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Modeling of a highly nonlinear chalcogenide dual-core photonic crystal fiber coupler

I.D. Chremmos [a,*], G. Kakarantzas [b], N.K. Uzunoglu [a]

[a] Microwave and Fiber Optics Laboratory, Department of Electrical and Computer Engineering, National Technical University of Athens, Iroon Polytechniou 9, Zografos 15773 Athens, Greece

[b] Photonics Communications Research Laboratory, Department of Electrical and Computer Engineering, National Technical University of Athens, Iroon Polytechniou 9, Zografos 15773 Athens, Greece

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Abstract

The switching operation of a nonlinear dual-core photonic crystal fiber (PCF) coupler, based on a highly nonlinear As_2Se_3 chalcogenide glass, is numerically studied for the first time. Combining the standard coupled-mode formulation with a full-vectorial integral equation analysis of the PCF geometry, we show that the device parameters can be tailored to achieve switching power requirement ~1 W at a coupler length of only few centimeters. The dispersion results show that efficient switching can be attained for pulsewidths greater than ~2 ps.

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1. Introduction

Among their unique waveguiding properties, photonic crystal fibers (PCFs) [1] have been found to offer new perspectives for nonlinear applications. Owing to their wavelength scale structure and capability of tight field confinement, PCFs can offer very small mode areas A_{eff} and enhance the effective nonlinearity $\gamma = 2\pi n_2/(\lambda A_{eff})$ by an order of magnitude [2]. The potential in this direction has recently been expanded with the fabrication of PCFs from multi-component soft glasses [3,4], with intrinsic material nonlinearities one or two orders of magnitude greater than that of pure silica ($n_2 \sim 2.5 \times 10^{-16}$ cm^2/W). The result is a dramatic magnification of the feasible effective nonlinearities, compared to those achieved with conventional

* Corresponding author. Tel.: +30 210 7723556; fax: +30 210 7723557.

E-mail address: jochremm@central.ntua.gr (I.D. Chremmos).

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fibers ($\sim$1 W^{-1} km^{-1}), which could reach the order of 2×10^4 W^{-1} km^{-1} for a PCF made from As_2Se_3 chalcogenide glass [5]. This advance offers totally new possibilities in the field of all-optical signal processing, since it enables the realization of compact nonlinear devices with low power requirements. The nonlinear directional coupler (NLDC) [6] is one of the fundamental nonlinear devices with application in all-optical routing and signal processing. In recent studies [7–9], linear dual-core couplers in PCF geometry have been shown to have wide coupling length range through adjustment of the hole size and spacing, which is an inherent part of the PCF fabrication process. In this way, the dual-core PCF coupler geometry provides the design procedure with the flexibility to control core separation, i.e., coupling, and field confinement, i.e., coupling and effective mode area, by using a single material. This is a major step beyond conventional fiber couplers, where separation between the two fibers is more difficult to handle and the refractive index difference is controlled only by changing the chemical composition of core and cladding. The combination of the PCF coupler properties with a high material nonlinearity, is expected to yield readily fabricated nonlinear switching devices with unprecedented characteristics. In this paper, the potential of such a device, based on a dual-core PCF coupler, is explored by using the classical coupled-mode theory formulation along with a full-vectorial integral equation analysis of waveguidance in the PCF. For our simulations, we use the As_2Se_3 chalcogenide glass studied in [5], which has a Kerr nonlinearity $\sim$400 times that of silica and refractive index $\sim$2.76. The numerical results report the possibility to obtain a practical nonlinear coupler with specifications of $\sim$1 W switching power and few centimeters length. The conditions for efficient pulse switching are also examined, by computing the total dispersion parameter β_2 for PCF cores made from the considered compound glass.

2. Modeling and results

The analysis of a NLDC is classically reduced to the study of two coupled nonlinear Schrödinger equations, obtained through a standard perturbation approach in the context of coupled-mode theory [6,10]. In the case of continuous wave (CW) propagation in a symmetric NLDC these are

$$\begin{aligned} &\mathrm{j}\partial A_1/\partial z + \kappa A_2 + \gamma |A_1|^2 A_1 = 0, \\ &\mathrm{j}\partial A_2/\partial z + \kappa A_1 + \gamma |A_2|^2 A_2 = 0, \end{aligned} \tag{1}$$

where $A_1(z)$, $A_2(z)$ are the field amplitudes associated with the fundamental modes of the isolated waveguides, κ is the linear coupling coefficient determined by the spatial overlap of these modes and $\gamma = 2\pi n_2/(\lambda A_{\mathrm{eff}})$ is the nonlinear parameter, with λ being the optical wavelength, n_2 the Kerr coefficient and A_{eff} the effective mode area. Cross-phase modulation terms do not appear in (1) since, in most cases, the interaction between the waveguides is weak enough to yield negligible nonlinear coupling. The CW model is also applicable to pulse switching, provided that the effect of dispersion can be neglected or, equivalently, the dispersion length L_D of the considered pulses is much larger than the coupler length. The case is known as quasi-CW switching and is discussed later. The most essential parameter of the switching operation is the critical power, i.e., the minimum required input power, so that at least a 50% of it remains in the core it is launched, at any position of the coupler. For the ideal coupler of (1), the critical power has been shown to be $P_c = 4\kappa/\gamma$ [6]. The power requirement of the coupler is therefore determined by the parameters κ and γ. Note that the standard coupled-mode analysis is generic and perfectly applicable to dual-core PCF couplers too, provided that an accurate method is applied to compute the involved parameters for the complex PCF geometry.

The linear-coupling coefficient κ arises from the spatial overlap of the modes of the two waveguides and is responsible for the periodic exchange of power between them with period $\pi/\kappa \equiv 2L_c$, where L_c is the coupling length. By definition, κ is given by a two-dimensional overlap integral [10] between the unperturbed transverse electric fields of the two cores in proximity. However, the computation of the integral can be prone to significant numerical error, especially when the core separation increases or when the interacting field is strongly