Journal of Research in Science Engineering and Technology
Volume 9, Issue 1, December 2021, pp. 29-37

Journal of Research in Science Engineering and Technology

www.researchub.org

A Novel Design of Optical RS Flip-Flop Based on Nonlinear Nano-Cavity in Hexagonal Photonic Crystal Substrate

Mojtaba Hosseinzadeh Sani[1]*, Parisa Sami[2], Chao Shen[3], Hamed Saghaei[4]

[1, 2, 3] Faculty of Electronic and Information Engineering, Xi'an Jiaotong University, China
[4] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Canada

Abstract

In this work, we present an all-optical flip-flop (AOFF) structure based on non-linear materials in two-dimensional photon crystal substrate. In this hexagonal square structure, we propose a nonlinear resonance nanocavity to show the trade-off between switching time and triggering power. The linear rods material is made of silicon with a refractive index $n_0 = 2.6$ and the non-linear rods material is made of AlGaAs with a refractive index of $n_1 = 1.4$ and $n_2 = 1.5\times10^{-17}$ W/μm². The proposed Flip-Flop is the RS type (RSFF) and center signal wavelength is λ = 1.550 μm, and is one of the most efficient and practical structures used in optically integrated circuits. This design has a fast switching function of 2 ps and low input power with a power of 100 mW. The minimum power loss in the structure is P_{loss} = 2 mw Another advantage of this structure is the high contrast of the output signals for the ON/OFF modes, which can help to easily detect or connect it to other optical devices. The proposed structure is designed to be very simple and very small dimensions (S = 86.21 μm²), which can be used in an integrated optical circuit. In addition, we provide a very in-depth view of system performance, as analyzed using the two-dimensional time-constraint (2D-FDTD) method.

Keywords

Hexagonal Photonic Crystal, RS Filip-Flop (RSFF), Nonlinear Nanocavity

1. Introduction

Photonic crystals are derived from the structure of natural crystals. Almost all metallic elements and many insulating elements and composites can be found crystalline in nature. Atomic materials and molecules also play a scattering role for electron waves. Electron waves are scattered to the sides due to the colonic repulsion of crystal ions and move at certain angles that inhibit the scattering effect of the ion group. Due to the fact that free electrons in materials have the function of electrical conduction, the shape of the crystal and the type of atoms used are directly involved in the electrical properties of

* Corresponding Author: Faculty of Electronic and Information Engineering, Xi'an Jiaotong University, China
E-mail addresses: mojtabasani69@gmail.com

Received 26 September 2020 / Accepted 15 November
DOI: https://doi.org/10.24200/jrset.vol9iss01pp29-37

the device. Photon crystals have a wide range of applications including analog to digital converters (Sani et al., 2020a; 2020b), all-optical Fiber (Saghaei, 2017; 2018), semiconductor optical amplifier (Stubkjaer, 2000), optical biosensors (Sani & Khosroabadi, 2020), nonlinear micro ring resonators (Qiang et al., 2007; Saghirzadeh Darki & Granpayeh, 2010), ultrafast nonlinear half-adder (Sani et al., 2020c; Saghaei et al., 2017), all-optical logic gates (Pooley et al., 2012), optical semiconductor amplifiers (Stubkjaer, 2000), optical Flip-flop (Abbasi et al., 2012; Mostafa & El-Rabaie, 2019)

Photonic crystals consist of scattering wave instruments that are regularly placed next to each other to form an interference pattern at more favorable angles. Thus, there are many similarities between a photon crystal and an array of identical antennas, so that it can be said that photon crystals are an array of very small antennas in a regular one, two, or three-dimensional arrangement in They are next to each other. If hypothetical isotropic antennas were used for this purpose, we had a network of antennas that could disperse the input power at different angles, like an array of antennas, due to the destructive and constructive interference of internal network members at different angles. However, if antennas with anisotropic scattering pattern are used, the scattering and scattering pattern of the product will overlap the pattern of each antenna and the network interference pattern. However, there are some differences. When an array of antennas is fed to send power at a certain angle, in the source photon crystals, it is the input wave signal that is scattered around by the scatterers. In addition, due to the fact that the most important field of work of photon crystals are in the range of light and infrared waves and millimeters, unlike the antenna arrays used metals are not very common due to their large losses in the frequency range. In this way, photon crystals can be thought of as arrays of dielectrics with distinct geometric shapes (such as cubes) arranged in a regular arrangement.

