Energy transmission in optical device makes for association of nonlinear directional coupler cascading

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***Abstract* — We present a numerical study of optical signals propagation and switching by using cascaded nonlinear directional couplers based on photonic crystal fibers (NLDC-PCF). We have explored the device's potential for energy switching by changing the input power for the use of modulated pulses with PAM-ASK. With pulses temporal width of *100 fs*, we have considered the influence of high order dispersion effects such as third order dispersion. We have considered too the nonlinear self-steepening, intrapulse Raman scattering and self-phase modulation effects. We have analyzed the device's transmission of energy efficiency with pump power around the critical power.**

Keywords* — *photonic crystal fiber; nonlinear directional coupler; power transmission; switching.

I. Introduction

Photonic Crystal Fibers (PCF) are optical fibers formed from a material with low and a material with high refractive index. The material which composes the core of a PCF is generally formed of non-doped silica, and the low refractive index area is composed of a periodic array of air holes which extends through its entire length. Because of its features, PCFs have found many important applications such as dispersion control, endless single-mode operation, supercontinuum generation, ultra broadband soliton transmission and power switching [1-4].

It has been shown theoretically and experimentally that dual-core PCFs can be used as two central coupled regions and as a directional optical coupler [5-6]. The nonlinear directional coupler (NLDC) constituted of these dual-core PCFs has attracted considerable attention because it offers possibilities for switching, routing and modulation of optical signals through another optical control signal over the nonlinear interaction in the coupling region between the waveguides [7-10].

The acquisition of all-optic logic gates can arises as a proposal for development of devices capable of processing optical signals. Based on nonlinear directional couplers (NLDC) these all optical logical gates depends of the critical power as essential factor to perform power switching and pulses interaction between the waveguides. The use of pulse amplitude modulation is a fundamental key for improve the amplifiers bandwidth and the optical transmission lines.

The dual-core photonic crystal fiber dual-core structure is shown in Fig. 1. The core are separated by a distance C, the hole-to-hole space is Λ and the diameter of air holes is *d*.

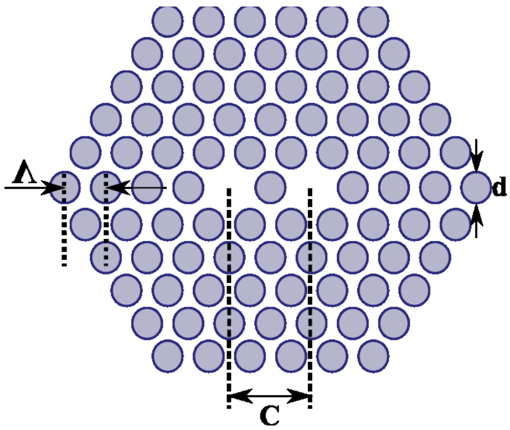

Fig. 1. Cross-section schematic of the dual-core photonic crystal fiber.

Based on Pulse Amplitude Modulation with Amplitude Shift Keying (PAM-ASK), which has different power levels for representation of logical values 1 and 0, we have investigated the behavior of the device shown in Fig. 2. We have analyzed the energy transmission between the waveguides by varying the power of the input signals around the critical power.

II. Device with Photonic Crystal Fiber Couplers Cascading

Several devices with purpose of performing logical operations by switching energy via optical fibers have been proposed in the literature. Recently, researches have proven the possibility of acquiring all-optical logic gates with smaller devices [11-13]. We propose a device consisting of two nonlinear directional couplers based on photonic crystal fiber (See Fig. 2). It is composed by three input waveguide, three output waveguide and three modulators operating with pulse amplitude modulation with amplitude shift keying (PAM-ASK).

