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Realization of all-optical logic gates through three core photonic crystal fiber

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ABSTRACT

We present the practical design of novel three core photonic crystal fiber (TPCF) for optical switching and logic operations by employing all optical control. To accomplish the proposed aim, we put forth two types of symmetrical TPCF designs, one with cores of planar geometry and the other with equilateral triangular geometry. The dynamics of the individual pulse parameters through the proposed geometries are analyzed numerically using split step Fourier method (SSFM). The steering characteristics of the coupler are demonstrated by the transmission curve. The truth tables expressing Boolean algebra for different logic operations are constructed from the transmission curves of the individual coupler configurations. Out of all configurations, we observe that the chloroform filled triangular core demonstrates all the logic operations namely OR, NOR, AND, NAND, X-OR, X-NOR and NOT with low input power. A figure of merit of logic gates (FOMEL) is also made to compare the performance of all the logic gates.

1. Introduction

Nonlinear couplers find special attention for their applications as wavelength division multiplexors, optical splitters, optical switches and optical logic gates [1]. Out of the diverse combinations, the triple core and multiple core couplers attracted much interest for their multiple output states with good power selectivity, coupling and switching contrast, compared to that of two core couplers [2–8]. In particular, couplers made of photonic crystal fibers (PCFs) have been paid a significant attention for their versatile design flexibility and optical properties such as desired zero dispersion wavelength, endless single mode, high dispersion, enhanced nonlinearity and low bending loss, etc. [9–11].

In current state of art, three core couplers are shown significant attention to realize an efficient all optical switch and logic gates. The optical steering properties of triple core PCFs are analyzed numerically as well as experimentally by many researchers. Studies show that enhanced nonlinearity and high dispersion contribution from PCF proves it to be a best platform to control the phase shift. Inter-core coupling through triple core PCFs developed from coupled mode theory (CMT) to study the intensity dependent effects and the experimental investigation of all optical switching in the presence of high intense pump beam for different wavelengths also have been performed [7]. Coupling and transmission characteristics of an optical pulse through the triangular triple core PCF have been analyzed using CMT by Li et al. and also, demonstrated the enhanced optical performance compared to that of dual core counterpart [8]. The coupling characteristics of three coupler based broad band directional coupler with low polarization dependent loss also been achieved [12].

Besides switching, three core couplers also form a basis to construct all optical logic gates. Several efforts have been made to achieve logic gates numerically through three core fiber coupler. Menezes et al. analyzed the steering of continuous wave (CW) optical beam through three core fiber couplers of triangular configuration (TC) and planar configuration (PC). Also, demonstrated AND, OR and NXOR gates through TC and AND, NAND, OR, XOR and NOT gates through PC. In addition, a detailed comparative studies of logical device also made using triple core and asymmetric dual core coupler system operating at CW regime [13–15]. AND gate construction through PCF Y-junction using Kerr effect and its verification using time domain simulation have been realized by Danaie et al. [16]. A photonic crystal structure of cross-wave guide geometry with nonlinear rods are also used to construct the AND, NOT and NOR logic gates by employing finite difference time domain method [17]. But up to date, there is no significant work has been done in achieving the optical logic gates by employing three core PCF (TPCF). But, TPCF with enhanced nonlinearity and dispersion forms an excellent candidate to achieve desired logical operation. Hence, we choose TPCF to implement the proposed aim.

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In the present work, first, we design the silica TPCF of triangular as well as planar geometry and the switching dynamics is studied. In addition, we are also interested in filling the cores with high index liquid to achieve an enhanced nonlinearity and dispersion. The consequence of filling cores with high index liquid for diverse applications have been made by a lot of researchers, to mention a few [18–21]. Furthermore, we are also inquisitive to inspect the dynamics of the individual pulse parameters using split step Fourier method (SSFM) from governing coupled nonlinear Schrödinger equations (CNLSEs). Secondly, we construct the logic gates from the proposed TPCF by employing the SSFM. Finally, the comparison of the performance of all gates are done using figure of merit of logic gates (FOMEL) as proposed by Menezes et al. [13–15].

2. Design of TPCF

We put forth two kinds of the TPCF for our study, one with silica core (STPCF) and the other with chloroform filled core (CTPCF). The interest towards chloroform filled core is primarily for its enhanced nonlinearity and high dispersion. To achieve high nonlinearity, either we need to design a PCF structure with large air holes or to fill cores with high nonlinear index materials such as SF_6, TF_{10}, CS_2 and nitrobenzene [10,22,23]. However, some of these structures show the serious drawback of disappearance of single mode. From the recent report by Zhang et al., the PCF core filled with chloroform found to exhibit both single mode as well as zero dispersion [24]. Also, in our previous reports, we have demonstrated an efficient pulse propagation for both the single core and dual core chloroform filled PCF [25–27]. The schematic of linear and triangular configurations are illustrated by Fig. 1 and the number 1, 2 and 3 represents the guiding cores. The design parameters are the air hole diameter (d) to the pitch constant (Λ) ratio $d/\Lambda = 0.666$ and inter core separation ($C = 2\Lambda$) at $\Lambda = 2\ \mu$m. For CTPCF, the core diameter (D_c) is equal to that of the air hole diameter ($D_c = d$). For STPCF, the liquid filled cores are removed and the solid back ground serves as cores. The effective refractive indices of the proposed geometries are calculated using the finite element method (FEM) with 37 504 triangular elements and the boundary conditions are provided by [28,29]. The coupling length L_c of the proposed designs are calculated from the obtained effective indices [27,30].

