Nonlinear propagation of solitonic pulses in mismatched dual-core highly nonlinear fibers

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We investigate experimentally and theoretically the effect of dual-core propagation constant mismatch on the nonlinear switching mechanism in a dual-core high index-contrast soft glass optical fiber. We focus femtosecond pulses on one core only to identify transitions among inter-core oscillations, self-trapping in the cross core and retaining of the pulse in the straight (excited) core, as governed by the pulse energy. A model based on the system of coupled nonlinear Schrödinger equations reveals the effect of the mismatch parameter and pulse duration on the full picture of the energy dependence in the solitonic propagation scheme. Optimal values of the mismatch and pulse width are selected to ensure stable conditions for effective nonlinear switching performance. The theoretical predictions are in rather good agreement with the experimental results.

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I. INTRODUCTION

The concept of nonlinear directional couplers based on dual-core fibers (DCF) was introduced theoretically in the early 1980s [¹,²]. Since then, considerable efforts were devoted to the characterization and optimization of the device performance [³,⁵]. New perspectives appeared with the advent of the photonic crystal fiber technology, which offers appropriate conditions for efficient coherent spectral broadening, especially in the case of anomalous dispersion [⁶,⁷]. Additionally, some theoretical investigations predicted that the dual-core asymmetry may be advantageous for the nonlinear switching dynamics in the solitonic propagation regime [⁸,¹⁰]. The asymmetry needs to be carefully applied, as too high value of the dual-core effective index mismatch arrests the coupling between the two parallel waveguide [¹¹]. Due to this requirement, fabrication of photonic crystal fibers (PCF) in this kind of system becomes rather challenging. By using the complex PCF technology process is extremely hard to realize DCF structures with sufficiently low asymmetry. As an alternative, recently as a very promising candidate for ultrafast pulse steering a dual-core high-index contrast soft glass optical fiber was proposed [¹²]. The simple cladding of such a fiber surrounding the highly nonlinear core ensures simultaneously high nonlinearity, high field localization, and a low level of dual-core asymmetry at significantly simplified technology [¹³]. In the above-mentioned experiments, also supported by numerical simulations [¹²], the applicability of our approach was demonstrated both in the vicinity of 1700 nm [¹¹] and C-band. However, the asymmetry of the dual-core structure was not investigated experimentally or theoretically. In this work we report new findings, obtained by exciting both fiber cores on the experimental side and introducing an effective refractive index mismatch between them in the frame of the numerical study. The reported results provide an essential step forward in the design of DCFs with an enhanced potential for applications, as multiplexers [¹⁴] and as nonlinear all-optical switches [¹⁵].

II. THEORETICAL MODEL

The model is based on the system of linearly coupled nonlinear Schrödinger equations (NLSEs) [¹⁶-¹⁸], written for complex envelopes $A(z,t)$ of electromagnetic waves in the mismatched cores of the DCF

$$\partial_z A_1 + \beta_{11} \partial_t A_1 + \frac{i\beta_{21}}{2} \partial_{tt} A_1 = i\kappa_{12} A_2 + i\delta_a A_1 + i\gamma_1 |A_1|^2 A_1, \quad (1)$$

$$\partial_z A_2 + \beta_{12} \partial_t A_2 + \frac{i\beta_{22}}{2} \partial_{tt} A_2 = i\kappa_{21} A_1 + i\delta_a A_2 + i\gamma_2 |A_2|^2 A_2. \quad (2)$$
All the coefficients were evaluated at the central frequency $\omega_0$ corresponding to the $\lambda_0 = 1700$ nm of the excitation pulses for the specific fiber cross-section employed in our experimental study using a mode solver from Lumerical. We assume the frequency-independence of the coupling coefficients

$$\kappa_{12} = \frac{k_2^2}{2\beta} \int_{-\infty}^{\infty} (n^2 - n_1^2) F_1^* F_2 dx dy,$$

$$\kappa_{21} = \frac{k_2^2}{2\beta} \int_{-\infty}^{\infty} (n^2 - n_2^2) F_1^* F_2 dx dy,$$

