Mach Zehnder Nonlinear Interferometer in Photonic Crystal Fibers with Nonlinearity Profiles

J. C. Sales, J. R. R. Sousa, K. M. V. Avila, L. R. Marcelino, J. S. Negreiros Jr, D. N. S. Cavalcante, F. T. C. B. Magalhães, A. C. Ferreira, A. S. B. Sombra

Abstract — **In this work, we present a numerical study to investigate the transmission, extinction ratio and crosstalk outputs of a Mach-Zehnder Interferometer in Photonic Crystal Fibers by varying the nonlinearity parameter of the fiber from β = 1 (linear profile) to β = 2 (double value) for three different nonlinearity profiles (constant, increasing and decreasing) and discussing one scenario (P_0 = 110 kW). We observed that the highest transmission (T = 67%), the highest extinction ratio (XR = 3.57 dB) and the lowest crosstalk (Xtalk = -5.25 dB) occurred in the third scenario (Po = 110 kW > Pc) considering the decreasing profile for β = 1.35. Such condition enables applications such as TDMA and logic circuits.**

Keywords **— Mach-Zehnder Interferometer; photonic crystal fibers; nonlinear switching.**

I. Introduction

Photonic crystal fibers (PCFs) have been widely used for several applications. PCFs with multiple cores might have an important role in power switching networks consisting of optical fibers. In this context, several approaches have been adopted in order to analyze the process of power switching between the N optical cores present in the structure.

The Mach–Zehnder Interferometer (MZI) has been used for many applications, such as for obtaining well-known optical logic gates [1], as well as for all-optical modulators from a symmetrical MZI in a schema of nonlinear porous silicon [2] and for all-optical delay flip-flop by using two quantum semiconductor dots (QD-SOA) assisted through MZI's [3].

In this work, we used a photonic crystal fiber instead of a conventional fiber, which is more used for obtaining non-linear effects, and performed an analysis of the behaviour of a Mach Zehnder interferometer by adding different nonlinearity profiles to one of the arms of the device. We analyzed the curves of transmission, extinction ratio, crosstalk and compression factor.

II. Theoretical framework

The mathematical equation which describes light propagation in optical fibers is the nonlinear Schrödinger equation (NLSE) [4] obtained from Maxwell's equations by considering a propagation medium free of charges. In its generalized form, we have equation 2.1.

$$\frac{\partial A}{\partial z}+\frac{\alpha}{2}A+\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-i\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=i\gamma\left(|A|^2\right)+i\frac{\gamma}{\omega}\frac{\partial(|A|^2 A)}{\partial t}-\gamma A T_R\frac{\partial |A|^2}{\partial t} \tag{2.1}$$

In this work, we applied the NLSE described in (2.1) to femtosecond pulses (~10^{-15} s). Since equation (2.1) does not accept an analytical solution, a numerical approximation is necessary for the understanding of the nonlinear effects in optical fibers.

The equations expressing the evolution of an electromagnetic field in a nonlinear coupler with higher order effects are given by equation 2.2, which represent the two arms of the coupler [5]. This equation is said as nonlinear coupled mode and do not distinguish the orthogonal polarization modes of the fiber [4].

$$i\frac{\partial A_1}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 A_1}{\partial t^2}-i\frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial t^3}+\frac{\beta_4}{24}\frac{\partial^4 A_1}{\partial t^4}+\gamma\left(|A_1|^2+\eta|A_2|^2\right)A_1+i\frac{\gamma}{\omega}\frac{\partial(|A_1|^2 A_1)}{\partial t}$$
$$-\gamma A_1 T_R\frac{\partial |A_1|^2}{\partial t}+k_0 A_2+ik_1\frac{\partial A_2}{\partial t^2}=0 \tag{2.2}$$

III. Numerical procedure

We used an ultrashort pulse of 100 fs as the input through channel 1 of the device, whereas the other input (channel 2) receives no light. The pulse has a hyperbolic secant shape. We used the 4th-order Runge-Kutta method for simulations [6].

The study was based on the analysis of power transmission and extinction rate, focusing on channel 4 of the output device.

The extinction ratio of a switching on–off device is calculated as the output power in on-state (channel 4) over the output power in the off-state (channel 3) or vice-versa.

The crosstalk (XTalk) denotes the presence of an unwanted signal due to some coupling mechanism between the disturbed and disturbing channels. For a proper device operation, Xtalk must be kept at a minimum.

We analyze the two-core PCF considered given by the equation (2.2), where the air-hole diameter d = 2.0 μm, the hole-to-hole distance Λ = d/0.9, the core separation C = 2Λ and the coupling length L_c = 1.8 cm. The corresponding parameters for (2.2 and 2.3) are $\beta_2 = -47$ ps^2/Km, $\beta_3 = 0.1$ ps^3/Km, $\gamma=3.2\times10^{-3}$ (Wm)$^{-1}$ and $\gamma/\omega = 1.44\times10^{-2}$ s/(Wm). The carrier wavelength is λ = 1.55 nm and the coupling coefficient is $k_0 = 82.8$(m)$^{-1}$ for our simulations.

