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Modelling a nonlinear optical switching in a standard photonic crystal fiber infiltrated with carbon disulfide

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ABSTRACT

In this letter, a numerical analysis is developed for the propagation of ultrafast optical pulses through a standard photonic crystal fiber (PCF) consisting of two infiltrated holes using carbon disulfide (CS_2). This material is a good choice since it has highly nonlinear properties, what makes it a good candidate for optical switching and broadband source at low power compared to traditional nonlinear fiber coupler. Based on supermodes theory, a set of generalized nonlinear equations is presented in order to study the propagation characteristics. It is shown in this letter that it is possible to get optical switching behavior at low power and how the dispersion, as well as, the two infiltrated holes separation influence this effect. Finally, we see that supercontinuum generation can be induced equally in both infiltrated holes despite no initial excitation at one hole.

1. Introduction

The study of nonlinear pulse propagation in fiber optics has brought several applications in the fields of telecommunication [1], optical metrology [2], ultrafast coherence spectroscopy [3], biological processes [4], and ultrafast optical switching [5]. The latter has been studied in fiber couplers made mainly of silica [6]. Nonlinear propagation techniques have permitted the design of tunable ultrafast laser sources [7] and optical nonlinear switching. In nonlinear ultra-short pulse propagation, several processes are involved such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), modulation instability (MI), soliton fission, dispersive wave (DW) generation, and Raman scattering [8]. All these effects can contribute to the creation of new frequencies within the pulse spectrum. Numerous optical pulse propagation methods have been studied to obtain a better understanding of the mechanisms for which it is possible to generate supercontinuum (SC) efficiently. Among these methods, the use of photonic crystal fiber (PCF) has attracted a lot of interest because of its highly nonlinear optical characteristics [9,10]. In general, the development of photonic devices has been highly promoted because of its fast performance and high signals transmission rates [1]. In addition, PCF has been selectively infiltrated with toluene, carbon tetrachloride, and carbon disulfide to study both theoretically and experimentally the generation of SC [11–14]. In order to couple light into just one of the infiltrated hole, one can use the two-photon direct laser writing technique [11]. However, nonlinear switching behavior in anomalous dispersion regime has not been analyzed in this type of structure [15,16], and this one is indeed the main focus of the paper.

Mode coupling theory is used to understand nonlinear switching behavior, where coupling coefficients are required to be calculated. This computation usually demands high numerical effort [6,17]. The supermode theory offers an alternative more efficient because it is not necessary to apply the direct calculation of coupling coefficients [18]. Therefore, numerical computation is faster and easier. In supermode theory, it is known that the intermodal dispersion arises from the fact that a directional coupler is actually a bimodal structure, which is able to support two normal modes: symmetric (even mode), and antisymmetric (odd mode); commonly named supermodes [18].

In this work we present a set of generalized nonlinear supermode equations which include the Raman response applied to fiber coupler. Three different infiltration cases are numerically studied, where optical switching behavior is proven at low power, making easier its implementation. Finally, supercontinuum generation can be achieved almost equally in both infiltrated holes regardless initial excitation at one hole.

2. Nonlinear super-mode propagation

When optical power in a directional coupler is high enough and ultrashort pulses are used, the nonlinearity effects become important. Then, power switching between two fiber cores gets nonlinearity dependent. We implemented the supermode theory

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to analyze the nonlinear pulse propagation coupling, and the energy transfer from one to another infiltrated hole. In the coupler, the total electric field can be written as a superposition of the even $(+)$ and odd $(-)$ supermodes [19]. That is: $E(x, y, z, t) = E_+ + E_- = A_+(z, t)\psi_+(x, y)\exp(i\beta_+ z) + A_-(z, t)\psi_-(x, y)\exp(i\beta_- z)$, where $A_+(z, t)$ and $A_-(z, t)$ are the slowly varying envelopes, $\psi_+(x, y)$, and $\psi_-(x, y)$ are the normalized mode fields, and β_+, and β_- are the propagation wavenumber for even $(+)$ and odd $(-)$ supermodes, respectively.

Usually, the nonlinear changes in the refractive index in a directional coupler does not change significantly the cross-sectional distributions of the mode fields (only the phase of the wave is affected). The function of the nonlinear coupler can still be described by the beating between the even, and the odd supermodes of the structure as in the linear case, but with the difference of the refractive index seen by one supermode is modified by the intensity in the other supermode due to the nonlinearity. The nonlinear coupling propagation equations are given in [20,18] for the even and odd supermodes. But, they just include the Kerr effect. Based on [20,18,8] and employing the slowly varying envelope approximation and using the following wave equation we get,

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \frac{1}{c}\frac{\partial^2}{\partial t^2}\int_{-\infty}^{\infty}\chi^{(1)}(t - t')E(t')\,dt' = \frac{3\chi^{(3)}\gamma}{4c^2}\frac{\partial^2}{\partial t^2}(|E|^2 E) \tag{1}$$

where c is the speed of light, $\chi^{(n)}$ is the susceptibility of n-th order, γ is the reduction factor of the intensity variation in the cross-section [8].