III. Theoretical Modeling

The nonlinear coupled mode equation is based on the Nonlinear Schrödinger Equation (NLSE). It governs the evolution of electromagnetic fields in a coupler with high nonlinearity and dispersion effects of high order. Thus, for an envelope propagating in a nonlinear directional coupler (NLDC) consisting of PCF and operating without losses (due to the short propagation length), we have

$$\begin{aligned}
&i\frac{\partial a_1}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 a_1}{\partial t^2}-i\frac{\beta_3}{6}\frac{\partial^3 a_1}{\partial t^3}+\frac{\beta_4}{24}\frac{\partial^4 a_1}{\partial t^4}+\gamma\left(|a_1|^2+\eta|a_2|^2\right)a_1+\\
&+i\frac{\gamma}{\omega}\frac{\partial\left(|a_1|^2 a_1\right)}{\partial t}-\gamma a_1 T_R\frac{\partial|a_1|^2}{\partial t}+\kappa_0 a_2+i\kappa_1\frac{\partial a_2}{dt}=0\\
&i\frac{\partial a_2}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 a_2}{\partial t^2}-i\frac{\beta_3}{6}\frac{\partial^3 a_2}{\partial t^3}+\frac{\beta_4}{24}\frac{\partial^4 a_2}{\partial t^4}+\gamma\left(|a_2|^2+\eta|a_1|^2\right)a_2+\\
&+i\frac{\gamma}{\omega}\frac{\partial\left(|a_2|^2 a_2\right)}{\partial t}-\gamma a_2 T_R\frac{\partial|a_2|^2}{\partial t}+\kappa_0 a_1+i\kappa_1\frac{\partial a_1}{dt}=0
\end{aligned}\quad (1)$$

where z is the distance along the fiber; t is the time coordinate with reference to the transit time of the pulses; a_1 and a_2 are the amplitude envelopes of the pulses carried by the two cores, respectively; β_2, β_3, and β_4 are the group-velocity dispersion (GVD), third-order dispersion (TOD), and fourth-order dispersion, respectively; γ is the nonlinear parameter that accounts for selfphase modulation (SPM); η is a small ratio that measures the relative importance of cross-phase modulation (XPM) with regard to SPM; the time-varying term next to the SPM and XPM terms represents self-steepening (where ω is the angular optical frequency); T_R is the Raman scattering coefficient; κ_0 is the coupling coefficient; and κ_1 is the coupling coefficient dispersion given by $\kappa_1=d\kappa_0/d\omega$ (evaluated at the pulse carrier frequency). The coupling coefficient dispersion κ_1 is a measure of the wavelength dependence of the coupling coefficient; it is equivalent to the intermodal dispersion of the composite two-mode fiber structure [04], [14-15].

The photonic crystal fibers have a very high nonlinearity. The effective nonlinear parameter is given by

$$\gamma=\frac{2\pi}{\lambda}\frac{\eta_2}{A_{eff}} \quad (2)$$

where A_{eff} is the effective mode area and λ is the wavelength. In this study we will not consider saturation effects of nonlinearity by the field intensity [16-17]. In according with the Equation (2), a reduction in the effective area increases the nonlinearity. That becomes the PCF highly nonlinear if compared with the conventional fibers. Due to the presence of materials with different characteristics of nonlinearity, the effective area of the PCF is given by

$$A_{eff}=\frac{\eta_2\left[\iint E(x,y)\cdot E^*(x,y)\,dxdy\right]^2}{\iint\bar{\eta}_2(x,y)\left[E(x,y)\cdot E^*(x,y)\right]^2 dxdy} \quad (3)$$

where $E(x,y)$ is the transverse electric field, $\eta_2(x,y)$ is the nonlinear coefficient of the material. Effective non-linarites of the order of 640 $W^{1}km^{-1}$ have been reported in a solid core PCF [18].

The interaction between fields that propagate in a NLDC occurs by transmission and coupling of pulses that propagate by it. In order to this happens, it is necessary that the distance between the waveguides be of the order of fading evanescent radiation [19]. The input power is fundamental in the coupling process between the waveguides. When a coupler's channel is excited with a high power, beyond the critical power, the pulse will not be transmitted to the other channel, thus the output will arise at the same guide. But, when the channel is excited with a low power, all the energy is transmitted for the other waveguide [20]. The coupling length L_C that in which a pulse of low power that propagate through one waveguide is completely switched from a core to another [14]. This length is defined by $L_C = \pi/2\kappa$ which κ is the linear coupling coefficient between the adjacent waveguides.