where functions $F_1(x,y)$ and $F_2(x,y)$ are normalized field-distribution profiles of fundamental modes in each core (the normalized condition: $\int_{-\infty}^{\infty} |F_1|^2 dx dy = \int_{-\infty}^{\infty} |F_2|^2 dx dy = 1$), $n_1$ and $n_2$ are refractive indices of the two cores, $n(x,y)$ is the refractive index profile of the DCF [4]. In our case, the refractive indices of both cores are identical (the PBG08 glass was used as core material) and asymmetry is associated with a difference in core shapes. Beyond the core, the refractive index is uniform and determined by the cladding material, viz., UV710 glass. The asymmetry parameter is

$$\delta_a = \frac{1}{2} (\beta_{01} - \beta_{02})$$

where $(\beta_{01})$ are group velocities in the individual channel. The nonlinear Kerr coefficients ($m = 1, 2$) are:

$$\gamma_m = k_0 n_2 \int_{-\infty}^{\infty} |F_m(x,y)|^4 dx dy$$

where $n_2$ is the nonlinear index of refraction of the PBG08 glass of which the core is made with value of $4.3 \times 10^{-19} m^2/W$, which is about 20 times higher than in the case of silica.

### III. Rescaling the Physical Parameters

In the simulations, we used rescaled parameters and neglected slight differences between the cores in terms of the coupling coefficient, therefore: $\kappa_{12} \approx \kappa_{21} = \kappa$. We define dimensionless parameters for time, distance, and amplitude: $t = \tau \sqrt{\beta_{21}/\kappa} = \tau t_0$, $z = \zeta/\kappa = \zeta_0$, and $\Psi = \sqrt{\gamma/\kappa A}$, and cast equations [1]-[2] in the following form (notice that we have defined unit of time $t_0$ and unit of length $z_0$, which will later be related to the pulse duration and propagation length):

$$i \partial_t \Psi_1 = i(\alpha_2 - \alpha_1) \partial_\tau \Psi_1 - \frac{1}{2} \partial_{\tau\tau} \Psi_1 - \sigma \Psi_1 - |\Psi_1|^2 \Psi_1 - \Psi_2,$$  

$$i \partial_t \Psi_2 = i(\alpha_2 - \alpha_1) \partial_\tau \Psi_2 - \frac{1}{2} \partial_{\tau\tau} \Psi_2 + \sigma \Psi_2 - |\Psi_2|^2 \Psi_2 - \Psi_1$$

where $\alpha_1 = \beta_{11}/\sqrt{\kappa |\beta_{21}|}$, $\alpha_2 = \beta_{12}/\sqrt{\kappa |\beta_{21}|}$, $\alpha = |\beta_{22}|/|\beta_{21}|$ and the mismatched parameter: $\sigma = (\beta_{01} - \beta_{02})/(2\kappa)$. If we now use the retarded time $T = \tau + \alpha_2 \zeta$,

$$i \partial_T \Psi_1 = i(\alpha_2 - \alpha_1) \partial_T \Psi_1 - \frac{1}{2} \partial_{TT} \Psi_1 - \sigma \Psi_1 - |\Psi_1|^2 \Psi_1 - \Psi_2,$$  

$$i \partial_T \Psi_2 = -\frac{1}{2} \partial_{TT} \Psi_2 + \sigma \Psi_2 - |\Psi_2|^2 \Psi_2 - \Psi_1$$

In the experiments, we have achieved the best results at $\lambda_0 = 1700$ nm, hence all the parameters refer to this wavelength. Below we present a table with effective values at this wavelength.

| Physical quantity | 1st core | 2nd core | Units |
|-------------------|---------|---------|-------|
| $n_{eff}$         | 1.7776  | 1.7771  |       |
| $\beta_0$         | 6.56172 * 10^6 | 6.55996 * 10^6 | 1/m   |
| $\beta_1$         | 6.58061 * 10^-9 | 6.58085 * 10^-9 | s/m   |
| $\beta_2$         | -9.890 * 10^{-26} | -9.890 * 10^{-26} | s^2/m |
| $\gamma$          | 0.85338 | 0.85584 | 1/(W.m) |
| $\kappa$          | 1017.8058 | 1017.8058 | 1/m   |