Nonlinear optical phenomena are nonlinear in that the response of a material to a light field depends nonlinearly on its field strength. For example, the second coordinate production changes to a quadratic with the intensity of the optical field due to part of the atomic response. So, the light intensity generated at the second harmonic frequency will be proportional to the square of the laser light intensity applied. To discuss more precisely the nonlinear effects, how the dependence of the bipolar displacement per unit volume or electric polarization on a material the size of the electric field of the applied light must be examined. In linear optics, the polarization induced linearly depends on the intensity of the applied electric field (Miao et al., 2006)

$$\mathbf{P} = \varepsilon_0 \chi^{(1)} \mathbf{E} \tag{1}$$

In this relation, the proportionality of $\chi^{(1)}$ is the linear acceptance and ε_0 is the vacuum permeability. In nonlinear optics, the optical response is often examined by extending Equation (1) and expressing P it as a series of powers relative to the intensity of the E electric field (Miao et al., 2006):

$$\mathbf{P} = \varepsilon_0 \left(\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{EE} + \chi^{(3)} \vdots \mathbf{EEE} + \ldots\right) \equiv \mathbf{P}^{(1)} + \mathbf{P}^{(2)} + \mathbf{P}^{(3)} + \cdots \tag{2}$$

Where $\chi^{(2)}$ and $\chi^{(3)}$ are second- and third-order nonlinear acceptances, respectively. Due to the fact that the materials in this study are AlGaN and also the photon crystal structures have a specific photon band gap and a certain emission frequency range, the second-order nonlinear effects are removed due to the isotropic of the materials and removed from the effects. The third order of nonlinearity, which is capable of propagating within a photonic gap and is therefore important to us, is only the intensity-dependent refractive index or nonlinear refractive index, also called the chorus effect. The nonlinear refractive index of many materials can be calculated by Equation (3).

$$n = n_0 + \bar{n}_2 \langle \tilde{E}^2 \rangle \tag{3}$$

Stated that n_0 represents the normal or linear refractive index at weak field intensity and the $\bar{n}_2$ show the second-order refractive index, which shows the rate of refractive index increase with light intensity. The high load sign of $\bar{n}_2$ to indicate it is the nonlinear refractive index of $\bar{E}$.

The proposed flip-flop structure is of type RS (RSFF) and has three outputs, one for the normal value (Q), one for the stored bit complement value ($\bar{Q}$) and one for the undefined state. On the other hand, this structure has two inputs "SET" and "RESET". Binary information can be applied to the input of a flip-flop in separate ways, creating a variety of small modes. Applying a pulse to each of the inputs changes the status of the outputs. These types of flip-flops are used as a basic structure, and through this basic structure, more complex devices can be designed and used in all optical memories.

2. Design and Optimization

The (RSFF) proposed logic circuit has three outputs Q and $\bar{Q}$ and is undefined, with two adjustment and reset (R) inputs. Flip-flop (RSFF) is a 1-bit memory that has two stable modes. While to, are assigned logical values 0 and 1. The functional characteristics of this (RSFF) are described in terms of values and pulses applied to the input and latency. After applying a set of inputs to the structure, after a short time, (RSFF) outputs are generated. The current output value ($\bar{Q}$) often depends on the previous output value (Q), which of course depends on the previous input values (Mano, 1988). Figure 1 shows the (RSFF) block, and Table 1 shows the various logic states.

