Logic gates based all-optical binary half adder using triple core photonic crystal fiber

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Received 12 January 2018, revised 3 May 2018
Accepted for publication 15 May 2018
Published 29 May 2018

Abstract
This study presents the implementation of an all-optical binary logic half adder by employing a triple core photonic crystal fiber (TPCF). The noteworthy feature of the present investigation is that an identical set of TPCF schemes, which demonstrated all-optical logic functions in our previous report, has revealed the ability to demonstrate the successful half adder operation. The control signal (CS) power defining the extinction ratios of the output ports for the considered symmetric planar and triangular TPCFs is evaluated through a numerical algorithm. Through suitable CS power and input combinations, the logic outputs are generated from extinction ratios to demonstrate the half adder operation. The results obtained display the significant influence of the input conditions on the delivery of half adder operation for different TPCF schemes considered. Furthermore, chloroform filled TPCF structures demonstrated the efficient low power half adder operation with a significant figure of merit, compared to that of the silica counterpart.

Keywords: all optical switching, optical logic gates, photonic crystal fiber coupler, half adder, coupled nonlinear Schrödinger equations, all optical coupler, nonlinear fiber optics

(Some figures may appear in colour only in the online journal)

1. Introduction
Nonlinear couplers play an indispensable role in all-optical fiber interconnects as couplers, splitters, wavelength division multiplexors, switches and optical computers [1]. Out of the multitude form of couplers, three core and multiple core couplers attracted special interest for their manifold output states, good power selectivity with excellent coupling and switching contrast [2–6]. In recent years, optical couplers constructed from photonic crystal fibers (PCFs) have attracted a great deal of attention for their versatile design flexibility and special optical properties, such as high nonlinearity, desired zero dispersion wavelength, high birefringence, large effective mode area, endless single mode and low bending loss, etc [7–9]. In particular, triple core couplers have been shown special attention to realize the long term goal of achieving an efficient all-optical switching and logic operations. Such all-optical devices play a significant role in handling large bandwidths as well as coping with the speed of telecommunication interconnections.

Numerous efforts have been made to investigate the performance of photonic crystal fiber couplers (PCFCs) for efficient all-optical functions. Owing to its significant contribution to the nonlinear and dispersion properties, a PCF forms the best choice for the construction of ultrafast all-optical controlled devices. Based on the coupled mode theory (CMT), the linear and nonlinear characteristics of the optical pulse propagation through a triple core PCF have been analyzed by Li et al [10]. An experimental demonstration of the dependence of frequency modulation of induced solitons on cross phase modulation (XPM) between the two orthogonal polarization components of the inducing solitons has also been reported [11]. Furthermore, it demonstrated the coherent energy exchange between the orthogonally polarized
components with the generation of new sidebands [12]. Apart from the applications of couplers as switches and splitter, they form the best candidate for the construction of logic gates based on all optical control. Continuous wave switching has also been accomplished through three core fiber couplers of planar- and triangular-configurations with successful demonstration of optical Boolean operations [13]. Moreover, it has revealed various logic operations and determined the figure of merit (FOM) numerically for asymmetric two core fiber couplers [14, 15]. Furthermore, a time domain simulation of an optical AND function in the presence of all optical control by employing a PCF Y-junction [16] has also been investigated. A successful demonstration of all all-optical logic gates and their figures of merit for aptly modeled planar and triangular PCFCs has also been analysed numerically [17]. Moreover, the indispensable role of structural asymmetry of PCFC for diverse combinations on the delivery of all optical logic gates has also been reported [18].

Recent reports have proved that logical functions will allow the realization of devices, such as binary counter, half adder and shift registers [19–21]. Out of these devices, half adder, whose function can be achieved through the combination of XOR and AND logic gates, forms the heart of digital processors. A triple core fiber coupler based numerical study for employing a planar coupler to achieve half adder with an apt control signal (CS) has been realized by Menezes et al [22, 23]. A schematic and truth table for logic operation of half adder is shown by figures 1(a) and (b). But, to date, the achievement of half adder employing the triple core PCF (TPCF) has not been realized. However, the TPCF with an excellent combination of nonlinear and dispersion characteristics allow it to be employed as the best candidate for the digital all optical controlled system to achieve half adder. Hence, the study intends to explore the transmission characteristics of the TPCF with a suitable control signal for the realization of Boolean operation of all optical half adder through split step Fourier algorithm (SSFM).

