Acousto-Optic Tunable Filter (AOTF) with Increasing Nonlinearity and Loss

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Abstract - **In this paper we did a study of the transmission characteristics of the AOTF operating with ultra-short light pulses (2ps), for soliton and non-soliton propagation regimes. In a preliminary study one has considered the performance of the device, with several lengths, operating in the nonlinear regime without loss and in the presence of loss. In this paper one considers the device of length 0.25mm with 4dB/mm of loss and constructed with several increasing non-linearity profiles. We compare five simple coefficients of self phase modulation (SPM) profiles, namely: linear, Gaussian, exponential, logarithm and constant. From our study, we suggest the best profile region of the non-linearity parameter to recover the original performance in the nonlinear transmission of the AOTF and to overcome the effect of the intrinsic loss in the device.**

I. Introduction

THE acoustic-optic tunable filter [1](AOTF) has attracted great attention in recent years, in part because it appears to be a suitable basis for multi-wavelength optical cross-connects. It is probably the only known tunable filter that is capable of selecting several wavelengths simultaneously. This capability can be used to construct a multi-wavelength router. Cross-connects are important in multi-wavelength networks because they can enable reconfigurable network architectures that can adapt to changing traffic patterns and enhance network survivability [2]. A multi-wavelength cross-connect capable of switching a moderate number of wavelengths could enable multihop networks providing access to millions of network nodes with a reasonable number of hops. The AOTF is attractive for this application because it provides simultaneous, transparent and nearly independent switching of many closely spaced and arbitrarily chosen wavelength channels, a large and flexibly addressed wavelength range, rapid tuning (order of a few μs) across the accessible wavelengths, low optical loss (3-4 dB/stage), and the potential for integration of several functions on the same substrate [2].

Recent improvements in the AOTF design included pass-band engineering to reduce side-lobs [3], flatten the wavelength response [4], which reduce the cross talk and increase the channel-width-to-channel-spacing ratio.

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In this paper, we did a study of the transmission characteristics of the AOTF operating with ultra-short light pulses (2ps of time duration, $1ps=10^{-12}s$).

In a preliminary study one has examined the performance of the device, with several lengths, operating in the nonlinear regime without loss and in the presence of loss. Lossless device is an idealized situation. In practice, large or small, material loss is unavoidable, especially when nonlinearities are based on absorptive process in semiconductors. The absorption, uniformly distributed over the device, will set a limit to the operation of the device [5,6]. Considering the loss, in this paper, one investigates the effect of several increasing self phase modulation (SPM) profiles on the performance of the AOTF. Five closely SPM profiles named linear, Gaussian, exponential, logarithm and constant has been considered. From our preliminary study of the SPM profile, we observed that for the nonlinear AOTF with loss, the increasing nonlinear profile could lead to pulse compression or pulse break up depending on the length of the AOTF, propagation regime and the magnitude of the loss.

II. Basics of the AOTF

The AOTF is shown schematically in figure 1. It consists of an optical waveguide occupying the same space as an acoustic waveguide. The acoustic wave is introduced into the acoustic guide using a surface acoustic wave (SAW) transducer. The acoustic field acts on the optical fields in the interaction region to convert the TE polarization to a TM mode, and vice versa. This interaction is frequency selective because of the requirement for momentum matching for significant interaction. The polarization conversion efficiency can be calculated by treating the device as a classical directional coupler, where the coupled modes are the TE and TM modes of the optical waveguide, and the coupling coefficient is proportional to the acoustic amplitude.

If, somehow, the light energy in a narrow 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 (see figure 2), we have a wavelength-selective filter [2,7,8].

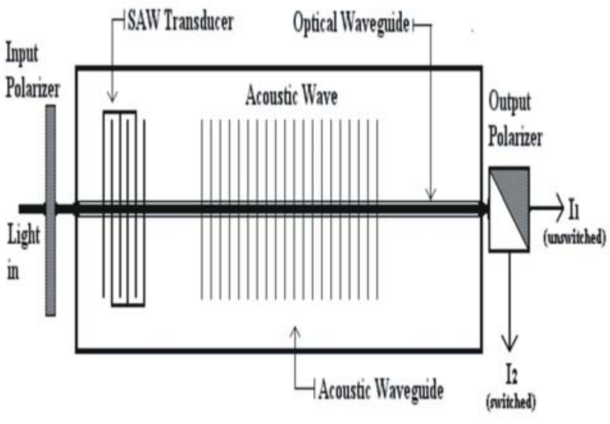

Fig. 1. Schematic of the acoustic optic tunable filter (AOTF).