When the incidence of light in one of the waveguides is low, the device behaves as a linear coupler, in other words, the optical beam propagate periodically between the waveguides that constitute the coupler. However, the transmission features are destroyed for high level power due to the change in the refractive index. When the incidence power is the critical power, the light will emerge at the two NLDC output with the equals values [14]. This blockage in the transmission happens for powers above the critical power:

$$P_C=\frac{A_{eff}\lambda}{\eta_{NL}L_C} \quad (4)$$

where η_{NL} is the nonlinear refractive index and L_C is the coupling length necessary to the complete energy transference from a waveguide to another.

IV. Pulse Amplitude Modulation With Amplitude Shift Keying

The dispersion control of the photonic crystal fibers can provide a great advance in both the data transmission rate as to minimize the intersymbol interference. Operating with pulses of temporal width in the order of 100 *fs*, the proposed device in this paper can provide a bandwidth at the *THz* order. However, there are other important factors on data transmission. One of them is the encoding of the signal through modulation.

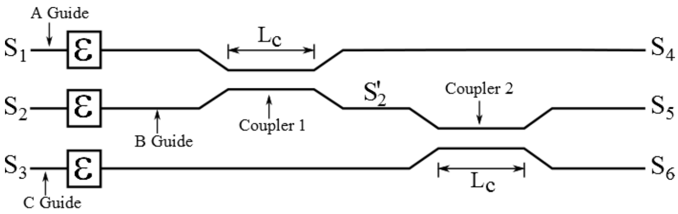

Fig. 2. Device built by couplers cascading.

The pulse amplitude modulation with amplitude shift key (PAM-ASK) proposed by this paper changes the input power. We use *a(z,t)* as the reference pulse under the hyperbolic secant form with an amplitude of a_0 [11-13]. The modulated signals have the same reference pulse shape, but with amplitudes of $(a_0 + \varepsilon)$ and $(a_0 - \varepsilon)$ for the logic values that represent the bit 1 and the bit 0, respectively. Thus, defining the modulation PAM-ASK:

$$\begin{aligned} a(0,t) &= a_0 \sec h(t) \\ a(0,t) &= (a_0+\varepsilon)\sec h(t) \\ a(0,t) &= (a_0-\varepsilon)\sec h(t) \end{aligned} \tag{5}$$

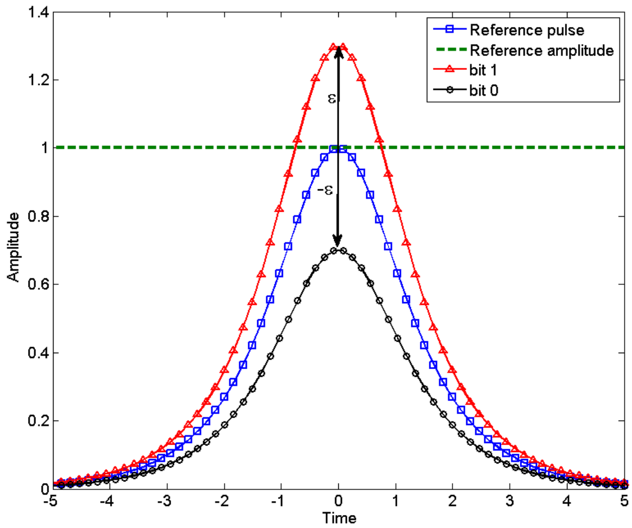

Fig. 3.Reference pulse (blue) to PAM-ASK, modulated pulse with $+\varepsilon$ parameter (red) and modulated pulse with $-\varepsilon$ parameter (green).

The Fig.3 shows the plot with the three pulses previously defined. Referring to Fig. 2, these are the pulses shapes when they pass through the modulator (*ε*). Thus, for PAM-ASK, every pulse with amplitude greater than the reference amplitude is considered as the logic level 1. Otherwise, the pulse is considered logic level 0. We have performed the input powers study in each logic level.