The paper is outlined as follows: the TPCF schemes considered and the necessary optical parameters required are provided in section 2. A numerical study of the pulse propagation through TPCF described by the coupled nonlinear Schrödinger equation (CNLSE) is obtained through the SSFM has been discussed by section 3. Section 4 deals with the construction of half adder and the verification of the truth table. Finally, section 5 concludes the paper.

2. Design of TPCF

For the proposed study, a similar set of TPCF designs, one with silica as the core material (STPCF) and the other with liquid chloroform as the core material (CTPCF) which have proposed in our earlier work, is considered [17]. The schematic of the considered linear and triangular TPCF configuration is portrayed in figures 2(a) and (b), respectively. The geometrical parameters of the designs considered are the same as [17], namely, the air hole diameter \( d \) to the pitch constant \( \Lambda \) ratio \( d/\Lambda = 0.666 \), and the inter core separation \( (C = 2\Lambda) \) at \( \Lambda = 2 \mu \text{m} \). For the CTPCF, the core diameter \( D_c \) is equal to that of the air hole diameter \( D_a = d \). In the case of STPCF, the liquid filled cores are removed and the solid silica back ground will serve as guiding cores. In figures 2(a) and (b), the light guiding cores are indicated by 1, 2 and 3. The necessary optical properties for half adder operation are provided by employing the finite element method [17, 18, 24–26]. The planar TPCF configuration is studied for two cases; case (i) planar configuration 1 (PC1) where the input of the half adder is provided through cores 2 and 3 and the control signal will be provided through core 1. Case (ii) planar configuration 2 (PC2) where the input is provided through cores 1 and 3 and the control signal will be provided through core 2. For triangular configuration (TC), the inputs and control signal will be provided as the same as that of the planar configuration.

3. Theoretical model

The physical principles behind the control of these optical gates is related to the coupling between cores, which itself depends on the intensity of the control signals: increasing the intensity of the control signal in a certain core tends to confine
the signal light more tightly into another core, which can be explained by using CNLSE only. In this case, if we consider the signal passing through the amplifier fiber, we can demonstrate the inevitable role of the phase variations in the system dynamics through coupled Ginzburg-Landau equations [27, 28]. But, in our study, the system does not comprise any amplifying media or saturable absorbers, hence, CNLSE is well suitable and preferably chosen for the analysis of the proposed objective. The propagation of the optical pulse through the considered TPCF structures are governed by a set of CNLSEs of the following form [1, 4, 17]

\[
\begin{align*}
    i \frac{\partial A_1}{\partial z} & = \frac{\beta_2}{2} \frac{\partial^2 A_1}{\partial t^2} + \gamma |A_1|^2 A_1 \\
    & + \kappa (A_2 + A_3) - \frac{i}{2} \alpha A_1 = 0, \\
    i \frac{\partial A_2}{\partial z} & = \frac{\beta_2}{2} \frac{\partial^2 A_2}{\partial t^2} + \gamma |A_2|^2 A_2 \\
    & + \kappa (A_1 + A_3) - \frac{i}{2} \alpha A_2 = 0, \\
    i \frac{\partial A_3}{\partial z} & = \frac{\beta_2}{2} \frac{\partial^2 A_3}{\partial t^2} + \gamma |A_3|^2 A_3 \\
    & + \kappa (A_1 + A_2) - \frac{i}{2} \alpha A_3 = 0,
\end{align*}
\]