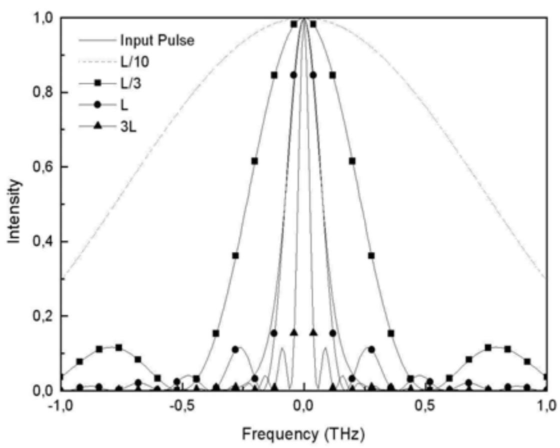

Fig. 2. Bandwidth of the input pulse and of the filter for ξ_L=L/10, L/3, L, 3L (L=0.76mm).

III. Theoretical Framework

We will consider two different situations of picosecond pulses propagating in an AOTF of length ξ_L: in the first one the AOTF will present nonlinear dispersion and SPM in the soliton regime ($L_{NL} = L_D$ □ ξ_L), in the second situation one will consider that the nonlinear dispersion is not a strong effect for the length of the device (L_{NL} □ $\xi_L << L_D$). In this case the nonlinear dispersion terms, in equations 1 and 2 will be negligible (second term in equations 1 and 2). The propagation ultra-short light pulses is described by the nonlinear Schrödinger equation [10]. For the sake of convenience, we neglect the weak nonlinear cross-phase modulation (XPM). The coupled differential equations describing the evolution of the slowly varying complex modal amplitudes a_1 and a_2 (TE and TM modes respectively) are:

$$i\frac{\partial u_1}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u_1}{\partial \tau^2} + Q(\xi)\,|u_1|^2\,u_1 + Ku_2 - \Delta\beta u_1 + i\Gamma u_1 = 0 \quad (1)$$

$$i\frac{\partial u_2}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u_2}{\partial \tau^2} + Q(\xi)\,|u_2|^2\,u_2 + Ku_1 + \Delta\beta u_2 + i\Gamma u_2 = 0 \quad (2)$$

Where u_1 and u_2 are the modal field amplitudes, $\Gamma=(\alpha L_D)/2$ is the normalized optical loss over one dispersion length (α is the optical loss), K is the linear coupling coefficient between TE and TM modes, $\Delta\beta=\beta_{TM}-\beta_{TE}$ is the phase mismatch of the modes, $Q(\xi)$ denotes the SPM (self phase modulation) profile, which is proportional to the nonlinear refractive index n_2 of the guide[9].

The variables ξ and τ are the normalized length and time units with $\xi = z / L_D$ and $\tau = t / T_0$. Here $L_D = T_0^2/|\beta_2|$ and $L_{NL} = 1/(\gamma P_0)$, with pulse width T_{FWHM} =2ps (T_0=1.134ps, $T_{FWHM} = 1.763T_0$), β_2 = -16.9 ps^2/mm (soliton profile) or $\beta_2 \approx 0$ (non-soliton profile) where β_2 is the normalized group velocity dispersion (GVD), P_0 is the peak power of the incident pulse (P_0 = 1W) and γ =13 $(Wmm)^{-1}$ is the nonlinear coefficient.

In this way we have analyzed numerically the ultrashort pulse transmission, in the propagation regimes: first order soliton and non-soliton, through the AOTF (equations 1-2). The initial pulse at the input core is given by:

$$u_1(0,\tau) = A\,\mathrm{sech}(A\tau)............ \rightarrow (3)$$

$$u_2(0,\tau) = 0........................... \rightarrow (4)$$

We also define the final compression factor C, achieved after propagation of the optical input pulse in the AOTF. It is defined as the ratio of the optical pulse FWHM at the input of the coupler τ_0 (FWHM of the $|u_1(0,\tau)|^2$, input pulse), to that at the output (transmitted) of the coupler, τ_2 (FWHM of the $|u_2(\xi_L,\tau)|^2$, transmitted pulse).

$$C = \frac{\tau_2}{\tau_0} \quad (5)$$

IV. Results and Discussions

In the first configuration equations 1 and 2 were solved (without non-linearity, dispersion and loss) under the action of a CW pulse which acts on channel 1. In figure 2 one has the spectra of the input pulse ($\Delta f \approx 0.157$THz) together with the transmission function of four different filters. We are considering the basic filter with length ξ_L=L=0.76mm and the filters with lengths ξ_L=L/10, ξ_L=L/3 and ξ_L=3L. The figure shows that the longer the device, the narrower the passband.

