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# Switching of ultrashort pulses in nonlinear high-birefringence two-core optical fibers

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ABSTRACT

We analyze the switching characteristics of ultrashort pulses in a nonlinear high-birefringence two-core optical fiber by solving a set of four generalized coupled nonlinear Schrödinger equations. In such a fiber, the critical power required for activating switching changes significantly with the polarization angle of the input pulse and, as a result, a pulse at a proper power level can be switched between the two cores of the fiber by changing the input polarization angle. This provides a simple mechanism of achieving optical switching with the fiber. We also study the effects of the group-delay difference (GDD) between the two polarization components and the coupling-coefficient dispersion (CCD) in the fiber on the switching characteristics. The GDD tends to break up the two polarization components in the input pulse and thus leads to an increase in the switching power. A larger GDD, however, can give a sharper switching contrast when the input polarization angle is varied. The CCD tends to break up the input pulse and cause pulse distortion, regardless of the polarization, so it also leads to an increase in the switching power. Unlike the GDD, a large CCD always reduces the switching contrast. To achieve high-quality switching, the fiber should have a small CCD.



## 1. Introduction

Nonlinear two-core optical fibers (TCFs) have drawn tremendous attention since the pioneering theoretical work by Jensen in 1982 [1] for their many potential applications in optical signal processing, especially as all-optical switches [2–12]. All-optical switching has been experimentally demonstrated in conventional TCFs [2–5] and, more recently, in a two-core photonic crystal fiber [6] using high-power ultrashort pulse lasers. To avoid pulse distortion caused by the group velocity dispersion (GVD) in the fiber, the use of soliton pulses for optical switching has been proposed [7]. Many other effects on the switching dynamics in TCFs, such as intermodal dispersion [13,14], third-order dispersion [15], and intrapulse Raman scattering [16,17] have been investigated.

A TCF that consists of two identical cores possesses two symmetry axes, and hence the fiber must possess geometry-induced birefringence, which means that the light waves polarized along the two symmetry axes of the fiber propagate at slightly different phase velocities. In addition, because the materials for the cores and the cladding of the fiber have different thermal expansion coefficients, stress-induced birefringence in the fiber is normally produced when the fiber is drawn from the preform at a high temperature. The total birefringence in a TCF is the combined result of the geometry birefringence and the stress birefringence. It is a complicated exercise to analyze a nonlinear birefringent TCF, because four coupled nonlinear equations need to be solved. The majority of the studies on TCFs deal with a simpler problem where the birefringence in the fiber is ignored [1–17]. A zero-birefringence TCF is described by two coupled equations and much more amenable to analytical treatment. There are only a few theoretical studies on birefringent TCFs [18–22], which include an analysis of all-optical continuous-wave (CW) switching [18], a study of soliton states [19] and their stability [20] in the absence of group-delay difference (GDD) between the two polarization components, a numerical investigation of vector soliton pulse switching [21], and a detailed analysis of the modulation instabilities in linearly and circularly birefringent TCFs [22]. In spite of these studies, the role of the birefringence in a TCF in affecting the switching characteristics of ultrashort pulses is yet to be fully understood.

The primary objective of this paper is to study the switching characteristics of a nonlinear high-birefringence (Hi-Bi) TCF with an emphasis on the understanding of the effects of the polarization state of the input pulse. Our analysis is based on numerically solving a set of four generalized coupled nonlinear Schrödinger equations which incorporate the effects of the GDD and the

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coupling-coefficient dispersion (CCD) in the fiber. The significance of these effects on the switching performance of ultrashort pulses is investigated. Our main results are summarized below:

- The critical power required for activating switching changes significantly with the polarization angle. This makes possible the realization of polarization-activated switching, where a pulse at an appropriate power level is switched between the two cores by varying the polarization angle.
- The GDD increases the switching power and is undesirable for power-controlled switching. However, it increases the switching contrast for polarization-activated switching.
- The CCD increases the switching power and reduces the switching contrast, and should be minimized for both power-controlled and polarization-activated switching.

Modern TCFs based on photonic crystal structures can be designed to possess strong birefringence by adjusting the arrangement and the size of the air holes around the core region [23]. A study of all-optical switching in such fibers must take into account the effects of the birefringence. In fact, the recent experimental demonstration of all-optical switching in a 9-mm long two-core photonic crystal fiber using 120-fs laser pulses (at a wavelength around 1550 nm with peak intensity up to a few TW/cm$^2$) exhibits significant polarization dependence [6]. With such ultrashort pulses, the effects of the GDD and the CCD in the fiber, both of which tend to break up the pulses, are expected to be important. The findings in this paper can provide insight into the switching behavior of a Hi-Bi TCF and thus facilitate the design of fibers and experiments to demonstrate the polarization-activated switching effects.

