-emitting diodes (LEDs) or super-luminiscent diodes (SLDs), with coherence lengths up to 100 micrometers. The optical path-differences that can be generated by electrooptic retarder go up to 10mm.

In the aim of this paper, in section 2, the operating principle of the generation-detection of optical delay is described. Such a principle gives the basis for the implementation of electric field sensing using optical delay as information carriers. In section 3 of this document, the use of birefringent optical waveguides (BOW) as optical retarders and electric field sensors are described. In section 4, the use of asymmetric Mach-Zehnder interferometers (AMZI) for the same purposes are presented. Finally the conclusions are given.

2. Optical delay modulation-demodulation operating principle.

To recall the operating principle, the block diagram of an integrated optics electric field sensor scheme, based on optical delay modulation is shown in Fig. 1. The system includes a low-coherence optical source, an electro-optic sensor (optical retarder), an optical fiber channel and a receiver module, which is implemented by a second optical retarder (either integrated optics or a passive fiber optics interferometer) as delay demodulator, and a photo-detector.

According to the block diagram, light coming from a low-coherence optical source is injected into the electro-optic sensor, which introduces an optical delay $\tau_0$, greater than the source coherence time $\tau_c$. In this model, when low-coherence light $s(t)$ is delayed, the light at the output of the optical retarder is given as [4]

$$s_o(t) = \frac{1}{2}s(t) + \frac{1}{2}s(t-\tau_0)$$  \hspace{1cm} (1)

It can be shown that the optical intensity at the output of the optical retarder is given as

$$I_o = s_o^*(t)s_o(t-\tau_0) = \frac{1}{2}I_0 + \frac{1}{2}\text{Re}\{G(\tau_0)\}$$

$I_0$ is the optical power at the input of the sensing retarder; $G(\tau_0)$ is the autocorrelation function. The transmitted optical intensity, normalized to the real part of $g(\tau_0) = \frac{G(\tau_0)}{G(0)}$ is

$$I_o = \frac{I_0}{2}\left\{1+|g(\tau_0)|\cos(2\pi\frac{1}{\lambda_0}\nu\tau_0)\right\};$$  \hspace{1cm} (2)

$\lambda_0$ is the center optical wavelength and $\nu$ is the light propagation velocity.

From expression (2), one finds that optical interference will exist on depending on the superposition of the two delayed waves in the range of the optical coherence, e.g. when the optical delay is shorter than the
coherence time or equivalently, when the optical path-difference, is shorter than the coherence length. As the optical delay is longer than the coherence time, the optical interference disappears and the optical intensity becomes $I_0/2$, Fig. 2. An optical delay can be dynamically modulated by an information signal thus becoming an optical information carrier. The modulated signal is centered on a static optical delay $\tau_0$ or optical path-difference $(d_{m0})$ and the modulation process is optimal when the static delay is longer than the coherence length.

![Optical autocorrelation](image)

**Fig. 2.** Transmitted optical intensity from an optical retarder.

As shown in Fig. 1, the demodulation process is achieved using the same operating principle; e. g. by introducing a second optical delay or optical path-difference $d_{m0}$ optically matched to the sensor’s retarder. Such a situation allows that the two delayed waves interfere mutually. When detecting the optical interference, a photodetector delivers an average optical power.

From (1), the optical signal at the output of the electrooptic sensor can be expressed as

$$s_{0}(t)=\frac{1}{2}s(t-\frac{\tau_0}{2})+\frac{1}{2}s(t+\frac{\tau_0}{2})$$

If the optical demodulator introduces a second delay $\tau_d$; the output optical signal $s_{d}(t)$ is

$$s_{d}(t)=\frac{1}{2}s(t-\frac{\tau_d}{2})+\frac{1}{2}s(t+\frac{\tau_d}{2})$$

The detected optical intensity at the output of the demodulator now becomes

$$I_r=|s_{d}^*(t)s_{d}(t)|=\frac{I_0}{4}+\frac{I_0}{4}g(\tau_0)+\frac{I_0}{8}g(\tau_d)+\frac{I_0}{8}g(\tau_d-\tau_0)+\frac{I_0}{8}g(\tau_d+\tau_0)$$

The detected optical intensity depends on the optical path-differences $d=\nu\tau_d$, $d_{m0}=\nu\tau_0$; $\nu$ is the light speed and as $g(\tau_0)\approx 0$, the output intensity, in terms of the optical path-differences is given as

$$I_r(d)=\frac{I_0}{4}+\frac{I_0}{4}g(d)+\frac{I_0}{8}g(d-d_{m0})+\frac{I_0}{8}g(d+d_{m0})$$

where $d$ is the optical path-difference variable at the output of the demodulator. Fig. 3 represents the autocorrelation function of the delayed light showing the fringe patterns corresponding to the optical path-difference at the output of the demodulator [1]. As observed from Fig. 3, the fringes are centered at $d=0, -d_{m0}, +d_{m0}$.