In the following, we will examine the AOTF with loss and increasing non-linearity for the non soliton and soliton regimes. The presence of loss is responsible for the increase of the time duration of the switched pulse and strong deformation of the pulse bandwidth. We expect that the increasing nonlinear profile will be effective to recover the original switching behavior associated to the lossless situation. The optical guide present an increasing SPM profile (Q(z)) with five closely SPM profiles named: linear, Gaussian, exponential, logarithm and constant. These profiles are expressed in terms of the parameters β (maximum value of Q) and ξ_L (length of the AOTF). The equations for these profiles are:

$$Q(z) = \frac{(\beta - 1)}{\xi_L} z + 1 \qquad \text{Linear} \qquad (6)$$

$$Q(z) = \exp\left(\frac{z}{\xi_L} \mathrm{Ln}\beta\right) \qquad \text{Exponential} \qquad (7)$$

$$Q(z) = \exp\left(\frac{z^2}{\xi_L^{\ 2}} \mathrm{Ln}\beta\right) \qquad \text{Gaussian} \qquad (8)$$

$$Q(z) = \mathrm{Ln}\left(e + \frac{z}{\xi_L}(e^{\beta} - e)\right) \qquad \text{Logarithm} \qquad (9)$$

$$Q(z) = \beta \qquad \text{Constant} \qquad (10)$$

In figures 3a, 3b, 4a and 4b one solve equations 1 and 2 considering an input pulse of 2ps in an ξ_L=L/3 (AOTF) with $K\xi_L=\pi/2$, Γ=0.035 (α ≈ 4dB/mm) for the soliton and non-soliton cases.

In figure 3a one has the compression factor for the switched pulse in a L/3 device with loss (α ≈ 4dB/mm) considering all the profiles of the nonlinearity for non-soliton propagation. For values of C<1, means that we have pulse compression for the switched pulse and for values of C>1, one has temporal broadening according with our previous definition of the compression factor. One can observe that there is always an optimum value for β that one can obtain a switched pulse with the same time duration of the input pulse (C=1). From figure 3a, one can conclude that for the constant profile, the value of β is the minimum (1.53) compared with the other profiles.

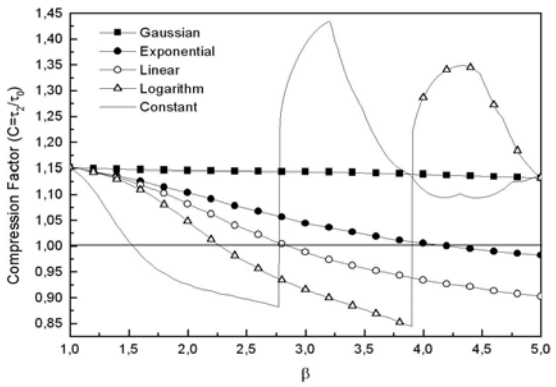

Fig. 3a. Compression Factor C (equation 5) as a function of β, for non-soliton regime with profiles given by equations 6 to 10.

In figure 3b one has the compression factor for the switched pulse along the filter length, considering the optimum values of β obtained from figure 3a. For the sake of convenience, one considered the maximum value of β studied (β_{max}=5) as the optimum value for the Gaussian profile in non-soliton propagation. One can notice that the Gaussian profile and the no-profile situation (β=1) present the worse behavior at the filter output.