## 2. Coupled-mode equations

We consider a lossless TCF with two identical single-mode cores aligned in the $x$ direction, where the light waves in the fiber propagate in the $z$ direction. Because of the presence of the birefringence in the fiber, there are two orthogonal polarization modes in each core, the $x$-polarization mode and the $y$-polarization mode, which propagate along the fiber at different phase velocities. A pulse with an arbitrary polarization state launched into one of the cores can be decomposed into the two principal polarization components. The propagation of the pulse in such a fiber is described by the following coupled nonlinear Schrödinger equations, which can be obtained by extending the existing equations for TCFs [7–11]

$$
\begin{aligned}
&i\left(\frac{\partial a_{1x}}{\partial z}+\beta_{1x}\frac{\partial a_{1x}}{\partial t}\right)-\frac{1}{2}\beta_{2x}\frac{\partial^2 a_{1x}}{\partial t^2}+\gamma_x\left(|a_{1x}|^2+\frac{2}{3}|a_{1y}|^2\right)a_{1x}\\
&\quad+\frac{\gamma_x}{3}a_{1y}^2a_{1x}^*\exp\left[-2i\left(\beta_{0x}-\beta_{0y}\right)z\right]+C_xa_{2x}+iC_{1x}\frac{\partial a_{2x}}{\partial t}=0,\\
&i\left(\frac{\partial a_{2x}}{\partial z}+\beta_{1x}\frac{\partial a_{2x}}{\partial t}\right)-\frac{1}{2}\beta_{2x}\frac{\partial^2 a_{2x}}{\partial t^2}+\gamma_x\left(|a_{2x}|^2+\frac{2}{3}|a_{2y}|^2\right)a_{2x}\\
&\quad+\frac{\gamma_x}{3}a_{2y}^2a_{2x}^*\exp\left[-2i\left(\beta_{0x}-\beta_{0y}\right)z\right]+C_xa_{1x}+iC_{1x}\frac{\partial a_{1x}}{\partial t}=0,\\
&i\left(\frac{\partial a_{1y}}{\partial z}+\beta_{1y}\frac{\partial a_{1y}}{\partial t}\right)-\frac{1}{2}\beta_{2y}\frac{\partial^2 a_{1y}}{\partial t^2}+\gamma_y\left(|a_{1y}|^2+\frac{2}{3}|a_{1x}|^2\right)a_{1y}\\
&\quad+\frac{\gamma_y}{3}a_{1x}^2a_{1y}^*\exp\left[2i\left(\beta_{0x}-\beta_{0y}\right)z\right]+C_ya_{2y}+iC_{1y}\frac{\partial a_{2y}}{\partial t}=0\\
&i\left(\frac{\partial a_{2y}}{\partial z}+\beta_{1y}\frac{\partial a_{2y}}{\partial t}\right)-\frac{1}{2}\beta_{2y}\frac{\partial^2 a_{2y}}{\partial t^2}+\gamma_y\left(|a_{2y}|^2+\frac{2}{3}|a_{2x}|^2\right)a_{2y}\\
&\quad+\frac{\gamma_y}{3}a_{2x}^2a_{2y}^*\exp\left[2i\left(\beta_{0x}-\beta_{0y}\right)z\right]+C_ya_{1y}+iC_{1y}\frac{\partial a_{1y}}{\partial t}=0.
\end{aligned}
\tag{1}
$$

In the above equations, $a_{jp}$ ($j=1$, 2 and $p=x$, $y$), a function of $z$ and $t$, is the slowly varying amplitude of the electric field of the $p$-polarization mode in the $j$-th core; $z$ and $t$ are the distance and time coordinates, respectively; $\beta_{0p}$ is the propagation constant of the $p$-polarization mode; $\beta_{1p}$ is the group delay of the $p$-polarization mode; $\beta_{2p}$ is the GVD with $\beta_{2p}<0$ and $\beta_{2p}>0$ for anomalous and normal dispersion, respectively; $\gamma_p$ is the nonlinear coefficient of the $p$ polarization; $C_p$ is the linear coupling coefficient of the $p$ polarization, which is responsible for the periodic power transfer between the two cores in a linear TCF; $C_{1p}=\mathrm{d}C_p/\mathrm{d}\omega$, evaluated at the optical carrier frequency of the pulse, represents the coupling-coefficient dispersion (CCD), which is equivalent to the intermodal dispersion arising from the group delay difference in the $p$ polarization between the even and odd supermodes of the TCF [24,25]. The first and second nonlinear terms in each of the above equations account for the self-phase modulation (SPM) and cross-phase modulation (XPM) effects, respectively. The third nonlinear term comes from the nonlinear coherent coupling between the two orthogonal polarization components in each core.

