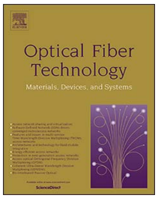
Optical Fiber Technology 42 (2018) 39–49

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte



Regular Articles

Nonlinear performance of asymmetric coupler based on dual-core photonic crystal fiber: Towards sub-nanojoule solitonic ultrafast all-optical switching

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ARTICLE INFO

Keywords:
Dual-core photonic crystal fiber
Soft glass
Asymmetric coupler
Ultrafast soliton fission
All-optical switching
Coupled generalized nonlinear Schrödinger equation

ABSTRACT

We demonstrate ultrafast soliton-based nonlinear balancing of dual-core asymmetry in highly nonlinear photonic crystal fiber at sub-nanojoule pulse energy level. The effect of fiber asymmetry was studied experimentally by selective excitation and monitoring of individual fiber cores at different wavelengths between 1500 nm and 1800 nm. Higher energy transfer rate to non-excited core was observed in the case of fast core excitation due to nonlinear asymmetry balancing of temporal solitons, which was confirmed by the dedicated numerical simulations based on the coupled generalized nonlinear Schrödinger equations. Moreover, the simulation results correspond qualitatively with the experimentally acquired dependences of the output dual-core extinction ratio on excitation energy and wavelength. In the case of 1800 nm fast core excitation, narrow band spectral intensity switching between the output channels was registered with contrast of 23 dB. The switching was achieved by the change of the excitation pulse energy in sub-nanojoule region. The performed detailed analysis of the nonlinear balancing of dual-core asymmetry in solitonic propagation regime opens new perspectives for the development of ultrafast nonlinear all-optical switching devices.

1. Introduction

Photonic crystal fiber (PCF) research after its great advancement in the last two decades still bears inspiring innovation potential in various disciplines of applied optics such as signal processing and telecommunications. Especially, multi-core PCFs are exciting media for temporal-spatial-spectral optical field transformations due to the possibility of tailoring of their dispersion, coupling and nonlinear optical properties by proper microstructure engineering [1]. Thanks to the coupling between optical fields in individual cores, dual-core PCFs (DC PCFs) can be used as couplers (for example as multiplexers [2]) or all-optical switches [3]. According to the supermode theory, the key parameter characterizing the coupling phenomenon is the coupling length L_C, representing the shortest distance at which the signal is transferred from one core to another in a periodical manner. The coupling length is defined by the formula

$$L_C = \frac{\pi}{|\beta_S - \beta_A|}, \tag{1}$$

where β_S and β_A are propagation constants of the symmetric and antisymmetric supermode, respectively. Supermodes are the fundamental eigenmodes of a dual-core fiber determined by the fiber material and microstructure [4]. The second important parameter of a dual-core fiber coupler is the inter-core coupling represented by an effective coupling coefficient κ_e, depending on the measure of optical asymmetry between the two fiber cores. The higher the asymmetry, the less efficient is the energy transfer between the cores. Effective coupling coefficient κ_e is defined as

$$\kappa_e = \sqrt{\kappa_{12}.\ \kappa_{21} + \delta^2}, \tag{2}$$

where κ_{ij} describes coupling from i-th core to j-th core and δ is propagation constant mismatch between the cores representing the asymmetry. Propagation constant mismatch δ is defined as $\delta = (\overline{\beta}_2 - \overline{\beta}_1)/2$, where $\overline{\beta}_{1,2}$ represent the propagation constants in the individual cores [4].

In practice, it is very difficult to produce ideally symmetric DC PCF [5] and the cores of a dual-core fiber exhibit slightly different effective

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Abbreviations: DC PCF, dual-core photonic crystal fiber; IR, infrared; NLDC, nonlinear directional coupler; SEM, scanning electron microscope; CNLSE, coupled nonlinear schrödinger equation; NLSE, nonlinear schrödinger equation; OPA, optical parametric amplifier; ER, extinction ratio

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https://doi.org/10.1016/j.yofte.2018.02.020
Received 28 November 2017; Received in revised form 3 February 2018; Accepted 23 February 2018

refractive indices n_{eff} causing mismatch of propagation constants. Due to the asymmetry two cores are distinguishable on the base of the propagation constant determining slow ($\overline{\beta}_1$) and fast ($\overline{\beta}_2 < \overline{\beta}_1$) core. The asymmetry prevents effective energy transfer between them, when

$$\delta \geqslant \frac{\sqrt{\pi^2 - 4L_C^2\kappa_{12}\kappa_{21}}}{2L_C} \tag{3}$$

Let us consider positive Kerr nonlinearity typical for the majority of glass materials. In this case, launching pulse with suitable peak-power into the fast core, Kerr-induced phase shift decreases the mismatch between the cores and thus causes balancing of the dual-core asymmetry. The situation reverses when the slow core is excited at the high-power levels: the asymmetry between the cores increases due to the Kerr effect and the cores may become practically uncoupled.