3. Theoretical model

The set of CNLSEs describing the optical pulse propagation through the TPCFs are given by [1,6]

$$i\frac{\partial A_1}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A_1}{\partial t^2} + \gamma|A_1|^2 A_1 + \kappa(A_2 + A_3) - \frac{i}{2}\alpha A_1 = 0, \tag{1}$$

$$i\frac{\partial A_2}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A_2}{\partial t^2} + \gamma|A_2|^2 A_2 + \kappa(A_1 + A_3) - \frac{i}{2}\alpha A_2 = 0, \tag{2}$$

$$i\frac{\partial A_3}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A_3}{\partial t^2} + \gamma|A_3|^2 A_3 + \kappa(A_1 + A_2) - \frac{i}{2}\alpha A_3 = 0. \tag{3}$$

For PC, there is no interaction between the cores, 1 and 3 and its corresponding equations can be obtained by fixing $A_3 = 0$ in Eq. (1) and $A_1 = 0$ in Eq. (3). Here A_1, A_2 and A_3 describes the optical pulse through the cores 1, 2 and 3 respectively. β_2 is the group velocity dispersion parameter and γ is the nonlinearity parameter. The coupling coefficient κ is defined as $\pi/2L_c$ and α is the extinction coefficient.

4. Dynamics and transmission characteristics

4.1. Dynamics of plane1 configuration (PC1)

For SSFM studies, we assume the Gaussian initial pulse through the core1 at $z=0$ given by $A(0,t) = A_0 \exp(-t^2/W_0)$, where A_0 is the amplitude, W_0 is the pulse width and 0.001% of the input field of input core is assumed to be the initial profile for other cores. With the following set of fixed initial conditions (x_{11}, x_{12}, x_{13}, x_{14}, x_{21}, x_{22}, x_{23}, x_{24}, x_{31}, x_{32}, x_{33}, x_{34})=(8.5×10^2, 0.4, 0.06, 0, 2.4×10^2, 0.4, 0.06, -1.6, 18.19, 0.4, 0.08, -3), where x_{m1}, x_{m2}, x_{m3}, x_{m4} with $m=1$, 2, 3 symbolize the amplitude, pulse width, chirp and phase of the pulse through core1, core2 and core3 respectively, the dynamics is studied at central wavelength $\lambda_0 = 1.55\ \mu$m and pulse width of 400 fs. The fiber parameters are $L_c = 1.2831$ mm, $\beta_2 = -0.1488$ ps^2/km, $\gamma = 0.0024\ \mathrm{W}^{-1}\ \mathrm{m}^{-1}$ and $\alpha = 2.5944\times10^{-8}$ dB/m for STPCF and (x_{11}, x_{12}, x_{13}, x_{14}, x_{21}, x_{22}, x_{23}, x_{24}, x_{31}, x_{32}, x_{33}, x_{34})=(2.48×10^2, 0.4, 0.08, -1.6, 6.2×10^2, 0.4, 0.07, 0, 2.46×10^2, 0.4, 0.08, -1.6), $L_c = 1.1024$ mm, $\beta_2 = -0.1248$ ps^2/km, $\gamma = 0.4706\ \mathrm{W}^{-1}\ \mathrm{m}^{-1}$ and $\alpha = 6.3344\times10^{-8}$ dB/m for CTPCF. The coupling dynamics is portrayed in Fig. 2. At $z=0$, the amplitude is maximum through the core1 and that of other cores are minimum as shown in Fig. 2(a)(i) and

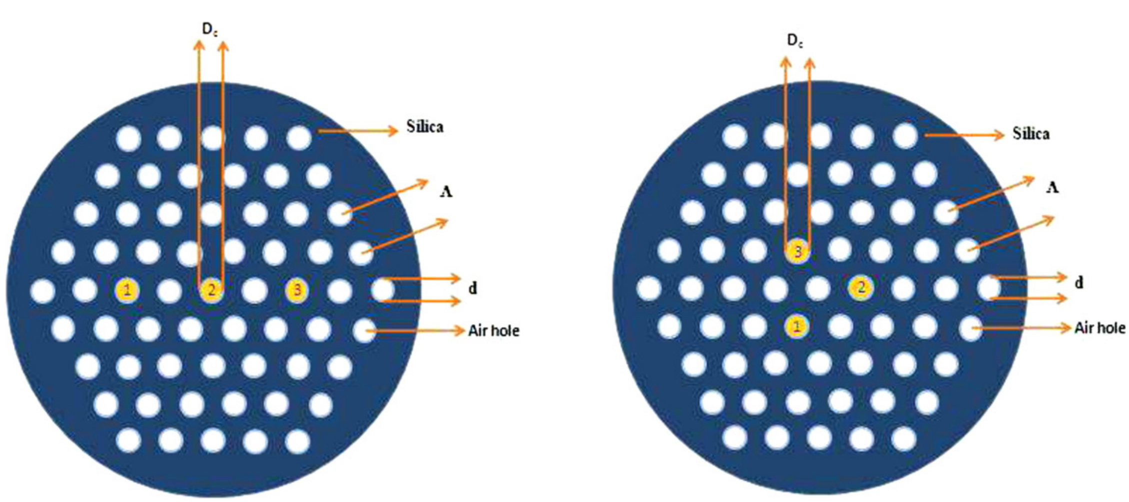

Fig. 1. Schematic of TPCF for planar and triangular configurations respectively.