Due to the small difference between GVD and nonlinearities in both cores, we can use for numerical modeling average values, $\beta_2 = -9.890 * 10^{-26}$ $s^2/m$, and $\gamma = 0.85461$ $W^{-1}m^{-1}$. This way we end up with the final system of propagation equations for our model of the mismatched DCF for high and low index cores respectively

$$i \partial_T \Psi_1 = i(\alpha_2 - \alpha_1) \partial_T \Psi_1 - \frac{1}{2} \partial_{TT} \Psi_1 - \sigma \Psi_1 - |\Psi_1|^2 \Psi_1 - \Psi_2$$

$$i \partial_T \Psi_2 = -\frac{1}{2} \partial_{TT} \Psi_2 + \sigma \Psi_2 - |\Psi_2|^2 \Psi_2 - \Psi_1$$

and $\alpha_2 - \alpha_1 = 0.023921$. The high index core (1st core) is the one with high group velocity and the low index core (2nd core) with the low group velocity. The units of propagation length and time for our experimental conditions can be evaluated to be

$$z_0 = \frac{\pi}{2 \kappa} = 1.54 mm$$

$$t_0 = \sqrt{|\beta_2|/\kappa} = 9.86 fs$$

The length of our fiber was about 18 mm, which corresponds to the dimensionless propagation distance of 18.3. It is worth mentioning, that after the completion of full periods of inter-core oscillations in the linear propagation regime the excited core stays dominant. In particular, the 18.3 mm propagation length, representing about 6 periods, expresses this effect, as confirmed by monitoring the
two fiber outputs. The asymmetry parameter $\sigma$ plays an important role in the dynamics of the pulse propagation in the fiber. In our study, the impact of the asymmetry is investigated by systematically increasing its value from 0, which represents a symmetric coupler without mismatch. The asymmetry parameter is increased up to the level where the nonlinear switching is still possible, but with lower sensitivity to small changes of the input energy in terms of output-port-dominance exchange.

We also examined the effect of the pulse-shape and concluded that the results are practically the same when we use Secant or Gaussian pulses. The pulse width effect was examined experimentally in the range of 110 and 150 fs, which is sufficiently broad, taking into consideration that the soliton order increases linearly with the increasing width $\text{FWHM}$ of the pulse. The input Gaussian pulse $\Psi(0, \tau) = ae^{\eta \tau^2}$. From the relation of FWHM convention

$$\eta \tau = \frac{t_{\text{FWHM}}}{2t_0} = \sqrt{\frac{\ln(2)}{2}} = 0.5887$$

(15)

it follows that $\eta = \frac{1.1774t_0}{t_{\text{FWHM}}}$ and $\eta = \left(\frac{1.1699}{150}, \frac{1.1699}{110}\right) = (0.0774; 0.1055)$. The energy of the pulse as a function of $a$ and $\eta$ can be expressed as $E = \int_{-\infty}^{\infty} |A(z, t)|^2 dt = \frac{na_0^2}{\gamma} \sqrt{\frac{2}{\eta}} = 14.739\frac{n a_0^2}{\eta} [\text{pJ}].$

![FIG. 1. The amplitude dependence of the propagation regime of the 150 fs Gaussian pulse in the case of the excitation of the low-index core, for different values of the propagation-constant mismatch, $\sigma$. The red color designates oscillatory behavior, when the final state depends on the actual length of the fiber. Blue means that, after a few initial oscillations, the pulse self-traps mostly in the excited (straight) channel; and green means the eventual self-trapping in the initially empty (cross) channel.](image)