V. Numerical Results

We have investigated the device performance shown in Fig. 2. The system is composed by two NLDC-PCF and three modulators PAM-ASK. The modulator's parameter is ε and it represents the pulse amplitude shift for the logic value definition. After passing the PAM-ASK modulator and phase control, the pulse enters the NLDC-PCF as shown in Equation (6).

$$\begin{aligned} S_k &= \left[a_0 + (-1)^{(1-BIT)}\varepsilon\right]\sec h(t) \\ S_k &= \left[a_0 + (-1)^{(1-BIT)}\varepsilon\right]\sec h(t) \\ S_k &= \left[a_0 + (-1)^{(1-BIT)}\varepsilon\right]\sec h(t) \end{aligned} \tag{6}$$

where the index k = 1, 2 or 3 refer to the gates 1, 2 or 3; $a_0 = \sqrt{P_0}$ is the amplitude and P_0 is the highest power of the pulse. The indexes *BIT* are logic values applied on the system (0 or 1); and ε represents the modulation PAM-ASK parameter. When *BIT* represents the logic level 1, we have $S_\kappa = (a_0+\varepsilon)\sec h(t)$. When *BIT* for the logic level 0 we have $S_\kappa = (a_0-\varepsilon)\sec h(t)$ (see Fig. 3). The amplitude of the modulated pulses is calculated from the temporal position of its respective maximal intensity.

According Equation (1) the reference frame moves with the pulse in the group velocity (v_g), thus the time is $t=t'-z/v_g$. We have used the propagation of a fundamental soliton, in other words, a first order soliton [Nonlinearity length is the same of the dispersion length ($L_{NL}=L_D$)] with full temporal width at half maximum (TFWHM) of the input pulse $\Delta t_{pulse}=100\ fs$. We have ignored the fourth order dispersion and the fiber losses. This is because of the short propagation length (ignorable losses regime). We have analyzed two dual-core couplers based on silica PCF with air-hole diameter of $d=2.0\ \mu m$, a hole-to-hole distance of $\Lambda=d/0.9$, A core distance of $C=2\Lambda$, coupling length of $L_C=1.8\ cm$, wavelength around of $\lambda=1.5\mu m$ and an effective area of $A_{eff}=41\mu m^2$. The corresponding parameters to Equation (1) are $\beta_2 = -47\ ps^2/km$, $\beta_3 = 0.1 ps^3/km$, $\gamma = 3\times10^{-3} Wm^{-1}$ e $\gamma/\omega = 2.6\times10^{-18} s/Wm$ [17]. The critical power is $P_C=1.09\times10^5\ W$ and the peak power for the first order soliton propagation is $P_0 = 4.56\times10^3\ W$. However, the reference amplitude at output is given by $A_R = P_0^{1/2}$. Posteriorly, we have assumed the coupling length $L_{C1} = L_{C2} = L_{NL} = L_D = 1.8$ cm [4]. The cascading of couplers is numerically resolved by Equation (1) with fourth order Runge-Kutta method.

The energy transmission factor between the waveguides is defined in function of the input signal as:

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$$T_i = \frac{\int_{-\infty}^{+\infty} \left| S_k \left(P_{in} \right) \right|^2 dt}{\int_{-\infty}^{+\infty} \left| S_1 \left(0 \right) \right|^2 dt} \quad (7)$$

where $k = 4,\ 5$ e 6 represents the three outputs; $S_\kappa(P_{in})$ is the output signal and depends on the input power while S_1 is the input signal *1*.

VI. Results and Discussions

First of all, we have analyzed the behavior of the device in Fig. 2 by inserting a pulse with a power of the order of P_0 until a power twice greater than the critical power (P_C), in other words, $P_0 \le P_{in} \le 3 \times P_C$. Entering the pulse in S_1, we have analyzed the power of the output of the three guides.