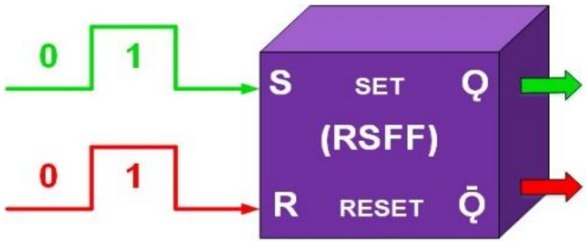

Fig. 1. RS Flip-Flop (RSFF) Block

Table 1. Logical states of Rs Flip-Flop (RSFF)

S	R	Q	$\bar{Q}$	State
0	0	Q	$\bar{Q}$	No change
0	1	0	1	Reset
1	0	1	0	Set
1	1	0	0	Undefined

Figure 2 shows the Brillon region in a hexagonal structure and the polarization modes and optical band gap. As can be seen in this figure, the designed lattice have been TM and TE polarization modes. Due to the larger optical gap for TM polarization mode, input light signal with TM mode is applied to the inputs Waveguide. The created optical gap for the TM mode have a wavelength range of λ = 1.231

μm ~ 2.033 μm and the frequency range (ω_2) of a/λ = 0.2705 ~ 0.4467. Due to the low wavelength rang and low frequency range (ω_1) of TE mode, we use TM polarization mode.

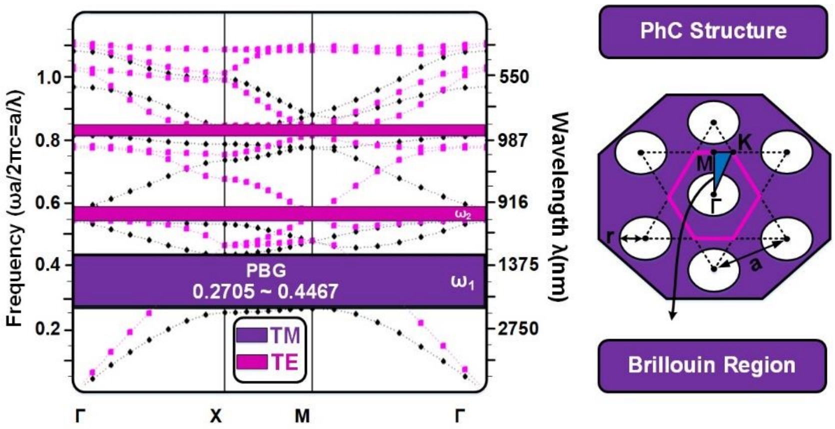

Fig. 2. Photonic band gap and brillouin region

In the proposed structure, the dielectric rods are made of silicon and are placed in the air bed. The photon crystal is designed as hexagonal and two-dimensional. The latice index value is a = 550 nm and the radius of the rodsis equal to r = 106.15 nm. The design has two inputs, set and reset, and has three outputs. The main switching operation is performed by nanocavtis resonance with nonlinear materials. The pink rod acts as the main nanocavity and radius is R_C = 328.1 nm and the green rods around the main nanocavity have a radius of R_S= 154.4 nm. Because the total dimensions of the small have been selected, it increases the speed and also has the ability to integrate. The overall size of the structure is equal to S = 86.21 μm^2.

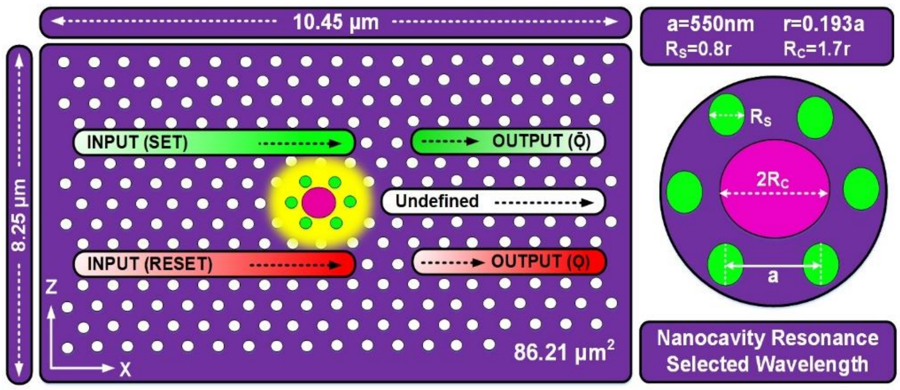

Fig. 3. All-optical Rs Flip-Flop (RSFF)