The experimental work was carried out with the standard setup presented in detail in our previous publications [13–19]. Femtosecond pulses centered at 1700 nm were generated in an optical parametric amplifier pumped by the second harmonics of commercial Yb:KGW laser system (Pharos, Light Conversion) operating at 10 kHz repetition rate. The pulses were guided through a half-wave plate and polarizer representing a tunable attenuator and through a second half-wave plate to set the proper pulse polarization. The in-coupling and out-coupling of the beam were provided by two 40x microscope objectives mounted on 3D-positioners, securing the setup of the optical parametric amplification (OPA) source to establish the two above-mentioned border values: 110 and 150 fs. For our simulations, we used the input Gaussian pulse $\Psi(0, \tau) = ae^{\eta \tau^2}$. From the relation of FWHM convention

$$\eta \tau = \frac{t_{\text{FWHM}}}{2t_0} = \sqrt{\frac{\ln(2)}{2}} = 0.5887$$

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![FIG. 2. The amplitude dependence of the propagation regime of the 150 fs Gaussian pulse in the case of the excitation of the high-index core, for different values of the propagation-constant mismatch, $\sigma$. The meaning of the color code is the same as in Fig. 1](image)

![FIG. 3. The comparison between the simulations and experiment for the case of 150 fs Gaussian pulse launched into the low-index core.](image)

IV. NUMERICAL RESULTS FOR NONLINEAR PROPAGATION

In numerical simulations, we used pulses with two different widths at the FWHM level, 150 and 110 fs to match the experimental data. In the case of the Gaussian pulse, the corresponding values of the inverse pulse width, defined above, were $\eta_1 = 0.077$ and $\eta_2 = 0.11$, respectively. Additionally, we investigated the effect of the mismatch in the effective refractive index to find optimal conditions for controllable switching performance. The propagation distance in the simulations was approximately 25 mm, and since the coupling length in the experiment was 1.54 mm, it corresponds to about 10 periods of inter-core-coupling oscillations. It provides a possibility for analysis of the nonlinear dual-core propagation even beyond the experimentally studied 18 mm length, and puts the findings into a broader context. Chosen simulation parameters (Table I) determined by the fiber submicron precision. The output of the fiber was monitored by an infrared camera by imaging the output facet on the detector surface. Under the single-core excitation of one fiber core, series of camera images were registered by changing the energy of the excitation pulses in the range of 0.1 – 1.5 nJ separately for the fast and slow core. Additionally, the recordings were repeated for different pulse widths achieved by tuning the OPA while simultaneously keeping the central wavelength at 1700 nm.
FIG. 4. The comparison between the simulations and experiment for the case of 150 fs Gaussian pulse launched into the high-index core.

structure allow direct comparison of the numerical results and experimental observations. During simulations, we considered both high-index- and low-index-core excitations, resulting in qualitative agreement with the experimental results in terms of input energy dependence of the propagation character. However, the considered simple model, which takes not into account neither the linear (absorption, Rayleigh scattering) and nonlinear (Stimulated Raman scattering, dispersion wave generation) dissipation effects, nor the dispersion of the coupling coefficient, cannot predict the precise values of the switching energies. Therefore, presenting the numerical results we refer to values of the pulse amplitude, properly comparing the predictions with the experimental results.

FIG. 5. Experimental results for the Gaussian pulses of width 150 fs (a) and 110 fs (b) launched into the low-index core of the fiber.

Preliminary experimental observations imply that introducing core asymmetry may lead to more stable and controllable switching performance (self-trapping of the pulse in the straight, initially populated or the opposite, initially empty channel, depending on the initial pulse amplitude) [2]. To put it in quantitative terms, in our simple model we varied the asymmetry parameter $\sigma$ from 0.1 to 0.3 for the 150 fs pulse and classified outcomes of the dynamics according to the dependence on the input pulse amplitude. Results are summarized in Figs. 1 and 2 which represent maps of the pulse-dynamic scenarios in two cases, when the incident pulse excites either the low- or high-index core. The color code is defined in the caption to Fig. 1. In the case of launching the pulse into the low-index core, at relatively low mismatch values ($\sigma < 0.3$) we observe several alternations of the pulse trapping between both channels with increasing amplitude. This outcome seems too fragile for the system to be used as an all-optical switch. However, at $\sigma = 0.3$ the self-trapping takes place in the initially empty (cross) channel in a broad range of pulse amplitude. Such a behavior is quite natural, in view of the propensity of light to stay in a medium with higher refractive index. This outcome persists for the amplitude of the input up to $a = 1.5$. Above this level, in a narrow interval of values of $a$, the self-trapping occurs in the straight channel.

