Asymmetric twin-core photonic crystal fiber for dispersionless all-optical delay control

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Abstract

We present a twin core photonic crystal fiber nonlinear coupler permitting dispersionless all-optical control of the delay of picosecond pulses. Nonlinear exact solutions illustrate the time delay control principle.

Introduction

The nonlinear directional coupler has long been proposed as a basic all-optical switching device [1]. To date, dual-mode fiber couplers have been exploited for dispersion compensation modules, for wavelength MUX-DEMUX applications [2], or for high-power pulse reshaping [3]. Twin-core photonic crystal fiber (PCF) based couplers have been recently demonstrated in both linear and nonlinear regime of operation [4-5].

In this work we propose and design a novel asymmetric twin-core PCF coupler, which is suitable for the all-optical control of the time delay of picosecond pulses. Such tunable optical buffer or delay line functionality is expected to be of crucial importance for future high-bit-rate systems (at channel rates of 100 Gbit/s or beyond). Our nonlinear coupler-based pulse delay mechanism is not affected by group-velocity dispersion (GVD), hence it is immune from GVD-induced pulse shape distortion and bandwidth limitation which affect most slow-light generation devices. In fact, similarly to the case of Bragg fiber gratings [6-7], the control of pulse delay is based on the formation of variable-speed optical solitons, which propagate undistorted in the coupler. We obtain the analytical description of these solitons and of their associated time delay properties.

Twin-core PCF filter design

We designed an asymmetric twin-core PCF that is best suited to operate in the high-power regime as a wavelength-dependent nonlinear delay element. Figure 1(a) shows the cross-section of the silica PCF: the left core is composed by a defect in the hexagonal hole structure (with a pitch of 1 μm and a cladding filling factor of 0.7) , accompanied by two larger holes with diameter D=0.9 μm. Whereas the right core has a small hole with diameter d=0.214 μm inside the defect. We computed the propagation constants of the PCF supermodes and of the individual modes in isolated cores by means of the finite element method with perfectly matched layer and edge/nodal triangular elements. We numerically solved the full vectorial wave equation for the electric field, and found its complex eigenpairs by means of the Arnoldi method as an eigensolver and an asymmetrical multifrontal method as a solver of a linear system of equations. We applied about 200 000 elements on half cross-section of the fiber, and included the dispersion of silica glass with the Sellmeier relation.

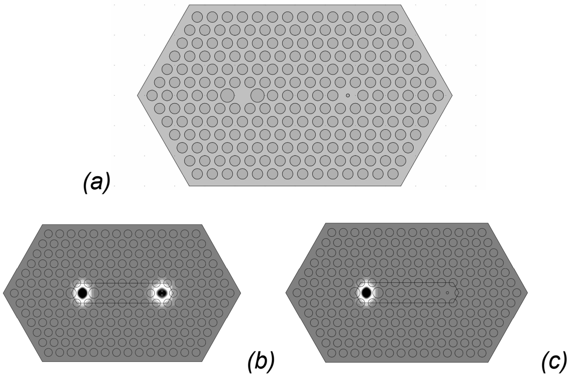

Figure 1: (a) Twin-core PCF cross-section; (b) Power in supermode at or (c) beyond the anticrossing wavelength

Figure 1(b-c) show the calculated power distribution in one of the two supermodes at the anti-crossing wavelength or beyond this wavelength, respectively.

Figure 2 summarizes the linear guiding properties of the twin-core PCF: we show the effective refractive indeces, group velocity dispersions (GVD), and effective areas of the individual core modes. In figure 2 we also show the sharp resonant enhancement of the linear coupling distance L_c among the cores at the anti-crossing wavelength.

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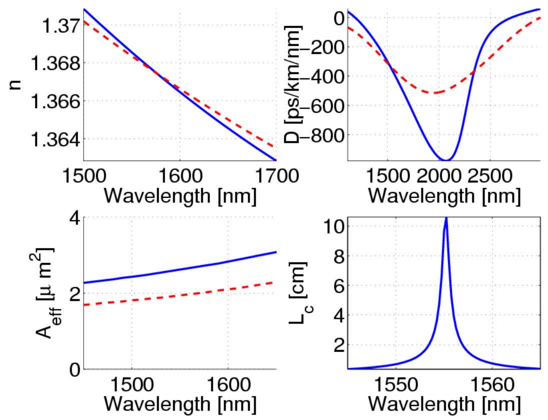

Figure 2: Wavelength dependence of the effective index, dispersion and effective area of the individual core modes (dashed and solid curves), as well of the linear coupling distance L_c.