3. Result and Discussion

The function of the structure is that when an optical signal is applied to the SET input, it goes straight through the waveguide path and exits the Q output. When the optical signal is applied to input RESET, its transmission the direct path of the waveguide and exits output $\overline{Q}$. Finally, when a signal is applied to both inputs, the applied signal intensity must be doubled and increased, causing the nonlinear nanocavity to absorb the optical signal at high power intensities and transmit it to an undefined output.

In Figure 1 of section (a), the optical signal with 0.1W is applied to the SET input. Because the power of the optical signal is weak, the nonlinear nanocavity resonance does not perform any absorption action, and the optical signal transmission its direct path and exits the Q output. In Figure 1 of section (b), the optical signal with 0.1W is applied to the RESET input, and in this case, due to the weak optical signal, the nonlinear rods are inactive and the optical signal transmission in a straight path and transmits to the $\overline{Q}$ output. In Figure 1, section (c), an input signal with a power of 0.1 W is applied to both inputs and the total signal applied reaches 0.2 W. Due to the increase in signal strength, the refractive index of nonlinear materials changes in proportion to the field strength and causes signal absorption and transmits it to an undefined output.

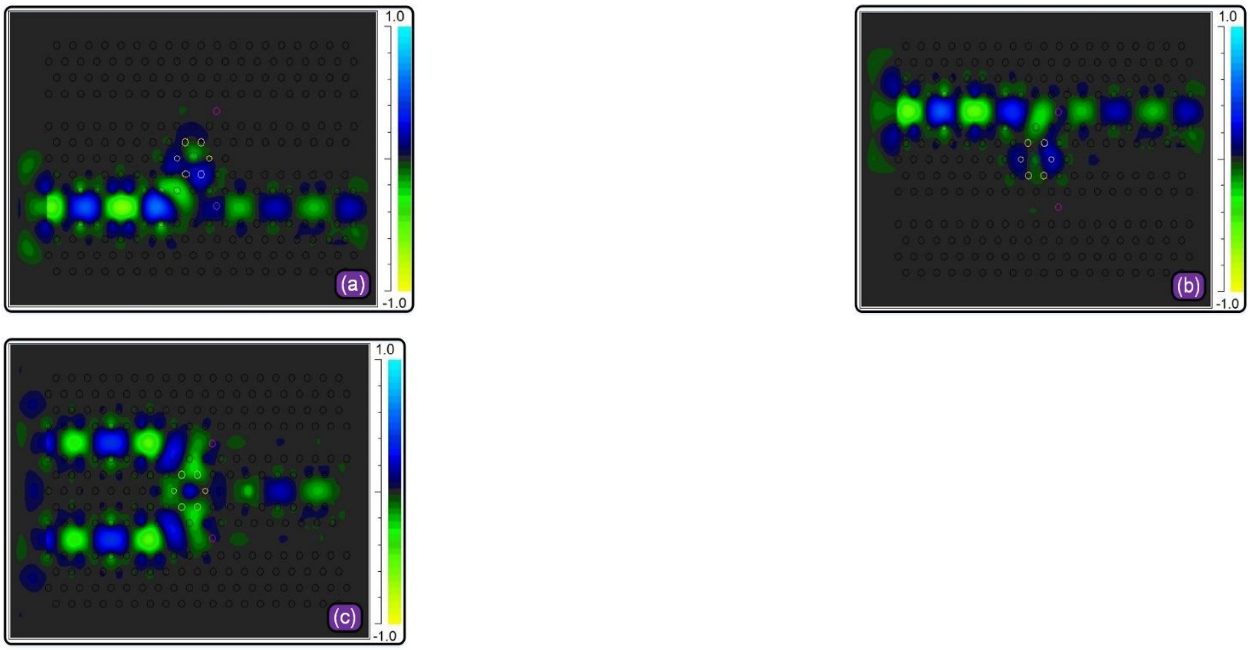

Fig. 4. Optical behavior of the structure for, (a) S=0, R=1, (b) S=1, R=0, (c) S=1, R=1