After further increase of the amplitude the self-trapping again takes place in the cross channel. We conclude that this is an optimal condition for switching with a high level of contrast and robust possibility to control the release of the pulse from a particular output port. If the high-index core is initially excited, we again observe, at first, oscillations-straight (excited) channel trapping transition in the region of low energy. When the energy is higher, self-trapping occurs also in the empty (cross) channel. Such switching behavior to the cross-channel takes place in some narrow intervals of values of $a$ (e.g., around 1.2 and 1.4 for the largest asymmetry, $\sigma = 0.3$, which is shown in Fig. 2). Additionally, the trapping threshold decreases when the asymmetry increases. The reason for the latter effect is that the initial asymmetry of the fiber strengthened the trend to the self-trapping in the high-index core. The higher the initial asymmetry, the lower pulse energy is sufficient to induce additional asymmetry (discrete self focusing in terms of the channels) for establishing the self-trapping process.

Analyzing the numerical results, we have concluded that the optimal value of the asymmetry parameter is 0.3 because for higher values of $\sigma$ the transient areas disappear from the dynamic maps after the first oscillation-trapping transition. The switching dynamics is different when we excite the low- or high-index-core, with the cross or straight core self-trapping dominance occurring, respectively, in the former and latter cases. Furthermore, in the case when the fiber length in the experimental realization is equal to a multiple of the inter-core-oscillation
FIG. 7. The dependence of the integral field energy on the propagation distance in both cores, as produced by the simulations. It shows the transition of oscillations to the cross core self-trapping for the input pulse amplitudes 0.975 (the upper panel) and 1.0 (the lower panel). Excitation pulses with width of 110 fs and Gaussian shape were launched into the low-index core of the fiber with asymmetry parameter $\sigma = 0.3$. The black arrow marks the length of the fiber in the experiment.

period, a different peculiarity is observed in the transition between the inter-core oscillations and self trapping in the high-index core. As concerns the dominance of the output core, it is preserved in the case of the excitation of the high-index core, and, on the contrary, it is exchanged in the case of the low-index core excitation. In addition to that, the self-trapping may be switched between the two channels in narrow intervals of the initial amplitude, as may be concluded from Figs. 1 and 2. This overall dynamics is more stable behavior in comparison to the one observed in the symmetric or weakly-asymmetric DCF studied before [12], where the chart of dynamical regimes was more intricate, exhibiting stronger sensitivity to small variations both of the amplitude and pulse width.

V. DETAILED COMPARISON WITH EXPERIMENTAL OBSERVATIONS

Here, we aim to compare predictions of the above theoretical model with the experimental observations made in a nonlinear DCF, with the structure expressing optical parameters presented in Table 1 at wavelength 1700 nm. Numerical simulations were performed with parameters matched to the experimental setup, including the wavelength, shape and duration of the incident pulse.

A. The core selection effect

In Fig. 8 we present the comparison between the theoretical model and experiments for the case of the low-index core excitation and the incident Gaussian pulse width $t_{\text{FWHM}} = 150$ fs (the top panel of Fig. 3). Camera images demonstrate a single transition of the light propagation regime from the inter-core oscillations to self-trapping in the cross core around the critical value of the pulse energy of $E = 0.87$ nJ. The simulation results predict the same one-step switching behavior, which takes place at the amplitude $a = 0.95$. In the case of the high-index-core excitation, the experiments reveal a different result, viz., transient switching behavior at higher pulse energy, i.e. around 1.26 nJ (Fig. 4). When further increasing pulse energy the same straight-core dominance was observed as in the linear propagation regime. The simulations predict similar outcome with the transient cross-core dominance effect around the amplitude level of 1.2. The transition between the oscillatory and straight core self-trapping predicted by the simulations at the 0.72 level is not observable experimentally because it does not change the core dominance at the output due...
FIG. 9. The dependence of the integral field energy on the propagation distance in both cores, as produced by the simulations. It shows the transition of the trapping from the straight core to the cross one for input pulse amplitudes 1.45 (the upper panel) and 1.5 (the lower panel). Excitation pulses with width of 110 fs and Gaussian shape were launched into the low-index core of the fiber with asymmetry parameter \( \sigma = 0.3 \).