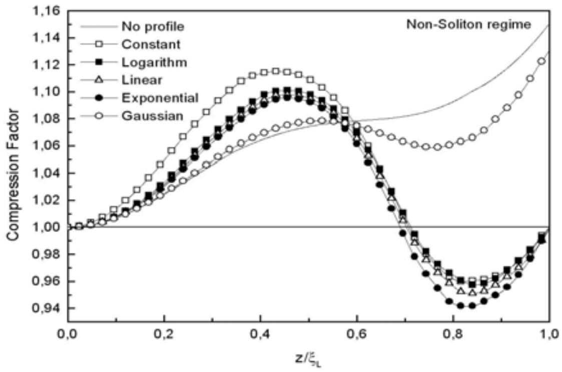

Fig. 3b. Compression Factor for non-soliton regime along the length of the device with β optimum values (C=1 in figure 3a).

In figure 4a one has the same study for the soliton propagation. from both figures (3a and 4a) one can notice that is always possible to obtain values for β where the switched pulse could be obtained with the same input time duration.

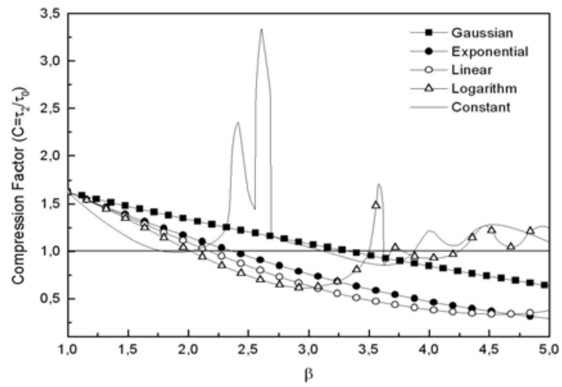

Fig. 4a. Compression Factor C (equation 5) as a function of β, for soliton regime with profiles given by equations 6 to 10.

The constant profile, in soliton propagation (figure 4a), also present the lowest value (1.79) for β comparing with the other profiles. In figure 4b one has the compression factor for the switched pulse along the filter length, considering the optimum values of β obtained from figure 4a for the soliton propagation. One can notice that for the constant profile the compression factor is around 1 all over the device. That is a much better behavior compared with the non-soliton regime and other profiles in soliton regime (compare figures 3b and 4b).

For the constant profile (β=1.79), in the figure 4b, the maximum deviation of the compression factor is around 0.9%. At the output of the device this deviation is around 0.2%.

Looking again for figures 3a and 4a one can notice regions where the compression factor present strong peaks. This behavior is associated to pulse break up that happens at high values of the nonlinearity.

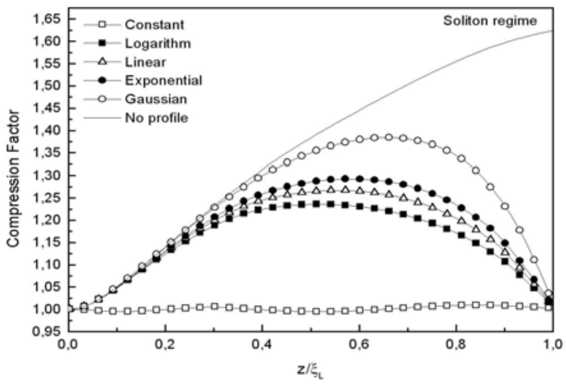

Fig. 4b. Compression Factor for soliton regime along the length of the device with β optimum values (C=1 in figure 4a).

V. CONCLUSIONS

From our study it was observed that the effect of dispersion and non-linearity has strong influence on the pulse propagation when one increases the length of the AOTF. For shorter length of the device the switched pulse is presenting time broadening for soliton and non-soliton profiles. For higher length of the device, pulse breakup was observed for non-soliton profile and time displacement for the soliton profile. We compare five simple coefficients of self phase modulation profiles considering the AOTF with 4dB/mm of loss and length 0.25mm. One can observe that there is always an optimum value for β (final value of the profile Q(z) of the non-linearity) that one can obtain a switched pulse with the same time duration of the input pulse.

Comparing the soliton and non-soliton pulse propagation, one can say that the constant profile present the lowest value for β comparing with the other profiles. This value is around 1.53 and 1.79 for the non-soliton and soliton propagation respectively.

One can say that one can operate the AOTF in a configuration that one can avoid the time displacement and break up pulse and have a switched pulse with a much better time duration compared with the lossy AOTF. With the increase of the β parameter the pulse has showed break-up even for the constant and logarithm profiles. One concludes that is possible to operate the AOTF in a soliton and non-soliton input profiles.

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