In the flip-flops, the speed of operation is of particular importance. Therefore, the delay time parameter becomes important in the proposed structure. The amount of time it takes for an optical signal to reach from the input to output waveguide is called the delay time. As shown in Figure 1 (a), an optical signal with a power of 0.1W is applied to the SET input (Input $_{SET}$ = 0.1W, Input $_{RESET}$ = 0W). This signal after passing through the input waveguide and the nanocavity resonance in the time of 2ps reaches the output of the structure. The amount of power lost in this case is equal to 2%. In Figure 5 (b), optical signal with a power of 0.1W is applied to the RESET input (Input $_{SET}$ = 0W, Input $_{RESET}$ = 0.1W). In this section, time delay is equal to 2ps and power loss is 2%. In Figure 5 (c), the optical signal is applied to both inputs (Input $_{SET}$ = 0.1W, Input $_{RESET}$ = 0.1W). As can see this figure, nonlinear nanocavity resonance reaches the optical signal and transmitted to the undefined output. Powe loss for this mode is 18 % and time delay is equal to 3.4ps.

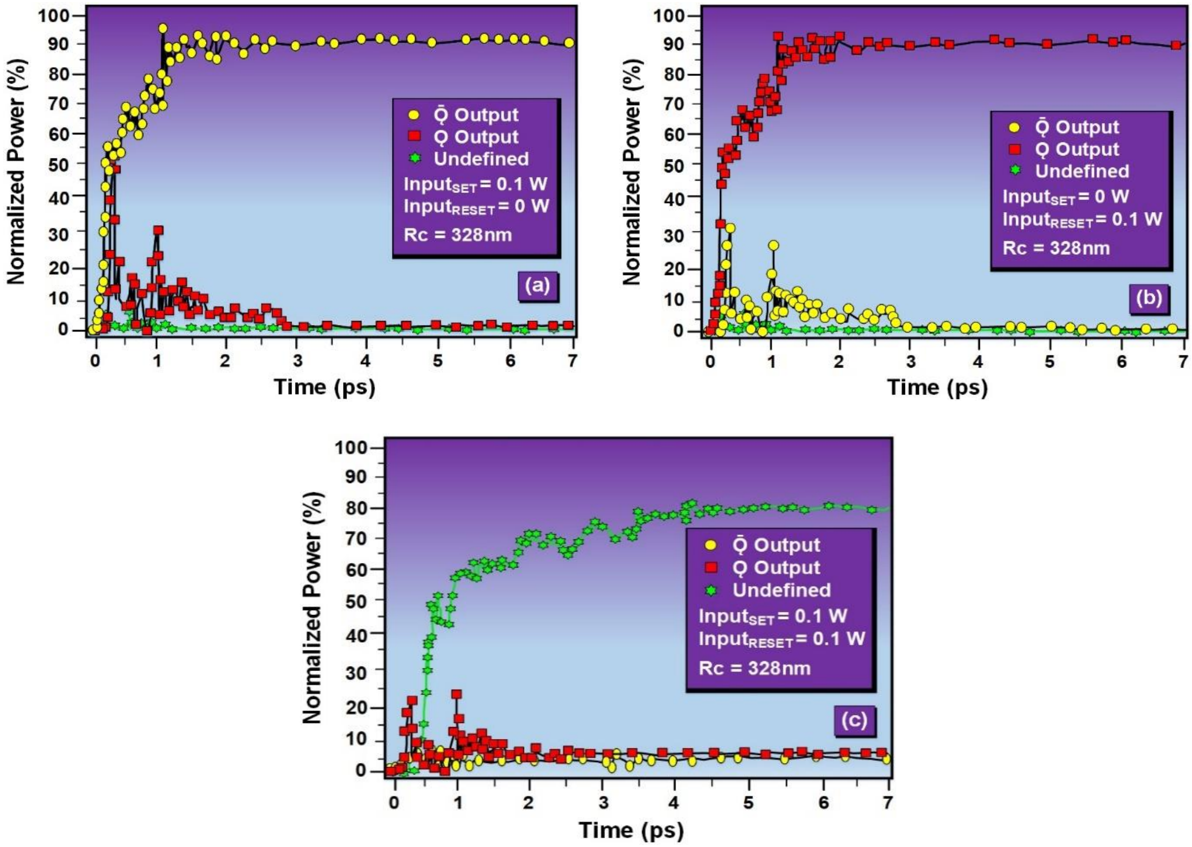

Fig. 5. Normalized output power of the structure in different modes for (a) P_{SET} = 0.1W, P_{RESET} = 0W (b) P_{SET} = 0W, P_{RESET} = 0.1W (c) P_{SET} = 0.1W, P_{RESET} = 0.1W