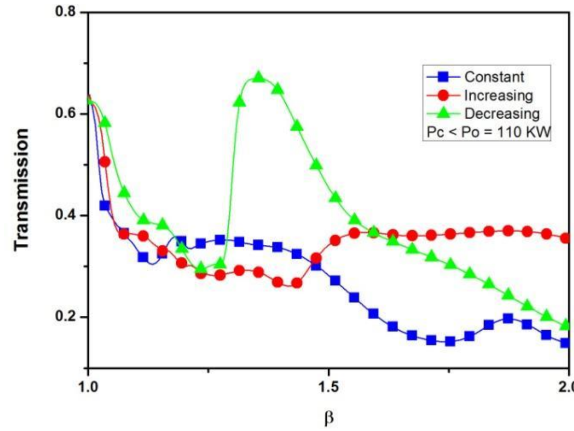
In the next section, we will discuss all the results obtained for P_0 = 110 kW, which presented the best results. We analyzed the results based on all parameters and considering the three nonlinearity profiles (constant, increasing and decreasing), taking into consideration the region where β ranges from 1 to 2.

IV. RESULTS AND DISCUSSION

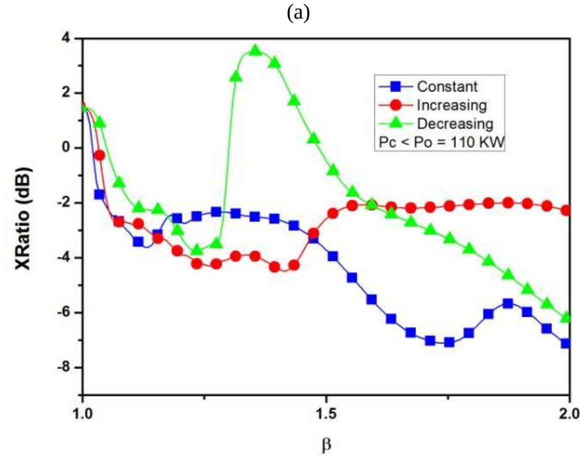
In Figure 1 (a, b and c), we analyze, respectively, the transmission (T), extinction ratio (XR) and crosstalk (Xtalk) for the third scenario (P_0 = 110 kW), in which the power input is above the critical power.

We observed that the value of β = 1.35 was significantly representative for the decreasing profile regarding the critical points of interest, denoting the highest transmission (T = 0.67), as well as the highest extinction ratio (XR = 3.53 dB) and the lowest crosstalk (Xtalk = -5.28 dB). On the other hand, the values of β = 1.74 and β = 2 showed similar outputs for the constant profile and represented the opposite peaks, presenting the lowest transmission (T = 0.14), as well as the lowest extinction ratio (XR = -7.23 dB) and the highest crosstalk (Xtalk = -1.07 dB). In order to find the most suitable case for enabling the generation of logic gates, we found the highest variation between peaks of transmission, which occurred for the decreasing profile, for which XR varies from -6.26 dB to 3.53 dB.

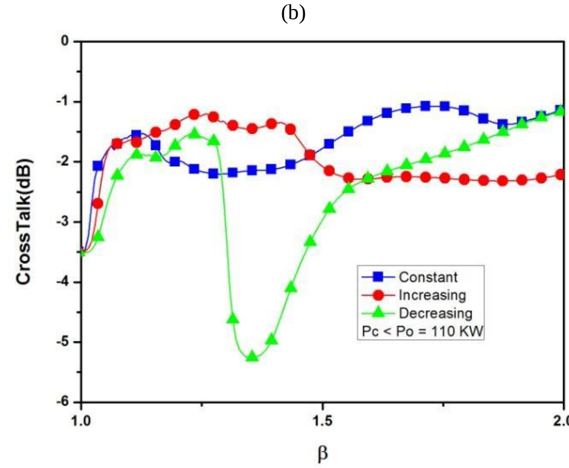
Regarding efficiency, we know that it is inversely proportional to crosstalk. Thus, the lower the crosstalk, the better the efficiency will be, once noise will be then reduced. Therefore, by applying the decreasing profile to this third scenario, in which Po > Pc, we found the best condition for our device, presenting the highest transmission, lowest crosstalk and greatest possibility of generating logic gates.



(a)



(b)



(c)

Figure 1: Results of the third scenario (Po = 110 kW) considering the constant, increasing and decreasing profiles as for (a) transmission; (b) extinction ratio; (c) and crosstalk.

V. CONCLUSIONS

By varying the nonlinearity parameter of a fiber in a Mach-Zehnder Interferometer made of Photonic Crystal Fibers and taking three different linear profiles (constant, increasing and decreasing) and three different scenarios (Po = Pc, Po < Pc and Po > Pc), we investigated the transmission, extinction ratio, crosstalk and compression factor outputs of the device and observed that the highest transmission (T = 67%), the highest extinction ratio (XR = 3.57 dB) and the lowest crosstalk (Xtalk = -5.25 dB) occurred in the third scenario (Po = 110 kW > Pc) when considering the decreasing profile for β = 1.35. Such condition enables applications such as TDMA and logic circuits.

Among the various applications of the device, we highlight the possibility of generating logic gates, given the reasonable extinction ratio when compared to half of the input power, which occurs when |Xr| > 0.4 dB [4].

To sum up, we observed that different nonlinearity profiles enable different behaviors in output, thus we can choose the profile which best fits each application (such as switching, filters in WDM systems, logic gates, all-optical logic systems etc.).

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