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Design and modelling of the photonic crystal fano structure for all optical switching applications

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Abstract
In this paper, the optical Fano switch based on the 2D slab photonic crystal is analyzed. Switching characteristics are improved by manipulating the Q factors of cavities. Modified device with enhanced Fano resonance has lower energy consumption than other previous optical switches. Results show that, the switching contrast is enhanced while the quality factor has remained in its highest value. Therefore, the typical important trade off between switching contrast and quality factor has vanished in the modified structure. The switching contrast is improved from 7 to 34 db in constant $\Delta\lambda_{peak-peak}$ of 0.3 nm in the modified structure which leads to decreasing the energy consumption of the device. In the previous devices, the maximum reported contrast is about 20 db for $\Delta\lambda_{peak-peak}$ of 0.6 nm. A coupled mode theory for analyzing the structure is developed. The results of finite difference time domain numerical simulation are in good agreement with the theoretical coupled mode theory. Results show that the switching contrast of the modified Fano switch is enhanced two times, consequently the loss is suppressed and the bandwidth is improved.

Keywords Optical switching · Photonic crystal switch · Fano switch · Non linear devices · All optical switching

1 Introduction

In recent years, the increase in video sharing and subsequently increase in network bandwidth has been depicted a new roadmap for future optical interconnects. The electronic limitations that emerge in forms of high losses in copper wires at high frequencies, leads global efforts to use optical solutions in communications. Recently, efforts in this area is concentrated on optical interconnects because of their ability to realize next generation of optical computers. Therefore, it is required for optical elements to become small and smaller and one of the best candidates for this goal is slab photonic crystal structures. These structures thanks to their high optical confinement abilities, could be used as so tiny

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optical devices with so high light-matter interaction (LMI). Current optical devices with ultra large volume are not suitable for using in optical computers, so inventing new devices with micro meter scale with very low energy consumption seems to be crucial for future optical computers (Miller 2009). These problems arise from the point that, optical switching operation is done using the nonlinear semiconductor effects such as two photon absorption, Kerr effect etc. and these effects just emerge when the light intensity is so high to ensure that they have considerable effect, however enhancing the nonlinear effects leads to high energy consumption for proper switching operations (Tajima et al. 2002). The problem is resolved by increasing the interaction between light and matter, so we will be able to employ nonlinear effects with lower energy consumption.

Photonic crystal cavities with high quality factor (Q) and ultra-small volume (V) (higher Q/V ratio leads to higher cavity intensity and then higher non-linear effects) are the best candidate for making ultra-small and ultra-low energy consumption devices proper for photonic interconnects (Miller 2009; Nozaki et al. 2011). Various optical devices (switch, modulator, sensor, filter, etc.) have been proposed based on photonic crystal structures. However, 3D- PhCs usually lead to complexities in connectivity and strict alignment, which make them rather challenging for fabrication (Benisty 1996; Mekis et al. 1998; Zhang and Qiu 2004). Alternatively, two dimensional photonic crystal slabs have been introduced (Krauss et al. 1996; Johnson et al. 1999), which provide easier fabrication. Over the past decade, much work has been devoted to the study of nanocavities in these 2D-PhC slabs. These nanocavities exhibit attractive properties such as high Q in small V, which make them potentially useful not only in chip scale photonic devices but also in some quantum optical devices.