The Figure 6 shows the general time chart for RS flip-flops. T0 time indicates the start of the clock set, with applied is the clock pulse to the set input, we receive the pulse from Q output. At time t_2, by applied the pulse to the reset input, the output $\bar{Q}$ have a pulse and the output Q does not receive any value. At t_4 time, a pulse is applied to both set and reset inputs, which is undefined in this case and no pulse is received from the outputs.

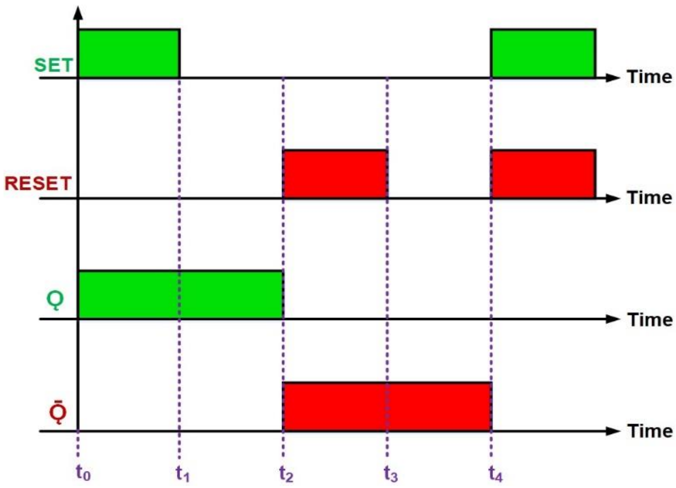

Fig. 6. Time chart of the different states of RS flip-flop (RSFF)

Figure 7 analyzes the proposed RS flip-flop performance. For the state where the input of the SET is active (Input $_{SET}$ = 100 mW, Input $_{RESET}$ = 0), or green pulse, the output Q receives an optical signal after 2 ps, of which 98% of the input signal is transmitted to the output, or in other words, we will have 2% power loss. Therefore, the amount of power received for this mode is equal to 98 mW (Power $_{Q}$ = 98 mW, Power $_{\bar{Q}}$ = 1mW, Power $_{Undefined}$ = 1mW). In the next state, a light signal or red pulse is applied to the RESET input (Input $_{SET}$ = 0, Input $_{RESET}$ = 100 mW), which in this case is received from the output of $\bar{Q}$ after 2 ps, and the received power in this case is equal to 98 mW (Power $_{Q}$ = 1 mW, Power $_{\bar{Q}}$ = 98 mW, Power $_{Undefined}$ = 1mW). In the final state, a light signal or yellow pulses are applied simultaneously to the set and reset inputs, in which case 82% of the power is transferred to the undefined output or received power in this case is equal to 82 mW, and the Q and $\bar{Q}$ outputs will be 9mW (Power $_{Q}$ = 9 mW, Power $_{\bar{Q}}$ = 9 mW, Power $_{Undefined}$ = 82mW). The delay time for this mode will be 3.4 ps.