Due to the small inter-core distances enabled by the PCF technology, L_C in the millimeter-range is easily accessible allowing the application of shorter fiber couplers in comparison to the classical dual-core fibers. Coupling properties of dual-core fibers exhibit birefringent character. Thanks to that, control of the intensity ratio between the two output ports (dual-core extinction ratio) by alternating the input polarization direction is possible [6,7]. In nonlinear regime, DC PCFs can be used as nonlinear directional couplers (NLDC) and represent an interesting alternative for all-optical signal processing applications. In the case of single core excitation of ideally symmetric DC PCF with length equal to L_C, low power pulses undergo periodic coupling and exit the fiber from the non-excited core. In contrast, high power pulses with proper peak-intensity level exit predominantly from the excited core because the nonlinearly-induced asymmetry decreases the inter-core coupling efficiency. However, the nonlinear propagation is often associated with pulse deformations, which may deteriorate the nonlinear switching process. Therefore, soliton propagation regime in anomalous dispersion region was suggested for establishing more effective NLDC performance. According to the theory, temporal solitons with proper characteristics remain stable during oscillations between the cores of a dual-core fiber [8], eliminating not only the dispersion, but also the dual-core propagation-caused perturbations. Employing PCF structures, numerous theoretical works analyzed the soliton-based NLDC possibilities, e.g. by designing asymmetric couplers [9], utilizing highly nonlinear glass [10] or suggesting Tbit/s rate all-optical logic components [11,12]. On the other hand, few experimental attempts motivated by the vision of fiber based solitonic NLDC were unsuccessful, mainly due to hardly controllable process of soliton fission, i.e. soliton temporal break-up into its fundamental components, which is inherently present during the nonlinear propagation in anomalous dispersion region [3,13].

Soliton fission is a generally adopted propagation scenario in the case of highly nonlinear PCFs in the anomalous dispersion region [14,15]. According to this concept, high order solitonic pulse breaks up into its fundamental components influenced by high-order perturbation effects. Moreover, subsequently the fundamental components undergo further spectral transformations due to Kerr and Raman nonlinearities typically resulting in broad and structured output spectra, whose complexity depends on the order of the initial soliton. In the case of propagation of low-order soliton in slightly birefringent PCF, nonlinear coupling between two orthogonal polarization components has been studied both theoretically and experimentally [16]. Both approaches confirmed the possibility of energy transfer from the fast to slow polarization component without observation of the opposite effect. This concept is straightforwardly adaptable for the coupling between fast and slow core of an asymmetric dual-core coupler. However, dual-core technology promises to demonstrate similar effect at significantly shorter fiber lengths in comparison to [16], where 2 m of the birefringent PCF was necessary.

Experimental NLDC study using DC PCF made of standard silica was for the first time reported in 2006 [3]. 9 mm long fiber was excited by 120 fs pulses with central wavelength of 1550 nm, localized in the anomalous dispersion region of the fiber. Obtained results revealed only unidirectional switching increasing the dual-core extinction ratio from −11.0 dB to −1.8 dB level applying tens of nanojoule pulse energies. Later on, a nonlinear narrow band true switching has been demonstrated, both in visible [17] and NIR spectral regions [18] at non-excitation wavelengths. The utilized special DC PCF possessed a square microstructure design and was made of soft silicate glass with linear and nonlinear refraction indices similar to standard silica. The fiber had a slight dual-core asymmetry, which altered the switching character depending on the choice of the excited core but its impact on the switching mechanism was negligible [19]. The best switching performance has been achieved with 1650 nm 100 fs excitation pulses using 14 mm long piece of the fiber. The switching wavelengths were shifted about 100 nm from the excitation one [20]. The best switching contrast has been at the level of 15 dB (7 dB vs. −8 dB), which is promising also from the application point of view. On the other hand, demonstrated switching required relatively high pulse energies (tens of nanojoules). Therefore, fiber material with higher nonlinear refractive index would be suitable for achieving switching at lower energies.

Following up on this direction, new generation of DC PCFs was manufactured from similar silicate soft glass however with about 20-times stronger Kerr nonlinearity. At the same time, the fiber possess higher degree of dual-core asymmetry as well. Utilizing these novel specialty fibers, we investigate nonlinear enhancement of the dual-core coupling in femtosecond solitonic propagation regime. Basic optical properties of the novel DC PCFs are presented, followed by the first experimental results of nonlinearly-induced spatial-spectral pulse transformations in these fibers. Excitation wavelength is varied in the 1500–1800 nm spectral region covering the flattened dispersion region (Fig. 1b) in order to study the wavelength effect on the nonlinear dual-core propagation. Experimental findings are supported by the results of dedicated numerical simulations revealing the spectral peculiarities of the studied inter-core energy transfer process.

2. Characterization of the fibers and the methods of their investigation

2.1. Employed fiber characteristics

A new generation DC PCF with hexagonal microstructure and enhanced nonlinear performance potential (Fig. 1a) was self-designed [21]. In–house synthesized highly nonlinear glass (PBG08) with well determined linear and nonlinear properties was used for fabrication of the fiber samples in correspondence to the theoretical optimization process. PBG08 is a lead-bismuth-gallium-oxide glass with composition $SiO_2{-}Bi_2O_3{-}PbO{-}Ga_2O_3{-}CdO$ and with improved transmission in the NIR spectral region. Nonlinear refractive index of this soft glass is $n_{NL} = 4.3 \times 10^{-19} m^2/W$, which is almost 20-times higher than that of fused silica and one of the highest values among other oxide glasses [22]. In addition, PBG08 has more than three-times lower relative Raman contribution coefficient f_R as compared to silica glass, which is beneficial for the stability of dissipative solitons [23].

Two fiber samples with slightly different structure were prepared as outcomes of two separate fiber drawing procedures. The samples are designated as NL37C and NL37D and their geometrical parameters are presented in Table 1. The core size values in the table are referred for the both cores, because they are indistinguishable taking into account the uncertainty of their determination.

After the fabrication, simulation of basic linear characteristics was performed in the case of both samples based on the scanning electron microscope images and dispersion of PBG08. For that purpose, a commercial mode solving software was used, that enables to compute the dispersion characteristics of the fiber supermodes. Additionally, individual core characteristics were calculated, putting an artificial air hole at the place of the opposite core preserving dimensions and