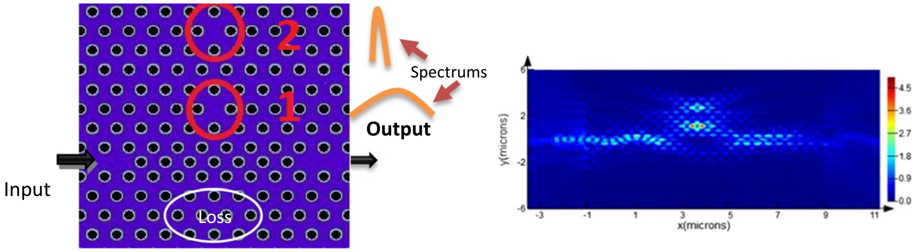
The all optical switch is the key component for optical interconnects. Several high speed all-optical switch types have already been reported, using optical nonlinearity. For instance, all optical switches based on inter-sub-band transition (ISBT) in semiconductor quantum wells are introduced which can operate ultra-fast in a few picoseconds or less (Gopal et al. 2002; Cong et al. 2007), but with a switching energy of several picojoules or more. This means that the power consumption would be several tens of milliwatts or more for operating at 10 Gbps, which is not proper for optical computers. Other types of all-optical switches based on semiconductor optical amplifiers (SOAs) (Nakamura et al. 2001; Nielsen et al. 2006) or parametric processes (Yamamoto et al. 1998; Lee et al. 2005; Andrekson et al. 2008) also designed which consume too low energy but yet too high for optical chips because they need high driving power. Recently by introducing photonic crystal (PhC) cavities, the situation has been changed and because of the properties of these devices to confine light strongly, the optical integrated circuits are more accessible. In all optical switches based on resonators, the data signal transmission will be controlled by shifting the resonance of resonators via an optical control source (Husko et al. 2009; Xu et al. 2005). Therefore, the energy consumption of the device is dependent on the shape of the transmission spectrum which leads to more or less refractive index shift requirement for achieving a certain extinction ratio (Husko et al. 2009; Nozaki et al. 2010; Bazin et al. 2014). In Lorentzian based switches, the extended tails of a Lorentzian spectrum leads to large switching energies, while In Fano resonance (Fano 1961) the Fano shape with its asymmetricity, featuring a large transmission change within a smaller $\Delta\lambda$, which is induced from transition from constructive to destructive interference between the discrete state and continuum, thus enabling low-energy switching. Fano resonance which is the base of Fano devices was first discovered by Fano (1961). Several groups are working on applying this concept to optical devices to achieve better performance such as all optical devices, lasers, spectrum filters etc. (Fano 1961; Nozaki et al. 2010, 2013; Peng et al. 2018). Lots of structures have been proposed by several teams and the Fano shaping mechanism has been discussed. Fano resonance is the result of interference between discrete and continuum states which leads to better spectrum for switching applications. The optical switches with Lorentzian spectrum (Nozaki et al. 2011) have higher energy consumption for interconnect applications because Lorentzian spectrum because of its shape, may be more prone to consume excess energy in compare to so sharp Fano resonances.

The paper is organized as follows: In Sect. 2, the structure of the optical switch is presented. Simulations and modelling equation are brought in Sect. 3. Results are discussed in Sect. 4. Finally, the conclusion is brought in Sect. 5.