Nonlinear control of pulse delay

The dimensionless nonlinear equations for the linearly coupled core mode envelopes $\varphi_{\mathrm{h,k}}$ read as

$$\frac{\partial \varphi_{h,k}}{\partial z} \pm \frac{\partial \varphi_{h,k}}{\partial t} = i\varphi_{k,h} + i\sigma_{h,k}\varphi_{h,k}\left|\varphi_{h,k}\right|^2 \quad (1)$$

where we neglected the action of GVD. Indexes h and k indicate the left or the right core mode. We found stable resonance (i.e., at the anticrossing wavelength) soliton solutions of eqs.(1), representing an overlap of φ_h and $\varphi_{,k}$. Resonance solitons result from a balance between linear coupling, group velocity difference and self phase modulation (SPM), and were obtained as an extension of the Bragg soliton solutions of ref.[7]. The effect of SPM is through the parameters $\sigma_{h,k}$ and it accounts for the effective mode area difference (see figure 2), making them distinct. We designed our twin-core PCF so that both the linear coupling distance (10cm) and the walk-off distance (~9cm) are much shorter than the GVD distance (~50m), even for pulses of a few picosecond duration. This could be achieved by our asymmetric selection of the mosaic of rods as shown in figure 1a. An important consequence of the existence of stable soliton solutions of eqs.(1) is that it is possible to launch in the coupler shape-preserving and fully synchronized pulses, even in presence of weak perturbations (e.g, GVD) or PCF imperfections. Flexible time delays are achieved by tuning the group velocity through adjustment of the input power ratio of the two cores. We report in figure 3 (upper insets) the intensity evolution of the two modes for a power ratio of 2.33 (A) or 0.42 (B), respectively. The corresponding time delay per unit length of PCF is -53 ps/m and +39ps/m. The numerical solutions include the effect of GVD: no noticeable difference from our analytical solutions of eqs.(1) was observed. Stable soliton mode coupling occurs at a specific input power level. At low intensities the input pulse completely spreads out in time (inset C for a pulse energy of 0.37nJ in both modes). The soliton pulse width is linearly proportional to the coupling length and to the group index difference between the two modes [7]. The soliton peak power is proportional to the ratio of the effective areas to the linear coupling distance. It is easy to adjust the microstructure of the twin-core PCF to a desired pulse duration and energy, by tuning the coupling coefficient and the guided mode diameters. Inset D shows the numerically calculated time delay per unit length of PCF versus mode energy ratio.

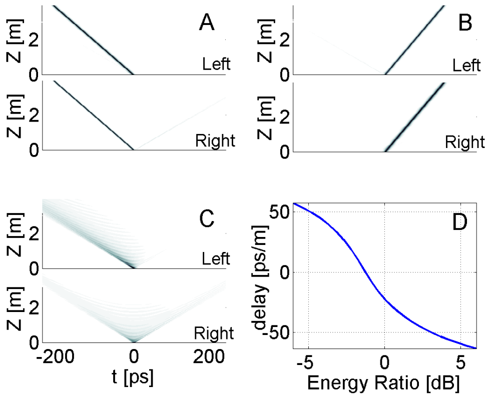

Figure 3: A. Pulse energy of 3.39nJ (left core) and 1.45nJ (right core) and 4.8ps pulsewidths. B: Pulse energy of 1.79nJ (left core) and 4.17nJ (right core). C: Energy of 0.37nJ in both modes D: Time delay per unit length of PCF upon the two modes energy ratio.

Conclusions

We designed a twin-core PCF nonlinear coupler to achieve a dispersionless tuneable delay line. Analytical solutions and numerical simulations confirm that such a waveguide may provide effective all-optical buffer functionality for picosecond pulses. This work was partially supported by the Polonium and the COST P299 projects.

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