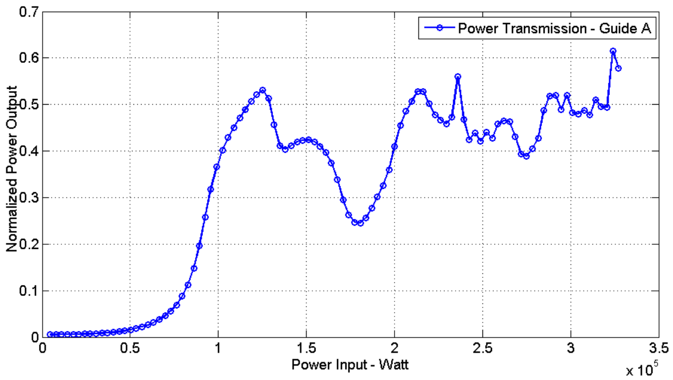

Fig. 4. Energy in the output of the guide A.

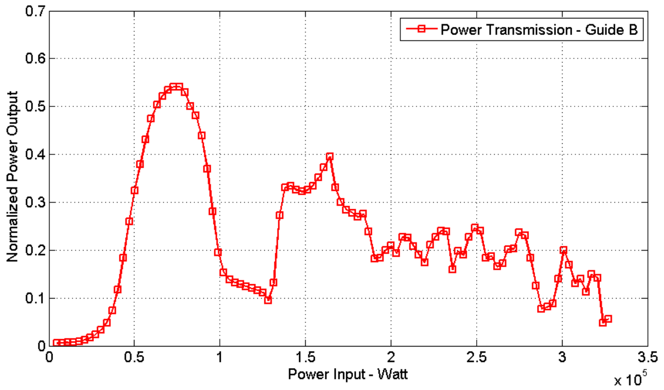

Fig.5. Energy in the output of the guide B.

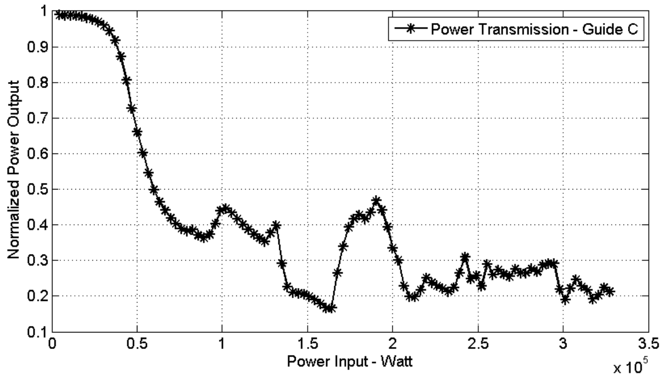

Fig. 6. Energy in the output of the guide C.

Considering the output of the guide A (see Fig. 4) we obtain the complete switching power when the input power is inserted below the critical power. However, as the input power increases, the transmission power of the guide A to the guide B decreases. When the pulse entered has its power quite higher than the critical power, around 60% of it remains in the same guide.

Analyzing the switching that occurs on the guide B (see Fig. 5), the energy is completely switched when a low power is inserted in the input. For the input $7.6 \times 10^4 W$ we have obtained that 54% of the energy emerges on the guide B. But, with increasing input power, the oscillation between A, B and C guides increase. The guide C emerges 100% of the energy when the input power *4.56 kW* (see Fig. 6).

The input power is the critical power, the energy that emerges in the guide A is the same energy in the guide B reaching 86% of the total inserted energy (the both energy sum). When the input power is $1.7 \times 10^5 W$ we observe the same amount of energy in the output of the three guides.

VII. Conclusion

In this paper a numerical study of the propagation and switching of optical signals using cascading couplers for photonic crystal fibers was presented. We explore the potential of the device in the switching power by changing the input power to use pulse modulated PAM-ASK. With temporal pulse width of 100 fs, we consider the influence of the effects of higher-order dispersion, such as third. Also, we consider the nonlinear effects of self-steepening, Raman scattering intrapulse and self-phase modulation. We analyze the efficiency of the transmission energy of said device with pump power around the critical power. However, the device presented shows characteristics in switching power or fully optical signals. The results presented here open a perspective on the development of applications for all optical signal processing from cascading couplers based on photonic crystal fibers.

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