Here \(A_1, A_2\) and \(A_3\) describe the input optical pulse propagating through cores 1, 2 and 3, respectively. \(\beta_2, \gamma\) and \(\alpha\) represent the group velocity dispersion, nonlinear Kerr coefficient and extinction coefficient, respectively. The coupling coefficient \(\kappa\) is defined by \(\kappa = \frac{2L_c}{\Lambda}\), where \(L_c\) is the coupling length. For planar configurations PC1 and PC2, \(A_3 = 0\) in equation (1) and \(A_1 = 0\) in equation (3), since there is no interaction between the guiding cores 1 and 3. The necessary fiber parameters for the TPCF configurations are determined at the central wavelength \(\lambda_0 = 1.55\ \mu m\) by employing FEM. For planar configuration, optical parameters of STPCF are:

\[
\begin{align*}
    \beta_2 & = -0.15\ \text{ps}^2/\text{km}, \\
    \alpha & = 2.59 \times 10^{-8}\ \text{dB}/\text{m} \text{ and } L_c = 1.28\ \text{mm}. \\
    \gamma & = 0.0024 \ W^{-1}\text{m}^{-1}, \\
    \alpha & = 6.33 \times 10^{-8}\ \text{dB}/\text{m} \text{ and } L_c = 1.1\ \text{mm}. \\
    \gamma & = 0.47 \ W^{-1}\text{m}^{-1}, \\
    \alpha & = 6.33 \times 10^{-8}\ \text{dB}/\text{m} \text{ and } L_c = 1.1\ \text{mm}. \\
    \gamma & = 0.42 \ W^{-1}\text{m}^{-1}, \\
    \alpha & = 6.85 \times 10^{-8}\ \text{dB}/\text{m} \text{ and } L_c = 3.95 \times 10^{-4}\ \text{m}.
\end{align*}
\]

For the dynamical study and the calculation of control power from the transmission characteristics of the proposed configurations, refer to [17].

The proposed novel triple core PCF based logic devices work on the principle of measurement of a phase dependent output power of one of the output ports. Based on the notion of soliton dynamics, the performance of the device is studied in a circularly designed triple core PCF in the anomalous regimes of an appropriately designed. In order to study the optical pulse propagation through the considered TPCF structures, we numerically solved three sets of CNLSEs. The birefringence has to be considered only if we design an elliptical core TPCF. In this case, we need to solve two sets of three coupled equations to analyse the dynamics, which is out of our interest. Hence, the birefringence will not play any significant role in the present work.

4. Construction of Half adder

For the accomplishment of the half adder, the planar configuration is studied for the two cases: (i) for PC1, CS is provided through core 1 and (ii) in the case of PC2, CS is introduced through core 2. Input 1 (I_1) and input 2 (I_2) are provided through cores 2 and 3 for PC1 and that for PC2 is

Figure 2. Schematic and input configurations of (a) planar and (b) triangular TPCF, respectively, with \(\Lambda = 2\ \mu m, d/\Lambda = 0.666\) and \(C = 2\Lambda\) for half adder operation. Reprinted from [17]. Copyright (2013), with permission from Elsevier.
provided through cores 1 and 3, respectively. Also, with that for the TC, the CS is provided through core 1, and I1 and I2 are introduced through cores 2 and 3. The input, output and CS combinations for half adder operation for all the considered configurations are provided in the bottom of figure 2. The CS applied to all the configurations may take the value 1 or 0 with a phase difference \( \Delta \phi = \Delta \phi_r \) between the input values I1 and I2, depending upon the logic gates needed. \( \Delta \phi \) takes the value from 0 to 2. The outputs of the logic gates from core 1 (O1) and core 2 (O2) are calculated from the extinction ratio XR1 (O1) and XR2 (O2) [13, 17, 18]. The XR studies analyzed here are for the coupler length (L) equal to 2 \( L_c \) for all the TPCF configurations. By choosing the suitable combinations of I1 and I2 as \( [0;0], [0;1], [1;0], [1;1] \) and their respective combinations of outputs (O1) and (O2) are used as a logic to construct the logic half adder. We assume the initial pulse \( A(0, t) = A_0 \exp \left( -\frac{t^2}{\tau^2} \right) \times \exp(i\Delta \phi) \) for CS and that of other cores are either \( B(0, t) = A_0 \exp \left( -\frac{t^2}{\tau^2} \right) \) or 0.001% of B(0, t) chosen accordingly to perform the half adder operation.