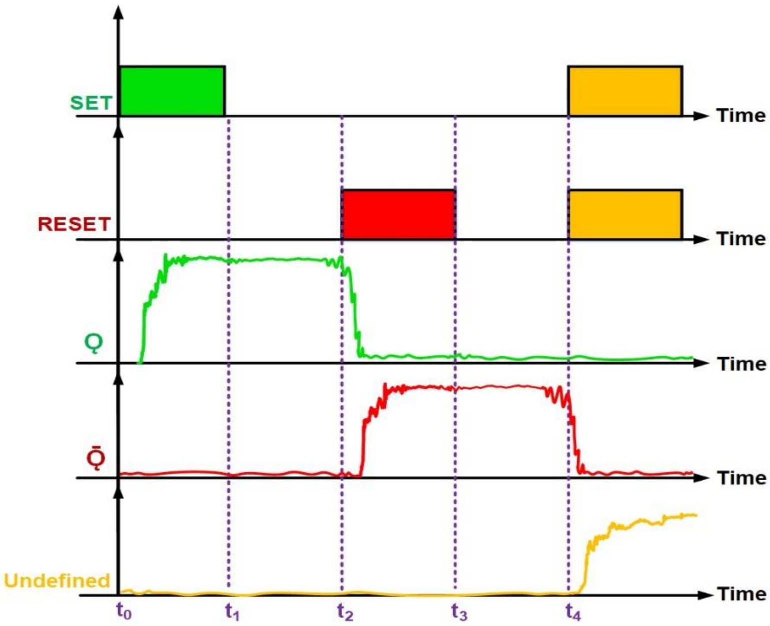

Fig. 7. The time dependent simulation results of the proposed optical RS flip flop (RSFF)

Table 2 the shows the percentage of transmitting power and lost power in waveguides and nano cavitation resonance and delay time. As can be seen in this table, the minimum power loss is 2% or P_{loss}= 2 mW and the minimum delay time is equal to 2 ps. According to the obtained values, it can be concluded that the RS flip-flop structure is designed with high performance speed and low power losses.

Table 2. Shows the percentage of transmitting power, lost power and delay time

Input $_{SET}$ (mW)	Input $_{RESET}$ (mW)	Output $_{Q}$ (mW)	Output $_{\bar{Q}}$ (mW)	Undefined (mW)	Delay (Ps)
0	0	0	0	0	0
100	0	98	1	1	2
0	100	1	98	1	2
100	100	9	9	82	3.4

In Table 3, our proposed structure is compared with similar proposed structures, which is smaller and more efficient than the similar structure in terms of dimensions, and is reduced in terms of delay time, and finally power losses are minimized. Therefore, according to the obtained specifications, the proposed structure can be used in high-speed optical integrated circuits and low power losses.

Table 3. Proposed Flip-Flop is compared with similar structures

Proposed	App	Transmission (%)	Delay (Ps)	Footprint (μm^2)
Abbasi et al. (2012)	RSFF	94	6	201.02
Moniem (2015)	SRFF	47	3.89	900
Mostafa & El-Rabaie (2019)	DFF	90	0.21	1
This Work	RSFF	98	2	86.21

4. Conclusion

We propose an all-optical RS flip-flop structure using nonlinear nanocavities resonance. This structure is designed in a hexagonal two-dimensional photonic crystal substrate. We tried to design the dimensions of the structure with the least possible. Due to the correct choice of linear and nonlinear rods and the radii of dielectric rods, the structure is optimized in terms of speed and power losses. The minimum power loss in the structure is 2 mw and the maximum delay time is 3.4 ps and the minimum delay is time 2 ps. The percentage of transmission power is 98% and the overall dimensions of the structure are 86.21 μm^2. According to the results, the proposed structure can be used in high-speed optical integrated circuits and low power losses.

