Novel Temperature Sensor Based in an Acousto-Optical Tunable Filter (AOTFS) Operating in a $LiNbO_3$ Crystal

C. S. Sobrinho, M. G. da Silva and A. S. B. Sombra

***Resumo*—Neste artigo, estudamos a performance de um novo sensor de temperatura acústico óptico integrado fabricado em cristais de $LiNbO_3$. Foi observado que um incremento uniforme de temperatura (24,5°C - 400°C) induz um decréscimo total na birrefringência óptica do cristal de 35,83%, para o comprimento de onda de 850 nm. Conseqüentemente, a largura da banda de transmissão do sensor aumenta cerca de 55,56%. Os resultados obtidos na simulação mostraram que a máxima intensidade temporal corresponde a uma sensibilidade de 0,52 mW (°C)$^{-1}$ sem o perfil de automodulação de fase e 0,61 mW (°C)$^{-1}$ em 24,5°C para a configuração com o perfil, alcançando o valor de 1 mW (°C)$^{-1}$ em 400°C.**

***Palavras-chaves*—Birrefringência, sensor, $LiNbO_3$, temperatura, sensibilidade, perfil de automodulação de fase.**

***Abstract*—In this article, we studied the performance of a novel integrated acousto optical temperature sensor fabricated in $LiNbO_3$ crystals. It was observed that an uniform increment in the temperature (24.5°C - 400°C) induces a total decrease in optical birefringence of crystal of about 35.83%, for the wavelength of 850 nm. Consequently, the acousto optical sensor transmission bandwidth increases about 55.56%. The results obtained in the simulation showed that the time intensity maximum corresponds a sensitivity of 0.52 mW (°C)$^{-1}$ without the profile of self phase modulation and 0.61 mW (°C)$^{-1}$ at 24.5°C for the configuration with the profile, reaching the value around 1 mW (°C)$^{-1}$ at 400°C.**

***Keywords*—Birefringence, sensor, $LiNbO_3$, temperature, sensitivity, profile of self phase modulation.**

I. INTRODUCTION

Lithium Niobate ($LiNbO_3$) is a ferroelectric material widely used in a variety of integrated and active acousto-optical devices due to its unique electro-optical, photo elastic, piezoelectric and non-linear properties [1]. The study of the birefringence as a function of temperature in $LiNbO_3$ crystals provides possibilities for design acousto optical temperature sensors achieving a good efficiency in the temperature sensing.

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The coefficients of the temperature-dependent generalized Sellmeier equation fitted to refractive index measurements and carefully reviewed literature data gives an accurate description of the temperature dependence of optical birefringence in $LiNbO_3$. On the basis of the generalized Sellmeier equation, all refractive-index-dependent effects in lithium niobate can be calculated in the desired composition, wavelength and temperature range [2].

Acousto optical (AO) interaction technology is currently generating considerable interest [3]. In the project of temperature optical sensors, the use of acousto-optical interaction offers the possibility of manipulating a laser source or processing signal radiation at high speed, since no mechanical moving parts are involved. The advances in the acousto-optical device applications have resulted principally from the availability of lasers, which produce intense, coherent light beams; from development of efficient broadband transducers which generate elastic waves up to microwave frequencies; and from the discovery of materials that have excellent elastic and optical properties. The basic element of such integrated acousto-optical devices is the acousto-optical mode converter (Fig. 1). Via an interaction between a surface acoustic wave (SAW) and the optical waves, a polarization conversion can be achieved. As this process requires phase matching, it is strongly wavelength-selective.

Considering the analysis of the variation of some parameters at output pulses (TM mode), as a function of the temperature change, we have investigated the effect of the increasing self phase modulation (SPM) profile on the performance of the acousto-optical temperature sensor (AOTS). The linear SPM profile has been considered [4]. In this paper the performance of a temperature sensor based on an AOTF in a $LiNbO_3$ crystal is studied.

II. BASICS OF THE ACOUSTO-OPTICAL TEMPERATURE SENSOR (AOTS)

The structure of the proposed acousto-optical temperature sensor is shown schematically in Fig. 1. It consists essentially of an integrated collinear acousto-optical TE-TM mode converter fabricated on a $LiNbO_3$ crystal, with an interdigital transducer for the excitation of the surface acoustic waves (SAW). Along the length of the crystal the acoustic field acts on the optical field to convert the TE polarization to a TM mode. This acousto-optical interaction is frequency selective because of the requirement for momentum matching for significant interaction. If the incident light is in the TE mode, the light energy in a spectral range around the wavelength to be selected is converted to the TM mode, while the rest of the light energy remains in the TE mode [5]. In a collinear interaction the spectral range (pass band) width around the chosen wavelength is inversely proportional to the acousto-optical interaction length and optical birefringence of the $LiNbO_3$ crystal. Any temperature change induces a consequent variation on the interaction length and optical birefringence, counted for the thermal expansion coefficient (TEC) and generalized Sellmeier equation, respectively. The mechanism of sensitivity of the sensor is based on the effects produced in the light converted for the TM mode when the crystal is submitted to distributed evenly temperature change.