![Autocorrelation of the detected light at the output of the optical demodulator](image)

**Fig. 3.** Autocorrelation of the detected light at the output of the optical demodulator.
Based on the previously described operating principle, an information signal can be transmitted using the optical path-difference $d_{m0}$ as a carrier. To recuperate the information as an intensity variation, the optical demodulator must be tuned to $d_{m0}$.

$$I_m(d \equiv d_{m0}) = \frac{1}{4} I_0 + \frac{I_0}{4} g(d_{m0}) + \frac{I_0}{8} g(d_{m0} - d_{m0}) + \frac{I_0}{8} g(d_{m0} + d_{m0})$$

As $d_{m0} >> I_c$, $g(d_{m0}) = g(d_{m0} + d_{m0}) = 0$; $g(d_{m0} - d_{m0}) = 1$

Finally, at the output of the optical demodulator, the detected optical intensity around $d_{m0}$ is given as

$$I_m(d \equiv d_{m0}) = \frac{1}{4} I_0 + \frac{1}{8} g(0)$$

(7)

An electric field $E(t)$ can modulate the optical path-difference and, at the demodulator, the electric field can be detected as an intensity variation on the autocorrelation of the received light. The variation is the strongest when the modulator and the demodulator are perfectly matched at $d_{m0}$. The modulated optical path-difference is

$$d_{m}(t) = d_{m0} + KE(t);$$

(8)

$KE(t)$ is the dynamic variation by the electric field and $K$ is the modulator sensitivity. According to (8), the electric field is recuperated as

$$I_e = \frac{I_0}{4} + \frac{I_0}{8} g(d_{m0} - d_{m0} + KE(t))$$

(9)

The dynamic variation on the detected optical intensity is depicted by Fig. 4. If $\Delta dm(t) = KE(t)$ is limited in a range of $\lambda_0/2$ around $d_{m0}$, then

$$I_e = \frac{I_0}{4} + \frac{I_0}{8} \cos(2\pi \frac{1}{\lambda_0} KE(t))$$

(10)

A linear detection of the modulating electric field can be achieved by shifting the static optical path-difference to

$$d_{m}(t) = d_{m0} - \frac{\lambda_0}{4} + KE(t);$$

Expression (9) now gives

$$I_e = \frac{I_0}{4} + \frac{I_0}{8} \cos\left(\frac{2\pi}{\lambda_0} KE(t) - \frac{\lambda_0}{4}\right)$$

(11)

Or, equivalently

$$I_e = \frac{I_0}{4} \left[1 + \frac{1}{2} \sin\left(2\pi \frac{1}{\lambda_0} KE(t)\right)\right]$$

(12)

The range between the maximum and minimum of $I_e$ determines the half-wave electric field $E_{s_e} = \frac{\lambda_0}{2K}$

Expression 12, becomes then

$$I_e = \frac{I_0}{4} \left[1 + \frac{1}{2} \sin\left(\pi \frac{1}{E_{s_e}} E(t)\right)\right]$$

(13)

Now when $E(t) \ll E_{s_e}$, the linear detection of the sensed electric field is achieved

$$I_e = \frac{I_0}{4} \left[1 + \frac{1}{2} \frac{\pi}{E_{s_e}} E(t)\right]$$

(14)
3. Electric field sensing-detection using birefringent optical waveguides as optical retarders.