The left hand side can be rewritten as

$$\begin{aligned} &2\beta_+\left[i\left(\frac{\partial A_+}{\partial z} + \frac{\partial \beta_+}{\partial \omega_+}\frac{\partial A_+}{\partial t}\right) - \frac{\partial^2\beta_+}{2\partial\omega_+^2}\frac{\partial^2 A_+}{\partial t^2}\right]\exp\left[i(\beta_+ z - \omega_+ t)\right] \\ &+ 2\beta_-\left[i\left(\frac{\partial A_-}{\partial z} + \frac{\partial \beta_-}{\partial \omega_-}\frac{\partial A_-}{\partial t}\right) - \frac{\partial^2\beta_-}{2\partial\omega_-^2}\frac{\partial^2 A_-}{\partial t^2}\right]\exp\left[i(\beta_- z - \omega_- t)\right] \end{aligned} \tag{2}$$

The Raman contribution to the nonlinear refractive index can be included into the wave equation replacing the right hand side of wave equation as

$$\frac{3\chi^{(3)}\gamma}{4c^2}\frac{\partial^2}{\partial t^2}\left[\left(\left(1 - f_R\right)|E|^2 + f_R\int_{-\infty}^{t} h_m(t)|E(z, t')|^2\,dt'\right)E\right] \tag{3}$$

where $f_R = 0.89$ is the fractional Raman contribution. The Raman response is $h_m(t) = 0.5048\exp(-t/\tau_{diff})(1 - \exp(-t/\tau_{rise})) + 0.8314\exp(-t/\tau_{int})(1 - \exp(-t/\tau_{rise})) + 1.633\exp(-\alpha'^2 t^2/2)\ \sin(\omega_0 t)$, where $\tau_{diff} = 1.68$ ps, $\tau_{rise} = 0.14$ ps, $\tau_{int} = 0.4$ ps, $\alpha' = 5.4\ \text{ps}^{-1}$, and ω_0 is the initial frequency [13]. Replacing the electric field in Eq. (3) and after some mathematical manipulation, we can show that the nonlinear equations can be generalized according to

$$\begin{aligned} &\frac{\partial A_\pm}{\partial z} + \beta_{1\pm}\frac{\partial A_\pm}{\partial T} + \sum_{k\geq 2}^{n} i^k\frac{\beta_{k\pm}}{k!}\frac{\partial^k A_\pm}{\partial T^k} + \frac{\alpha_\pm}{2}A_\pm \\ &= i\gamma_\pm\left[1 + i\tau_{shock}\frac{\partial}{\partial T}\right]\left[\left(1 - f_R\right)\left(\left(|A_\pm|^2 + 2|A_\mp|^2\right)A_\pm + A_\pm^* A_\mp^2\exp(\mp i4Cz)\right)\right. \\ &+ f_R\int_0^t d\eta h_m\left(\eta\right)\left(\left(\left|A_\pm(z, t-\eta)\right|^2 + \left|A_\mp(z, t-\eta)\right|^2\right)A_\pm\left(z, t\right)\right. \\ &+ A_\pm\left(z, t-\eta\right)A_\mp^*\left(z, t-\eta\right)A_\mp\left(z, t\right) + A_\mp\left(z, t-\eta\right)A_\pm^*\left(z, t-\eta\right) \\ &\left.\left.A_\mp\left(z, t\right)\times\exp(\mp i4Cz)\right)\right] \end{aligned} \tag{4}$$