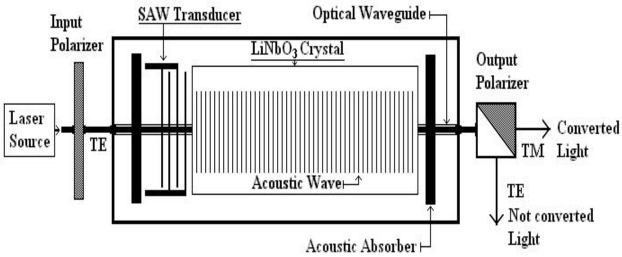

Fig. 1. Schematic of the integrated acousto-optic temperature sensor (AOTS).

III. Theoretical Framework

We will consider ultrashort input pulses of T_{IP}=2ps (F_{IP}=0.157THz) propagating through the acousto optical temperature sensor (AOTS). The propagation of ultrashort pulses through the AOTFS is described by the nonlinear Schrödinger equation (NLSE) [6]. For the sake of convenience we neglect the weak nonlinear cross-phase modulation (XPM). The time domain coupled differential equations describing the evolution of the slowly varying complex modal amplitudes A_1 and A_2 (TE and TM modes, respectively) are:

$$\frac{\partial A_1}{\partial z} = -i\kappa_{12}A_2 - i\frac{\Delta\beta}{2}A_1 + i\gamma Q(z)|A_1|^2 A_1 - \frac{i}{2}\beta^{(2)}\frac{\partial^2 A_1}{\partial t^2} \quad (1)$$

and

$$\frac{\partial A_2}{\partial z} = -i\kappa_{12}^{*}A_1 + i\frac{\Delta\beta}{2}A_2 + i\gamma Q(z)|A_2|^2 A_2 - \frac{i}{2}\beta^{(2)}\frac{\partial^2 A_2}{\partial t^2}, \quad (2)$$

where κ_{12} is the linear coupling coefficient between TE and TM modes, $Q(z)$ denotes the SPM profile, γ is the basic nonlinear coefficient, $\beta^{(2)}$ is the group velocity dispersion (GVD). The phase mismatch of the modes is $\Delta\beta = \beta_1 - \beta_2 + K$, which in a collinear interaction is proportional to the optical birefringence (Δn) of the guide ($LiNbO_3$) [5]:

$$\Delta\beta = \frac{2\pi|\Delta n|}{\lambda_C} + \frac{2\pi f_a}{V_a}, \quad (3)$$

where λ_C is the pump wavelength, f_a is the acoustic frequency and V_a is the velocity of sound in the medium ($LiNbO_3$). When the phase-matching condition (Bragg condition) is satisfied ($\Delta\beta$=0), one knows the acoustic frequency necessary for exact tuning of the pump wavelength λ_C. We are considering that the acousto optical temperature sensor is operating at the condition when $|\kappa_{12}|\xi_L=\pi/2$, so that the power conversion is 100% when $\Delta\beta\xi_L=0$ and drops to 50% when $\Delta\beta\xi_L=\pm0.8\pi$. Consequently, according to (3), for a collinear interaction, the full bandwidth at half maximum (F_S) of sensor is inversely proportional to birefringence and acousto optical interaction length through of relation

$$F_S = \frac{0.8C}{|\Delta n|\xi_L}, \quad (4)$$

where C is the velocity of light in the vacuum. In the nonlinear propagation regime $\beta^{(2)}$=–0.127ps^2/mm and γ=0.098(Wmm)$^{-1}$. We are also supposing an idealized situation without loss.

In this work, we will examine the sensitivity of the parameters: time duration, bandwidth, time intensity maximum, frequency intensity maximum and output energy in the output pulse (converted for the TM mode) as a function of temperature. When the birefringent crystal ($LiNbO_3$) waveguide is submitted to temperature increment (ΔT_C), both ξ_L and Δn change but in amounts and different ways. The change in the acousto optical interaction length (ξ_L) arises from thermal dilatation of the material, which is characterized for the thermal expansion coefficient (TEC) [$(d\xi_L/dT_C)/\xi_L=4.8\times10^{-6}$ $(^oC)^{-1}$] of the $LiNbO_3$ crystal [7]. The value of the birefringence ($\Delta n=n_o-n_e$) is calculated through of the temperature-dependent generalized Sellmeier equation [see (5)], proposes for authors in [2], which give an accurate description of the ordinary (n_o) and extraordinary (n_e) indexes as a function of the three independent variables wavelength, temperature and composition of $LiNbO_3$.