A birefringent optical waveguide on LiNbO$_3$ electrooptic crystal acts as an optical retarder when it is configured as a polarization interferometer [4]. Birefringency is observed when the optical waveguide is realized in Z or X-cut, Y-propagating LiNbO$_3$. According to the operating principle in section 2, an optical delay can be generated when 45° polarized light is injected in the birefringent waveguide. The injected light is projected in two orthogonal modes, transversal electric (TE) and transversal magnetic (TM), which will propagate at different velocities as determined by the ordinary and extraordinary refractive index in the optical waveguide. The optical delay, or its equivalent optical path-difference $d_{m0}$, depend on the birefringency ($n_o-n_e$) and on the length of the optical waveguide [4, 5]. An optical retarder based on a birefringent optical waveguide is shown in Fig 5.

A static optical path-difference ($d_{m0}$) is introduced by the optical waveguide and is given as $d_{m0} = (n_o - n_e)L$, where $n_o$ and $n_e$ are the sensor ordinary and extraordinary refractive index, respectively; $L$ is the length of the optical waveguide. A practical measurable optical path-difference is achieved when using low-coherence optical sources, LEDs or SLDs. These optical sources have coherence-lengths of some hundreds of micrometers and when associated to birefringent optical waveguides of some centimeters, optical path-differences in the range of 1-10 mm are easily generated. According to expressions (2) and (8), the modulated optical signal at the output of the birefringent sensor is given as

$$I_{sensor}(E) = \frac{1}{2}I_0 + \frac{1}{2}I_0 \cos \left( \frac{2\pi}{\lambda_0}(d_{m0} - \frac{\lambda_0}{2E_p})E \right)$$

(15)

and

$$E_p = \frac{\lambda_0}{(r_{33}n_e^3\Gamma_{TM} - r_{13}n_o^3\Gamma_{TE})L}$$

(16)

where $E_p$ is the half-wave electric field; $\lambda_0$ is the optical wavelength; $n_o, n_e$ are the ordinary and extraordinary refractive index, respectively; $r_{13}, r_{33}$ are the electrooptic coefficients and $\Gamma_{TM}, \Gamma_{TE}$ are the optic-electric overlapping integrals. As described in section 2, if the electric field variations are small as
compared to $E_\pi$, according to (14), the received optical power at the output of the demodulator is proportional to the sensed electric field

$$I_s(t) = \frac{I_0}{4} \left(1 + \frac{\pi E(t)}{2 E_x}\right)$$  \hspace{1cm} (17)

An experimental electric field sensing scheme, using a birefringent optical waveguide as retarder and electric field sensor, is shown in Fig. 6. The scheme includes an SLD emitting at $\lambda_0=1310$ nm showing a coherence length of 70 µm; a birefringent retarder as the sensor; the optical demodulator is a segment of polarization maintaining optical fiber (PMF); a PIN-based photoreceiver and an oscilloscope for displaying the sensed and detected signals. In the experimental set-up, a voltage signal from a high-voltage amplifier is converted in electric field by using a set of parallel plates. The electrooptic sensor is a birefringent waveguide of 17.5 cm, which introduces $d_m=1.45$ mm. At the receiver, the optical demodulator is a segment of PMF, which introduces a delay $d_m=1.45$ mm to ensure the optical matching. A more detailed description of a complete sensing-detection scheme has been reported elsewhere [5]. The optical path-differences of the sensor and demodulator were measured in order to implement an electric filed sensing-detection process based on optical delays [6]. The measured autocorrelation of the cascaded sensor and demodulator is illustrated by Fig. 7, showing the optical matching.

![Fig. 6. Electric field sensing scheme based on a birefringent optical retarder.](image)

The electrooptic transfer function of the sensing scheme is determined by applying a DC electric field in a range between 0 and 1 MV/m. At the receiver, light is demodulated and at the output of the PMF, the optical transfer function as given by expression (12), is illustrated by Fig. 8a. From the physical parameters of the birefringent sensor ($n_e=2.15$, $r_{33}=30.8 \times 10^{-12}$ m/V, $\Gamma_{TM}=1$) in (15), the half-wave electric field $E_p$ is 540 kV/m. From the electrooptic response it is found that linear sensing-detection is achieved for electric fields in the ranges between $0-2 \times 10^5$ V/m and $5-7 \times 10^5$ V/m. Fig. 8b. illustrates the sensing-detection of a 100kHz, 10kVpp/m AC electric field.

![Fig. 7. Interference fringe patterns at the output of the cascaded birefringent sensor and PMF demodulator. The demodulator is tuned around $d_m$.](image)
4. Electric field sensing-detection using asymmetric Mach-Zehnder interferometers as optical retarders.