B. The pulse-width effect

In Figure 5, the series of camera images in panel (a) show experimental observations for the case of the low-index core excitation using a 150 fs Gaussian input pulse. The images in panel (b) show the corresponding situation when pulse duration is 110 fs. In this case, more sophisticated dynamics, including three transitions between the output straight/cross core dominance at pulse energies 0.42 nJ, 0.69 nJ, and 1.03 nJ is observed, in contrast to the simpler behavior corresponding to the pulse width of 150 fs. In Figure 6, we present the predictions of the theoretical model for the same conditions at which the experiments were performed. One can see that, in the case of the pulse width of 150 fs, only the transition between the inter-core oscillations and self-trapping in the cross core occurs, at the amplitude 0.95. In contrast, the simulations carried out for the pulse width of 110 fs exhibit three transitions: the above mentioned one plus a transition to the self-trapping in the straight core, soon followed by the inverse transition. The reason for the more complex character of the exchange of the self-trapping core in the case of the shorter pulse is the linear decrease of the soliton order \( N \) with decrease of the pulse width, according to the expression

\[
N^2 = \frac{\gamma P_0 T_0^2}{|\beta_2|} \tag{16}
\]

where \( P_0 \) is the pulse peak power. The higher soliton order corresponds to the higher level of complexity of the soliton fission process, which prevents the multiple core exchanges. The soliton self-compression effect, characterized by the factor \( F_c \) is determined also by the soliton order according to empirical relation \( F_c = 4.1N \) [20], causes the appearance of shorter pulses in this case. Consequently, the stronger selective self-focusing (which favors a particular channel) prohibits the transfer to the straight core at higher pulse amplitudes. Additionally, it is important to take into account that the longer pulse carries higher energy at a constant amplitude level. For this reason lower amplitudes were considered for the 150 fs pulse width than for the width of 110 fs. In the former case, the largest amplitude of 1.36 was chosen, leading even to a higher pulse energy than in the latter case, with the largest amplitude of 1.46.

Finally, in Figs. 7-9 we illustrate the propagation-distance-dependent energy exchange between the two cores, which signals the onset of the same sequence of three transitions as observed experimentally (panel (b) of Fig. 5). Black arrows indicate the observation point, which corresponds to the fiber length used in the experiment. All three transitions exhibit a clear exchange between the cores following a slight increase of the pulse amplitude. Correspondingly, all of them were identified experimentally by the camera monitoring of the output fiber facet with convincing switching contrasts. Thus, the experimental observations confirmed the predictions of the numerical study, as well as the single-transition character of the energy dependence in the case of 150 fs pulses.

VI. CONCLUSIONS

In conclusion, by means of experimental investigations and systematic numerical simulations, we have studied the switching dynamics in asymmetric nonlinear DCFs (dual-core fibers), with the propagation-constant mismatch between the guiding channels. We used a relatively simple numerical model taking into account all essential parameters of the fiber and input pulses, tailored to match the experimental conditions. An important control parameter is the inter-core difference of the effective refractive index, which can be estimated from the cross-section image of the DCF structure. However, such calculation bears high level of uncertainty, because it is defined by the overlap integrals of the field distribution in the two cores [4]. Therefore, its value is sensitive to fluctuations of the fiber microstructure along the propagation direction, even at the nanometer scale. On the other
hand, in numerical simulations of the nonlinear propagation we introduce average parameter $\sigma$ and determine the optimum value of the mismatch to be $\sigma = 0.3$. The simulations confirm experimental observations in terms of energy-dependent pulse dynamics when changing the excited core (low- or high-index), and tuning of the pulse width. Note also that previously, good agreement was found in the study of the soliton propagation in the symmetric DCF [12]. Here the theoretical and experimental findings are summarized in back-to-back maps and camera images showing the outcome at the end of the fiber as functions of amplitude and energy of the excitation pulse. The comparison demonstrates only qualitative agreement between experimental findings and theoretical results, which were produced by the simplified model. As mentioned above, this study is similar to the case of the symmetrical coupler [12], where we could properly identify individual steps of the dominance exchange between the two guiding cores. However, at shifted energy levels we observe much more robust and controllable switching dynamics. The outcomes of the current work, as concerns the numerical and experimental approach alike, reveal a dynamics. The outcomes of the current work, as concerns the design of novel all-solid DCFs intended for all-optical switching purposes. We have also improved the numerical model, which is an efficient tool for analyzing the pulse-width effect on the switching in the femtosecond soliton propagation regime. An additional asset of the model is its applicability to the design of fiber couplers with the appropriate mismatch, considering parameters of commercially available ultrafast sources of laser pulses.

