# Nonlinear Switching Based on Dual-Core Nonlinear Couplers Applied to Soliton and Gaussian Pulse Propagation

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*Abstract*— **In this work, we investigated the optical switching process for two shapes of femtosecond pulses (Soliton and Gaussian) propagating inside a symmetrical dual-core non-linear directional coupler by simulating their propagation via the coupled non-linear Schrödinger equations. In all simulations, we considered the dispersive effects of second and third order, besides the self-phase modulation, self-steepening non-linear effects and added Raman scattering. The critical power increased for a Raman factor varying from 1 to 10 fs, and the two pulse shapes reached thresholds above 150 W from a 5 fs factor.**

*Keywords* — **dual-core nonlinear fiber directional coupler, Gaussian, soliton pulse, Raman effect, optical switching.**

## I. INTRODUCTION

THE continuous development of optical devices has opened up new possibilities for research in nonlinear optics. Optical devices may be used for various applications such as sensing, communications in optical networks, optical telemetry in medical applications, optical modulators and optical encryption [1].

Some authors have been studying nonlinear effects in couplers for all-optical switching, by enabling high-order effect of Intrapulse Raman Scattering (IRS) [2] and others studied the nonlinear effect of cross-phase modulation (XPM) [3]. The study of optical devices has been increasingly necessary in nonlinear optics, enabling several studies on the relaxation of Kerr nonlinearity and optical switching [4]. Not long ago, the authors in [5] studied a dynamic behaviour of the ultrashort pulse propagation in erbium-doped birefringent fibre systems, which were based on coupled higher order nonlinear Schrödinger–Maxwell–Bloch equations.

The authors in [2] conducted a study on dual-core nonlinear directional couplers based on the propagation of a femtosecond pulse by considering high order effects such as third-order dispersion (TOD) and self-steepening (SS) [2]. Based on the importance of the effects of intrapulse Raman scattering, we investigated this effect in depth in this paper. To the best knowledge of the scientific community, our contribution in this paper is to analyse intrapulse effects of Raman scattering with other mentioned effects. Thus, we analysed in this paper the SS, TOD and intrapulse effects of Raman scattering on dual-core symmetric nonlinear directional couplers. We studied the nonlinear switching in view of the possible use of these devices in optical networks.

## II. THEORETICAL FRAMEWORK

In this work, we analyzed the optical switching process considering soliton and Gaussian femtosecond pulses propagating through a symmetrical dual-core nonlinear directional coupler (DNLDC) by simulating their propagation via the coupled nonlinear Schrödinger equations (NLSEs).

The propagation of ultrashort pulses through nonlinear directional couplers can be mathematically operated by a pair of coupled non-linear Schrödinger equations (CNLSEs), which are given in [6] as Eq.1 and 2.

$$\frac{\partial A_1}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 A_1}{\partial T^2} - \frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial T^3} - i\kappa_0 A_2 + \kappa_1 \frac{\partial A_2}{\partial T} = i\gamma\left(|A_1|^2 A_1 + \frac{i}{\varpi_0}\frac{\partial}{\partial T}(|A_1|^2 A_1) + \xi |A_2|^2 A_1 - T_R A_1 \frac{\partial |A_1|^2}{\partial T}\right) \quad (1)$$

$$\frac{\partial A_2}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 A_2}{\partial T^2} - \frac{\beta_3}{6}\frac{\partial^3 A_2}{\partial T^3} - i\kappa_0 A_1 + \kappa_1 \frac{\partial A_1}{\partial T} = i\gamma\left(|A_2|^2 A_2 + \frac{i}{\varpi_0}\frac{\partial}{\partial T}(|A_2|^2 A_2) + \xi |A_1|^2 A_2 - T_R A_2 \frac{\partial |A_2|^2}{\partial T}\right) \quad (2)$$

where $A_1$ and $A_2$ are the field amplitudes that slowly vary with time propagating through core 1 and core 2, respectively, and the nonlinear parameter $\gamma$ is defined as $\gamma = 2\pi n_2/ \lambda_0 A_{eff}$, $n_2$ is the nonlinear refractive index, $\lambda$ is the optical wavelength, $A_{eff}$ is the effective area of the core and $\beta_2$ and $\beta_3$ are the second and third-order dispersion coefficients, respectively. The term containing $1/\omega_0$ is related to the self-steepening effect, TR is the factor responsible for Raman scattering and $\kappa_0$ and $\kappa_1$ are, respectively, the linear and the intermodal coupling coefficients.

## III. NUMERICAL PROCEDURE

In all simulations, we considered second and third-order dispersion and self-phase modulation (SPM) and self-steepening nonlinear effects. We studied each of the two pulse shapes adding only Raman scattering. We highlight that the study was performed for distinct polarization modes and different values of the Raman factor, as well as power range varying from 1 W to 300 W.