In the case that the birefringence in the fiber, namely $|\beta_{0x}-\beta_{0y}|$, is large, the nonlinear coherent coupling term oscillates rapidly along the propagation direction and its contribution is averaged out to zero [18], which suggests that this term can be ignored for a Hi-Bi TCF. In practice, the polarization dependences of the GVD, the nonlinearity coefficient, and the coupling coefficient dispersion, are weak, so we can put $\beta_{2x}=\beta_{2y}\equiv\beta_2$, $\gamma_x=\gamma_y\equiv\gamma$, $C_x=C_y\equiv C$, and $C_{1x}=C_{1y}\equiv C_1$. With these assumptions, Eq. (1) is simplified to the following set of equations:

$$
\begin{aligned}
&i\left(\frac{\partial a_{1x}}{\partial z}+\beta_{1x}\frac{\partial a_{1x}}{\partial t}\right)-\frac{1}{2}\beta_2\frac{\partial^2 a_{1x}}{\partial t^2}+\gamma\left(|a_{1x}|^2+\frac{2}{3}|a_{1y}|^2\right)a_{1x}+Ca_{2x}+iC_1\frac{\partial a_{2x}}{\partial t}=0,\\
&i\left(\frac{\partial a_{2x}}{\partial z}+\beta_{1x}\frac{\partial a_{2x}}{\partial t}\right)-\frac{1}{2}\beta_2\frac{\partial^2 a_{2x}}{\partial t^2}+\gamma\left(|a_{2x}|^2+\frac{2}{3}|a_{2y}|^2\right)a_{2x}+Ca_{1x}+iC_1\frac{\partial a_{1x}}{\partial t}=0,\\
&i\left(\frac{\partial a_{1y}}{\partial z}+\beta_{1y}\frac{\partial a_{1y}}{\partial t}\right)-\frac{1}{2}\beta_2\frac{\partial^2 a_{1y}}{\partial t^2}+\gamma\left(|a_{1y}|^2+\frac{2}{3}|a_{1x}|^2\right)a_{1y}+Ca_{2y}+iC_1\frac{\partial a_{2y}}{\partial t}=0,\\
&i\left(\frac{\partial a_{2y}}{\partial z}+\beta_{1y}\frac{\partial a_{2y}}{\partial t}\right)-\frac{1}{2}\beta_2\frac{\partial^2 a_{2y}}{\partial t^2}+\gamma\left(|a_{2y}|^2+\frac{2}{3}|a_{2x}|^2\right)a_{2y}+Ca_{1y}+iC_1\frac{\partial a_{1y}}{\partial t}=0.
\end{aligned}
\tag{2}
$$

By introducing the normalized parameters

$$
Z=\frac{z}{L_D},\quad T=\frac{1}{T_0}\left[t-\left(\frac{\beta_{1x}+\beta_{1y}}{2}\right)z\right],\quad A_{jp}=\sqrt{\gamma L_D}a_{jp},\quad L_D=\frac{T_0^2}{|\beta_2|},
$$

where $T_0$ is a characteristic width of the input pulse and $L_D$ is the dispersion length, Eq. (2), assuming anomalous GVD ($\beta_2<0$), can be expressed in the normalized form

$$
\begin{aligned}
&i\left(\frac{\partial A_{1x}}{\partial Z}+\delta\frac{\partial A_{1x}}{\partial T}\right)+\frac{1}{2}\frac{\partial^2 A_{1x}}{\partial T^2}+\left(|A_{1x}|^2+\frac{2}{3}|A_{1y}|^2\right)A_{1x}+RA_{2x}+iR_1\frac{\partial A_{2x}}{\partial T}=0,\\
&i\left(\frac{\partial A_{2x}}{\partial Z}+\delta\frac{\partial A_{2x}}{\partial T}\right)+\frac{1}{2}\frac{\partial^2 A_{2x}}{\partial T^2}+\left(|A_{2x}|^2+\frac{2}{3}|A_{2y}|^2\right)A_{2x}+RA_{1x}+iR_1\frac{\partial A_{1x}}{\partial T}=0,\\
&i\left(\frac{\partial A_{1y}}{\partial Z}-\delta\frac{\partial A_{1y}}{\partial T}\right)+\frac{1}{2}\frac{\partial^2 A_{1y}}{\partial T^2}+\left(|A_{1y}|^2+\frac{2}{3}|A_{1x}|^2\right)A_{1y}+RA_{2y}+iR_1\frac{\partial A_{2y}}{\partial T}=0,\\
&i\left(\frac{\partial A_{2y}}{\partial Z}-\delta\frac{\partial A_{2y}}{\partial T}\right)+\frac{1}{2}\frac{\partial^2 A_{2y}}{\partial T^2}+\left(|A_{2y}|^2+\frac{2}{3}|A_{2x}|^2\right)A_{2y}+RA_{1y}+iR_1\frac{\partial A_{1y}}{\partial T}=0,
\end{aligned}
\tag{3}
$$

with

$$
\delta=\frac{\beta_{1x}-\beta_{1y}}{2|\beta_2|}T_0=\mathrm{sgn}(\beta_{1x}-\beta_{1y})\frac{L_D}{2L_{WG}},\tag{4}
$$

$$
R=\frac{C}{|\beta_2|}T_0^2=\frac{\pi L_D}{2L_C},\tag{5}
$$

and

$$
R_1=\frac{C_1}{|\beta_2|}T_0=\mathrm{sgn}(C_1)\frac{L_D}{2L_{WC}},\tag{6}
$$