VII. ACKNOWLEDGEMENTS

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VIII. DISCLOSURES

The authors declare no conflicts of interest.

[1] S. M. Jensen, IEEE J. Quantum Electron. 18, 1580 (1982).
[2] A. A. Maier, Sov. J. Quantum Electron. 12, 1490 (1982).
[3] R. Hui, Introduction to Fiber-Optic Communications, 1st ed, Chap. 6 (Elsevier, 2020).
[4] G. P. Agrawal, Fiber couplers, in Applications of Nonlinear Fiber Optics, (Academic Press, 2008, pp. 54-99).
[5] B. A. Malomed, A variety of dynamical settings in dual-core nonlinear fibers, in Handbook of Optical Fibers, (Springer, 2019, pp. 421-474).
[6] J. Herrmann, U. Griebner, N. Zhavoronkov, A. Husakou, D. Nickel, J. C. Knight, W. J. Wadsworth, P. S. Russell, and G. Korn, Phys. Rev. Lett. 88, 1739011-1739014 (2002).
[7] F. Luan, A. Yulin, J. C. Knight, and D. V. Skryabin, Opt. Express 14, 6550 (2006).
[8] X. He, K. Xie, and A. Xiang, Optoelectronics Adv. Mater. - Rapid Commun. 4.3, March 2010 4, 3, 284-286 (2010).
[9] T. Uthayakumar, R. V. J. Raja, K. Nithyanandan, and K. Porsezian, Opt. Fiber Technol. 19, 556-564 (2013).
[10] A. Govindarajan, B. Malomed, A. Mahalingam, and T. Uthayakumar, Appl. Sci. 7, 645 (2017).
[11] L. Curilla, I. Astrauskas, A. Pugzlys, P. Stajanca, D. Pysz, F. Uherek, A. Baltuska, and I. Bugar, Opt. Fiber Technol. 42, 39-49 (2018).
[12] V. H. Nguyen, L. X. T. Tai, I. Bugar, M. Longobucco, R. Buczynski, B. A. Malomed, and M. Trippenbach, Opt. Lett. 45, 5221 (2020).
[13] M. Longobucco, I. Astrauskas, A. Pugzlys, D. Pysz, F. Uherek, A. Baltuska, R. Buczynski, and I. Bugar, Opt. Commun. 472, 126043 (2020).
[14] H. Jiang, E. Wang, J. Zhang, L. Hu, Q. Mao, Q. Li, and K. Xie, Opt. Express 22, 30461 (2014).
[15] S. Trillo, E. M. Wright, G. I. Stegeman, and S. Wabnitz, Opt. Lett. 13, 672 (1988).
[16] M. Liu and K. S. Chiang, Appl. Phys. B Lasers Opt. 98, 815-820 (2010).
[17] J. Zhao, Z. Wang, Y. Liu, and B. Liu, Front. Optoelectron. China 3, 283-288 (2010).
[18] J. H. Li, K. S. Chiang, and K. W. Chow, Opt. Commun. 318, 11-16 (2014).
[19] M. Longobucco, I. Astrauskas, A. Pugzlys, N. T. Dang, D. Pysz, F. Uherek, A. Baltuska, R. Buczynski, and I. Bugar, Appl. Opt. 60, 10191 (2021).
[20] G. P. Agrawal, Pulse compression, in Applications of Nonlinear Fiber Optics, (Academic Press, 2008, pp. 263-318).

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