We consider soliton and Gaussian pulses with $T_0$ of 25 fs , where $T_0$ is the half-width, propagating through a nonlinear directional optical coupler.

By using Matlab software, we numerically solved the nonlinear coupled systems (equations 1-2) by using Runge-Kutta method of fourth order, numerically spaced from $\tau$ = -1ps to $\tau$ = 1ps, considering the initial conditions given by the equations above.

We numerically analysed the signal transmission through the NLDC in function of an input power. The switching efficiency of a nonlinear coupler can be measured through the optical power transmission coefficient. Nonlinear switching is the process of continuous energy distribution between the cores for a given input power. Therefore, the transmission characteristics of these devices are determined by the power of the input signal. By increasing the input power above a critical level, the incoming signal can be switched from one core to the other depending on the optical power level.

The values of the coefficients used in equations 1 and 2 for the numerical simulation are: $\beta_2 = -20$ ps$^2$/Km, $\beta_3 = 0.108$ ps$^3$/Km, $n_2$ = 2.35 x 10-20 m$^2$/W, $A_{eff}$ = 55 µm$^2$, $\gamma$ = 1000 W$^{-1}$km$^{-1}$, $\kappa_0$ = 0.032 km$^{-1}$ e $\kappa_1$ = 0 and the wavelength $\lambda$ = 1.55 µm. We varied the Raman factor (TR) from 1 fs to 10 fs.

## IV. Results and Discussion

Although there are some studies on nonlinear switching in optical coupler, none of them has compared the switching of the different ultrashort pulse shapes analysed in this work considering the contribution of Raman nonlinear effects, which was the main contribution of this work.

As a result, we found that, in general, by increasing the input power, the analysed pulses present similar behaviour regarding the pulse evolution, although they present different switching critical power thresholds. The soliton and Gaussian pulses present critical powers close to each other.

In Figure 1, we note that, without Raman effects, the critical power is reached at 113.72 W for the soliton pulse and at 111.49 W for the Gaussian pulse.

When considering the Raman effect, as shown in Figure 2, we can note that the critical power threshold increases as the Raman factor grows, but it saturates from a 5 fs factor for the Gaussian and soliton pulse shapes. On the other hand, these pulse shapes have almost the same values, and near 4 fs the three pulses have a similar power. From 5 fs on, thresholds have a more significant growth.

## V. Conclusions

By adding the IRS effect, we found the critical power threshold increases as the Raman factor grows, but it saturates from a 5 fs factor for the Gaussian and soliton pulse shapes. However, these pulse shapes have almost the same values, and near 4 fs the three pulses have a similar power threshold. From 5 fs on, threshold values have a more significant growth, especially for the Gaussian pulse shape.

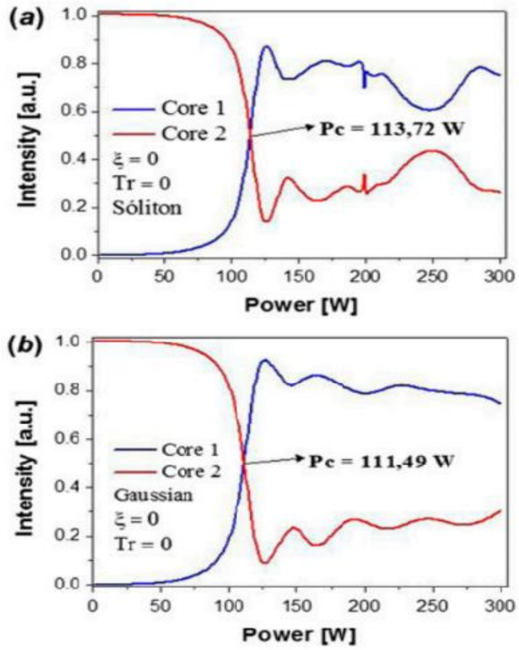


Fig. 1. The two types of pulses with no Raman effects (a) Soliton (b) Gaussian

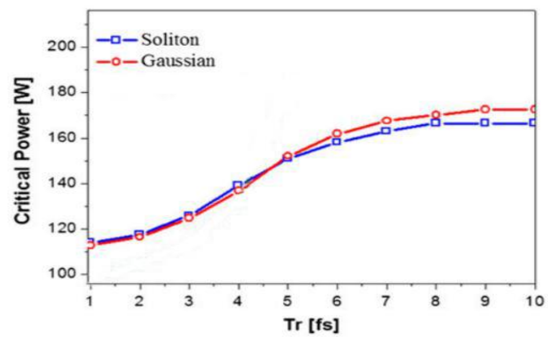


Fig. 2. Soliton and Gaussian pulses with SS, TOD and Raman effects.

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