### 4.1. Plane 1 configuration

The XR of the PC1 for STPCF and CTPCF are shown by figure 3. The extinction ratios are same as that of the previous configuration but the system can demonstrate a logic half adder only for certain CS values. For the condition, CS = I1 = I2 = 0, the phase values do not influence the logic operation. In the case of CS = 0, the output exists only for the following combinations of inputs [I1;I2] = [0;0], (1;0), (1;1) but for CS = 1, the output exists for all the input combinations [I1;I2] = [0;0], (0;1), (1;0), (1;1) and obeys for all the configurations considered. From figures 3(a) and (b), with CS = 1 (\( \Delta \phi \)), I1 = 0 and I2 = 0, for any phase, the extinction ratio of O1 is around 10 dB, implying that most of the CS power is equally distributed to the O1 and O2. For input [I1;I2] = [0;1], the XR1 value is around \(-80 \) dB, which implies that most of the input power through I2 and CS power are transferred to the O2 port. In the case [I1;I2] = [1;0], initially a small amount of input power is transferred equally to the output ports O1 and O2 with a minor fluctuations in the power ratios at the points of a greater

### Table 1. Plane 1 configuration (PC1).

| I1 | I2 | CS | O1(Carry) | O2(Sum) | O1(Carry) | O2(Sum) |
|----|----|----|-----------|---------|-----------|---------|
| 0  | 0  | 0  | 0         | 0       | 0         | 0       |
| 0  | 1  | 1  | -4.03 dB  | 4.03 dB  | 1         | -4.42 dB |
| 0  | 1  | 1  | -1.49 dB  | 1.49 dB  | 1         | -0.39 dB |
| 1  | 0  | 1  | 2.72 dB   | -2.72 dB | 0         | 2.72 dB  |
| 1  | 1  | 0  | 8.25 dB   | 8.25 dB  | FOM       | 7.53 dB  |

### Table 2. Plane 1 configuration (PC1).

| Phase (\( \Delta \phi \)) | 1.4 | 1.5 | 1.6 | 1.4 | 1.5 | 1.6 |
|--------------------------|-----|-----|-----|-----|-----|-----|
| XR1 (dB)                 | 4.03| 2.02| 0.40| 4.42| 2.45| 0.88|
| FOM                      | 8.25| 8.09| 4.62| 7.53| 6.95| 4.02|

Figure 3. Extinction ratio (XR1) of (a) STPCF and (b) CTPCF of PC1 as a function of the phase parameter. Reprinted from [17]. Copyright (2013), with permission from Elsevier.
Figure 4. Extinction ratio (XR1) of (a) STPCF and (b) CTPCF of PC2 as a function of the phase parameter. Reprinted from [17]. Copyright (2013), with permission from Elsevier.

Figure 5. Extinction ratio (XR1) of STPCF and CTPCF of TC as a function of the phase parameter. Reprinted from [17]. Copyright (2013), with permission from Elsevier.

Table 3. Triangular configuration (TC).

| Silica CS($\Delta \phi_B = \pi$) | Chloroform CS($\Delta \phi_B = \pi$) |
|-------------------------------|-----------------------------------|
| I1  | I2  | CS | O1(Carry) | O2(Sum) | CS | O1(Carry) | O2(Sum) |
| 0   | 0   | 0  | 0         | 0       | 0  | 0         | 0       |
| 0   | 1   | 1  | -36.64 dB | 36.64 dB | 1  | -36.72 dB | 36.72 dB |
| 1   | 0   | 0  | -12.23 dB | 12.23 dB | 0  | -12.17 dB | 12.17 dB |
| 1   | 1   | 0  | 0.00 dB   | -0.00 dB | 0  | 0.00 dB   | -0.00 dB |
|     |     | 1  | 0         | 0       | 1  | 0         | 0       |
| FOM | 48.88 dB | 48.88 dB | FOM | 48.90 dB | 48.90 dB |

Table 4. Triangular configuration (TC).