References

Abbasi, A., Noshad, M., Ranjbar, R., & Kheradmand, R. (2012). Ultra compact and fast All Optical Flip Flop design in photonic crystal platform. Optics Communications, 285(24), 5073-5078. https://doi.org/10.1016/j.optcom.2012.06.095

Mano, M. M. (1988). Computer engineering hardware design: Prentice-Hall, Inc.

Miao, B., Chen, C., Sharkway, A., Shi, S., & Prather, D. W. (2006). Two bit optical analog-to-digital converter based on photonic crystals. Optics express, 14(17), 7966-7973. 10.1364/OE.14.007966

Moniem, T. A. (2015). All-optical SR flip flop using 2-D photonic crystal. Optical and Quantum Electronics, 47(8), 2843-2851. https://doi.org/10.1007/s11082-015-0173-7

Mostafa, T. S., & El-Rabaie, E.-S. M. (2019). All-Optical D-Flip Flop with Multi-Wavelength Operation Based on Photonic Crystal. Paper presented at the 2019 7th International Japan-Africa Conference on Electronics, Communications, and Computations,(JAC-ECC). 10.1109/JAC-ECC48896.2019.9051118

Pooley, M., Ellis, D., Patel, R., Bennett, A., Chan, K., Farrer, I., . . . Shields, A. (2012). Controlled-NOT gate operating with single photons. Applied Physics Letters, 100(21), 211103. https://doi.org/10.1063/1.4719077

Qiang, Z., Zhou, W., & Soref, R. A. (2007). Optical add-drop filters based on photonic crystal ring resonators. Optics express, 15(4), 1823-1831. 10.1364/oe.15.001823

Saghaei, H. (2017). Supercontinuum source for dense wavelength division multiplexing in square photonic crystal fiber via fluidic infiltration approach. Radioengineering, 26(1), 16-22.

Saghaei, H. (2018). Dispersion-engineered microstructured optical fiber for mid-infrared supercontinuum generation. Applied Optics, 57(20), 5591-5598. https://doi.org/10.1364/AO.57.005591

Saghaei, H., Zahedi, A., Karimzadeh, R., & Parandin, F. (2017). Line defects on As2Se3-Chalcogenide photonic crystals for the design of all-optical power splitters and digital logic gates. Superlattices and Microstructures, 110(1), 133-138. https://doi.org/10.1016/j.spmi.2017.08.052

Saghirzadeh Darki, B., & Granpayeh, N. (2010). Improving the performance of a photonic crystal ring-resonator-based channel drop filter using particle swarm optimization method. Optics Communications, 283(20), 4099-4103. https://doi.org/10.1016/j.optcom.2010.06.013

Sani, M. H., & Khosroabadi, S. (2020). A novel design and analysis of high-sensitivity biosensor based on nano-cavity for detection of blood component, diabetes, cancer and glucose concentration. IEEE Sensors Journal, 20(13), 7161-7168. 10.1109/JSEN.2020.2964114

Sani, M. H., Khosroabadi, S., & Nasserian, M. (2020b). High performance of an all-optical two-bit analog-to-digital converter based on Kerr effect nonlinear nanocavities. Applied Optics, 59(4), 1049-1057. https://doi.org/10.1364/AO.379575

Sani, M. H., Khosroabadi, S., & Shokouhmand, A. (2020a). A novel design for 2-bit optical analog to digital (A/D) converter based on nonlinear ring resonators in the photonic crystal structure. Optics Communications, 458(1), 124760. https://doi.org/10.1016/j.optcom.2019.124760

Sani, M. H., Tabrizi, A. A., Saghaei, H., & Karimzadeh, R. (2020c). An ultrafast all-optical half adder using nonlinear ring resonators in photonic crystal microstructure. Optical and Quantum Electronics, 52(2), 107. https://doi.org/10.1007/s11082-020-2233-x

Stubkjaer, K. E. (2000). Semiconductor optical amplifier-based all-optical gates for high-speed optical processing. IEEE journal of selected topics in quantum electronics, 6(6), 1428-1435. 10.1109/2944.902198