where $\tau_{shock} = 1/\omega_0$, $\beta_{k\pm}$ and $\gamma_\pm = \omega_0 n_2/cA_{eff}$ are the dispersion parameters and nonlinear coefficient for even and odd supermode, respectively. A_{eff} is the effective area of each supermode, T is the normalized time ($T = t - (\beta_{1+} + \beta_{1-})/2z$), n_2 is the CS_2 nonlinear refractive index, λ is the wavelength, $C = (\beta_+ - \beta_-)/2$ is the coupling coefficient, and α are the losses inside the fiber which will be considered negligible due to that CS_2 does not exhibit absorption in the visible and near infrared region [13]. The propagation constant $\beta_\pm$ was expanded in Taylor series as $\beta_\pm = \beta_{0\pm} + (\omega - \omega_0)\beta_{1\pm} + \frac{1}{2}(\omega - \omega_0)^2\beta_{2\pm} + \ldots$ where $\beta_{k\pm} = \left.\frac{\partial^k\beta_\pm}{\partial\omega^k}\right|_{\omega=\omega_0}$. The total electric field in the coupler can be rewritten in terms of the electric fields at each infiltrated hole E_1 and E_2. That is $E(x, y, z, t) = E_1 + E_2 = A_1(z, t)\psi_1(x, y)\exp(i\beta_0 z) + A_2(z, t)\psi_2(x, y)\exp(i\beta_0 z)$, where $A_{1,2}$ are the slowly varying envelope for the infiltrated holes 1 and 2, respectively. $A_{+,-}$ can be related to $A_{1,2}$ as $A_\pm = \frac{1}{2}(A_1 \pm A_2)\exp(\mp iCz)$.

3. Simulation results and analysis

The Split-Step Fourier method [8] is used to solve numerically the equations equations 4. Two holes are infiltrated in a PCF with CS_2 [13]. Three cases are under study, see Fig. 1. In the first case, the separation between two infiltrated holes is 4.7 μm, for the second case is 5.4 μm and for the third case the separation is 4.7 μm.

The PCF under study is a standard PCF with a solid core diameter of 2.8 μm, air holes diameter of 2.6 μm, a lattice pitch of 2.7 μm, and total length of 15 cm. The fiber is pumped through an optical pulse with wavelength of $\lambda_0 = 1.55$ μm, width of $T_0 = 100$ fs, and CS_2 nonlinear refractive index $n_2 = 3.1 \times 10^{-19}\ \text{m}^2\ \text{W}^{-1}$ [13]. The dispersion (see Fig. 2), and nonlinear coefficient are numerically calculated using finite element method for both even and odd supermodes by using the commercial software COMSOL®. At λ_0, for case 1, $\gamma_\pm \approx 2.4226\ \text{W}^{-1}/\text{m}$ and for case 2, $\gamma_\pm \approx 1.6367\ \text{W}^{-1}/\text{m}$.

We set $A_1(0, 0) = \sqrt{P_0}$ (core 1) and $A_2(0, 0) = 0$ (core 2), where P_0 is the initial peak power. The nonlinear coupling length (L_{NC}) is define as the length at which the energy starts considerably to be transferred from core 1 to core 2. Fig. 3 shows the time and spectral evolution for case 1 at $P_0 = 230$ W. For this situation, soliton formation is given in core 1, while significant energy start to appear in core 2 at around 10 cm and the spectrum spread out at the end of fiber length. We will discuss about this later on. After defined L_{NC}, variations of L_{NC} as a function of P_0 are calculated for two case (Fig. 4). The third case is ignored since L_{NC} is not obtained for any P_0. This makes sense due to the fact that; practically, there is no medium which allows the connection between the cores. The zero dispersion ($\beta_2 = 0$) is taken into account because L_{NC} is related to dispersion length (L_D) and can limit the switching behavior due to higher nonlinear order effects are ignored when $L_{NC} \sim \pi/2L_D$. In Fig. 4, the formation of solitons ($\beta_2 < 0$) facilitates the nonlinear coupling (L_{NC}–soliton) at low power, while more P_0 is needed to get the same L_{NC}–soliton when $\beta_2 \geq 0$. Additionally, case 1 exhibits

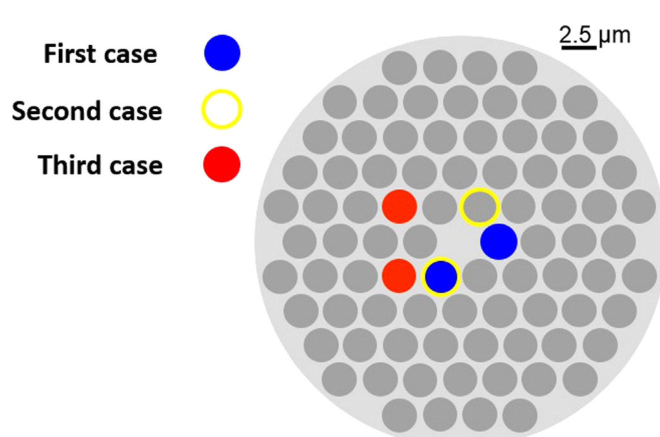

Fig. 1. Study cases for two infiltrated holes with carbon disulfide.