$$\Delta n(c_{Li},\lambda_C,T_C) = [c_{Li} - a(\lambda_C) - c(\lambda_C)F]/b(\lambda_C), \quad (5)$$

where c_{Li} represent the Li content (46.5 mol % Li_2O [8]) on the $LiNbO_3$ crystal and the terms $a(\lambda_C)$, $b(\lambda_C)$, and $c(\lambda_C)$ can be calculated for the desired pump wavelength. The term F is as function of the temperature through of

$$F = f(T_C) - f(24.5\ ^oC), \quad (6)$$

where

$$f(T_C) = (T_C + 273)^2 + 4.0238\times10^5\left[\coth\left(\frac{261.6}{T_C+273}\right) - 1\right].$$

In the following, we investigate the effect of an increasing linearly self phase modulation profile on the performance of the AOTFS. This profile is expressed in terms of the parameters ϕ (maximum value of Q) and ξ_L (length of the AOTFS):

$$Q(z) = \frac{(\phi - 1)}{\xi_L} z + 1 . \quad (7)$$

Note that in these normalized SPM profile the coefficient Q monotonically increases from 1 until the ϕ final value the measure that the propagated distance z, for the input pulse, increases from 0 until the ξ_L length of the AOTFS.

IV. Numerical Procedure

We have analyzed numerically the quasi-soliton pulses transmission of 2 ps through the (AOTS) acousto optical temperature sensor [(1) – (2)]. The initial pulse at the input crystal is given by:

$$A_1(0,t) = \sqrt{P_0}\,\mathrm{sech}\left(\frac{t}{T_0}\right) \quad (8)$$

and

$$A_2(0,t) = 0. \quad (9)$$

This system of coupled NLSE [(1) - (2)] was solved numerically using the fourth order Runge Kutta method with 1024 temporal grid points taking in account the initial conditions given by [(8) – (9)]. The variation of birefringence as a function of the temperature variation is quantified in [(1) - (2)] taking in account (3). In order to solve the system of coupled NLSE with this method, used only to ordinary differential equations, was necessary replace the differential operator $\partial^2/\partial t^2$ by its equivalent in the domain frequency ($-\omega^2$). Soon after the use of the FFT algorithm makes the numerical evaluation of the frequency domain terms on the right side of [(1) - (2)] straightforward and relatively fast.

The energy of pulse at output of the AOTFS (TM mode) with length ξ_L is calculated for

$$E_{OP} = \int_{-\infty}^{+\infty} |A_2(\xi_L,t)|^2\, dt. \quad (10)$$

We also calculated the maximum intensity in time $TI_{OP}=\max(|A_2(\xi_L,t)|^2)$ and frequency $FI_{OP}=\max\{|FFT[A_2(\xi_L,t)]|^2\}$ domain, with your full time duration (T_{OP}) and bandwidth (F_{OP}) at half maximum intensity point (FWHM), respectively.

V. Results and Discussions

The first step of this work was to investigate the resultant effect of a temperature variation in the values of the acousto optical interaction length and optical birefringence of the $LiNbO_3$ crystal. The increment in the acousto optical interaction length is just $\Delta\xi_L/\xi_L$~0.18% when ΔT_C=400°C-24.5°C=375.5°C. In contrast, the decrease in birefringence due to the temperature increase is at least 35.83%, for the pump wavelength λ_C=850nm. From our study it was evident that the birefringence is decreasing as one increase the temperature in the sensor, independent of the used wavelength.

The transmission bandwidth is increasing as one increase the temperature in the sensor, as expected [see (4)]. At the maximum temperature (T_C=400°C), the full transmission bandwidth at half maximum (3dB) is approximately 0.123THz. Consequently, the acousto optical sensor transmission bandwidth increases about 55.56%, relatively the initial transmission bandwidth at 24.5°C. In our study we are considering a 2ps input pulse, which will have a bandwidth about F_{IP}=0.157THz. For the sake of convenience, at the reference temperature (24.5°C), we are establishing that $F_S=F_{IP}/2$=0.079THz.

The operating of the sensor with pump wavelength λ_C=850nm leads to $\Delta n \cong 0.059$ at T_C=24.5°C. To chose a sensor operating with the half bandwidth of the input pulse (F_{IP}) one need a device with length around ξ_L=50.81mm. The velocity of sound in the medium ($LiNbO_3$) is $V_a=4\times10^3$m/s and the acoustic frequency necessary to tune the pump wavelength λ_C=850nm is f_a=282.29MHz.