| Silica |
|--------|
| Phase ($\Delta \phi$) | XR1 (dB) | FOM |
| 1      | 0.6     | 36.65 | 48.88 dB |
| 0.7    | 0.7     | 3.53  | 12.81 dB |
| 0.8    | 0.8     | 7.36  | 15.76 dB |
| 0.9    | 0.9     | 13.52 | 19.59 dB |
| 1.0    | 1.1     | 13.60 | 25.75 dB |
| 1.2    | 1.2     | 7.40  | 25.83 dB |
| 1.3    | 1.3     | 3.56  | 19.63 dB |
| 1.4    | 1.4     | 0.61  | 15.79 dB |

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phase, and most of the output power exits through the CS port. Finally, for the case $[I_1;I_2] = [(1;1)]$, the power variation exhibits similar behavior as that of the condition $[I_1;I_2] = [(1;0)]$ and the power level oscillating between the output ports $O_1$ and $O_2$ is further reduced.

For the half adder function, the SUM and CARRY of the half adder are provided by the outputs $O_1$ and $O_2$ as AND and XOR logic gates respectively. For PC1, both STPCF and CTPCF demonstrate the half adder operations, only for the phase values $\Delta \theta = 1.4$, 1.5 and 1.6. The FOM of the half adder used to identify the best configuration among the half adders achieved for different phase values are defined by the sum of the modulus of the individual combinations of the extinction ratios to obtain the logic half adder. The maximum FOM is achieved for the phase $\Delta \Phi_R = 1.4 \pi$. The half adders achieved for STPCF and CTPCF with the best FOM are shown in table 1. In table 2, the FOM calculated for PC1, for all phase values which demonstrate the half adder operation, are provided.

### 4.2. Plane 2 configuration

For PC2, CS is introduced through core 2 and the XRs obtained are displayed in figure 4. For the input condition, $[I_1;I_2] = [(0;0), (1;1)]$, the exit power is almost equal for $O_1$ and $O_2$ and most of it exits through the CS exit. Next, for inputs, $[I_1;I_2] = [(0;1)]$, the XR plot displays a negative value for XR1 indicating that most of the input power is exited via $O_2$ and CS ports. In the case of input, $[I_1;I_2] = [(1;0)]$, most of the exit power transfers through $O_2$ and that through the CS output $O_2$ is almost negligible. The PC2 configuration reveals only EX-OR logic operation, hence, there is no possibility of obtaining of the half adder.

### 4.3. Triangular configuration

XRs for different input combinations for TC is provided in figure 5. For the input condition, $[I_1;I_2] = [(0;0), (1;1)]$, the XR1 is almost zero, implying that the exit power through $O_1$ and $O_2$ are almost equal, and most of the exit power is transmitted through CS output. For the condition $[I_1;I_2] = [(0;1), (1;0)]$, the input power oscillates between the output ports $O_1$ and $O_2$ with negative and positive values around 36 dB, respectively. Comparing all the configurations considered, TC demonstrates more possibility to construct half adder operation for the multiple phase values ($\Delta \theta = 0.6$, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 14). The maximum FOM achieved for the phase value $\Delta \Phi_R = \pi$ is tabulated in table 3, and the FOM achieved for other possible phase values are provided in tables 4 and 5 for STPCF and CTPCF.

### 5. Conclusion

In this article, all optical logic half adder operation is demonstrated via diverse TPCF configurations by employing SSFM. Out of the three combinations considered, PC1, PC2 and TC, PC2 does not exhibit the combination of XOR and AND logic gates to perform the logic half adder function. In the case of PC1, TPCF demonstrates the possibility to construct half adder for three different phase values, and that for TC shows the existence of nine different phase values through which Boolean operation for half adder can be performed. The prime advantage of the present study is that the identical set of TPCF configurations used to demonstrate the all-optical logic gates in our previous report reveals the potential to construct all-optical logic half adder operation. When compared to the half adder realized through PC1, that obtained through TC demonstrates an excellent FOM. Moreover, it is worth to notice that the FOM of STPCF is a little bit greater than CTPCF, however, CTPCF exhibits excellent transmission characteristics with minimal input power owing to its elevated nonlinearity. In particular, TC CTPCF will be the most suitable candidate to function as an ultrafast all optical half adder.

## Acknowledgments

RVJ Raja wishes to thank DST fast track programme for providing financial support.

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