As explained in the introduction of this paper, an AMZI can also be used as optical retarder and electric field sensor. An AMZI is configured by asymmetric optical waveguides in an optical Mach-Zehnder structure. An AMZI can be constructed on Z or X-cut, Y-propagating LiNbO3 electrooptic crystals. When light coming from a low-coherence optical source is injected in the AMZI, the optical wave is split in two half-amplitude waves, which travel through the optical arms. As the arms are of different length, such a condition ensures the introduction of a static optical path-difference difference \( d_{m0} \). Additionally, when the input light is linearly polarized on the vertical axis (transversal magnetic mode, TM), the optical wave does not observe the birefringency of the crystal and at the output of the interferometer, the optical waves become delayed only depending on the differential length of the waveguides and on the observed refractive index, either \( n_e \) or \( n_o \). An AMZI can be used as electric field sensor. An X-cut, Y-propagating AMZI electrooptic sensor is shown in Fig. 9. In this case, the optical wave is polarized as a TM mode, which is aligned to the X-axis direction. For such an optical polarization, the optical path-difference is given as \( d_{m0} = \nu r_0 = n_o \Delta l \), where \( n_o \) is the ordinary refractive index and \( \Delta l \) is the differential length between the asymmetric optical arms.

For the AMZI sensor, the operating principle follows the model of an optical retarder as is described in section 2 of this paper. When an electric field is sensed by the optical waveguides, the optical path-difference is modulated and the optical power at the output of the sensor is given as

\[
I_r(E_s) = \frac{1}{2} I_0 + \frac{1}{2} I_0 \cos \left( \frac{2\pi \nu r_0}{\lambda_0} \left( d_{m0} - \frac{\lambda_0}{2E_s} \right) \right);
\]

\[
E_s = \frac{\lambda_0}{2n_o^2 r_0 \Delta L};
\]

where \( E_s \) is the half-wave field.
An experimental setup for sensing electric fields using an AMZI is illustrated in Fig. 10. The scheme includes an SLD emitting at $\lambda_0 = 1310$ nm, which shows a coherence length of 70 $\mu$m; an AMZI as retarder and sensor; the optical demodulator is a segment of polarization maintaining optical fiber (PMF); a PIN-based photoreceiver and an oscilloscope for displaying the sensed and detected signals. The electrooptic sensor shows $\Delta l = 0.1$ mm and introduces $d_m = 0.22$ mm.

In the experimental setup, the AMZI sensor is matched to the optical demodulator. The overlapping of optical path-differences is determined by measuring the optical autocorrelation of the transmitted light when the sensor and demodulator are cascaded [7]. From such a measurement, the interference fringe patterns are registered and are shown in Fig. 11. The superposed fringe patterns show the optical matching at $d_m = 0.22$ mm.

The testing electric field was generated by a high voltage amplifier, which feeds a pair of parallel plates. The electrooptic transfer function for the electric field sensing scheme is depicted in Fig. 12a. The theoretical half-wave electric field $E_{\pi}$ is in the order of $1.4 \times 10^8$ V/m. The optical transfer function shows the linear sensing range between $-0.3 \times 10^8$ and $+0.3 \times 10^8$ V/m, on depending on the sensed electric field.
intensities. Fig. 12b shows the input-output signal after the sensing-detection of a 10 kHz, 100kVpp/m saw-tooth AC electric field, around the quadrature point of the electrooptic transfer function. The experimental scheme shows a very high linearity for electric fields in a range between 0 and 10MVpp/m.

5. Conclusions
The use of LiNbO$_3$ electrooptic retarders as electric field sensors has been described in this paper. Electric fields can be sensed by electrooptical retarders, in configurations of polarization or Mach-Zehnder interferometers. These devices introduce optical delays which are modulated by the sensed electric field. The main characteristic of the sensing schemes is that the electric field is imprinted on optical delays or equivalently on the corresponding optical path differences. The operating principles of electric field sensing-detection schemes based on optical retarders have been also described. The implementation of such schemes requires of optical delays greater than the coherence-length of the optical source. The electric field modulated delay can be detected by a second retarder acting as optical demodulator. The sensor and demodulator must be optically matched for ensuring the optimum detection of the sensed electric field. Experimental schemes were described, using either a birefringent optical waveguide or AMZI as electric field sensors.

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