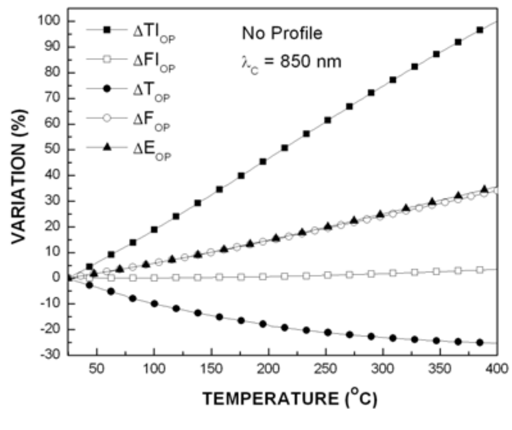

Fig. 2. Variation percentile of all analyzed parameters for the transmitted pulses at AOTFS output (TM mode) in the range (24.5°C to 400°C), obtained from the numerical solution of [(1) - (2)] in the nonlinear propagation regime, without profile SPM (ϕ=1) and with λ_C=850nm.

In Fig. 2, one has the five analyzed parameters in the range (24.5°C to 400°C) and for λ_C=850nm. The value of time duration at 400°C reveals a total decrease of

ΔT_{OP}=25.35%, relatively to its value T_{OP}=4.29ps at initial temperature (24.5°C). The time intensity maximum presents a total increase of ΔTI_{OP}=100.09% in the range (24.5°C to 400°C). This two previous behavior are associated to energy increasing observed on the output pulse in the TM mode, which results a total increment of ΔE_{OP}=35.66%, relatively to initial energy E_{OP}=1.12pJ at 24.5°C.

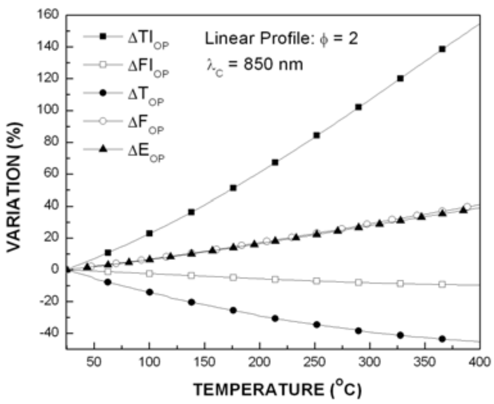

Fig. 3. Variation percentile of all analyzed parameters for the transmitted pulses at AOTFS output (TM mode) in the range (24.5°C to 400°C), obtained from the numerical solution of [(1) - (2)] in the nonlinear propagation regime, with profile SPM linear (ϕ=2) and with λ_C=850nm.

The transmission bandwidth increment as a function of temperature is increasing the bandwidth and frequency intensity maximum of output pulse. At 24.5°C one has F_{OP}=0.072THz and FI_{OP}=1.08W. The temperature increase leads to total increment of ΔF_{OP}=33.98% and ΔFI_{OP}=1.42%, at T_C=400°C, respectively.

In Fig. 3, we examine the performance of the AOTS in the same previous range of temperature (24.5°C to 400°C), when the optical guide ($LiNbO_3$ Crystal) presents an increasing linearly SPM profile [Q(z)] with ϕ=2. According to our previous values, the time intensity maximum presents the largest variation (ΔTI_{OP}=154.76%), followed for the time duration (ΔT_{OP}=45.39%) and bandwidth (ΔF_{OP}=41.09%), relatively to their values at the reference temperature: TI_{OP}=0.23W, T_{OP}=3.89ps and F_{OP}=0.078THz, respectively. The energy does not follow the previous behavior presenting a smaller variation than this previous parameters (ΔE_{OP}=39.04%). At 24.5°C one has FI_{OP}=0.95W. The temperature increases until T_C=400°C the frequency intensity maximum is presenting the total decrease around ΔFI_{OP}=9.65%.

VI. Conclusions

We can conclude that the AOTFS sensitivity is better in a configuration considering the increasing linearly SPM profile with ϕ=2. Comparing all the analyzed parameters, we can conclude that the time intensity maximum presents the best results in the two analyzed situations, with (ϕ=2) and without (ϕ=1) the use of linear profile. We can observe that the slope of curve for the case without profile stay around dTI_{OP}/dT_C=0.52 $mW(^oC)^{-1}$ with changing temperature. Looking for case with the profile, this is not happening. The results reveal that the slope is around dTI_{OP}/dT_C=0.61 $mW(^oC)^{-1}$ at 24.5°C and reach the value around dTI_{OP}/dT_C=1 $mW(^oC)^{-1}$ at 400°C.

The study of the performance of this novel integrated acousto-optical (AO) temperature sensor fabricated in $LiNbO_3$ crystals and operating with ultrashort light pulses (2 ps), provides possibilities for achieving, high efficiency in ultra fast all-optical temperature measurements processing, especially for monitoring in ambient where the durability, corrosion resistance, water proof and explosion proof, small size, low weight and immunity to electromagnetic interference are crucial factors to improve the performance of the system.

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