2 Structural concept

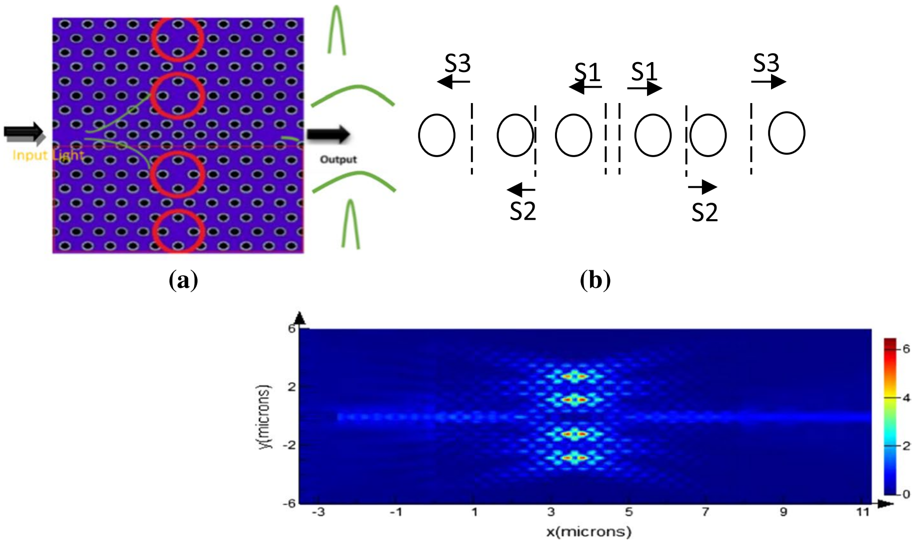
2.1 Physical structure

In PhC based Fano resonator, a simple nano-cavity could stand for the discrete state while the waveguide stands for the continuum, and when the spectrum of the states combine in certain frequencies, the Fano resonance will occur. Both of the Waveguides and cavities can play the role of continuum states (Yu et al. 2016; Nozaki et al. 2013). In quality factor (QF) point of view, two elements with high contrast QFs can interact and consequently, Fano resonance can be occurred. In structure shown in Fig. 1a (Fano 1961), a PhC nano cavity-waveguide based structure has been used for making better light confinement toward better non-linear effects and then smaller and lower energy consumption. The resulted sharp and asymmetric transmission spectrum named Fano resonance, enables us to design ultra-low and fast devices. Regarding to the simulation results shown in Fig. 1b, diffraction of light occurs when the light reaches the central cavities. Diffraction leads to light loss (power dissipation). The problem can be solved by modifying the structure as shown in Fig. 2a, as a consequence, the diffracted light deviated under the waveguide, will be collected efficiently and we won't have any loss due to diffraction. By symmetrizing the structure, another interesting effect emerges which leads to Fano shape improvement which will be discussed later. The modified structure discussed in this paper is shown in Fig. 2a. It is based on the works have been done in (Nozaki et al. 2013). The structure consists of four cavities for manipulating the light and an in/out waveguides for transmitting the light. Four cavities consist of 2 similar pairs of cavities while each pair is designed to make an



(a) (b)

Fig. 1 **a** Two cavity Fano optical switch (Nozaki et al. 2013). **b** FDTD simulation results for electric field profile



(a) (b)

(c)

Fig. 2 **a** Symmetric structure. **b** The procedure of making new cavity. **c** FDTD simulation results for electric field profile

asymmetric Fano shape, as a result two fano resonance are appeared at the output, and also waveguides are applied just for guiding the light needed to be switched to the structure.

It should be noted that, as (Nozaki et al. 2013), the two-state system which is required for making Fano resonance at the output, consists of two different cavities as shown in Fig. 1a. Noted that cavities have the same structure however, regarding their position in the structure, they have different quality factors (QFs). To be clear, the up cavity has weaker coupling to other components and therefore it has higher quality factor (Q) and the down cavity because of its vicinity to waveguides and also up cavity, has lower Q factor. Cavities (i.e. Nano-cavities) are made simply by shifting two near holes and next two neighbors in opposite directions which displacement is done for suppressing the cavity vertical losses as described in (Asano et al. 2010). Here, two different approaches have been considered to improve the switching characteristics of the structure as more as possible to make higher difference between quality factors of down and up cavities (separately in each pair). As the first approach, the up cavity in the structure is more softened by appropriate shifting of four around holes (Fig. 2b) instead of just two around holes according to experimental results (Asano et al. 2010)while down cavity is unchanged. It is shown that, this new softening method leads to higher Q factor (Asano et al. 2010) and results will show that higher Q contrast is required for having better Fano shape. In this structure, the topology leads one cavity to act as a continuum state (somewhere the modified waveguide is considered as continuum state (Yu et al. 2016) and another cavity with higher Q factor to stand for discrete state (Fano 1961), as mentioned before these states are essential to have Fano resonance. The second significant work has been done to improve the structure (Nozaki et al. 2013), was to make high Q state become higher while the continuum remained unchanged by increasing Q factors contrast topologically instead of cavity structure improvement which has been described. In fact, as shown in Fig. 2a, for suppressing the losses of light induced from diffraction the same two cavity system added into the region under the waveguide. Therefore, the input light which is deviated into dual cavity systems after collision with air holes in the waveguide is shaped and transmitted to the output while the delay of the structure for shaping the fano spectrum is unchanged. As a consequence, all the light (Fig. 2c), is collected and the efficiency of light collection is doubled in respect to previous structure (Nozaki et al. 2013) and this leads to steeper Fano shape as well as increasing of light intensity in the output. Besides, this symetrization, improve light transmission and reflection two times better than previous structures when switch is on and off respectively.

2.2 Design parameters

As shown in Fig. 2a, the bulk photonic crystal, is made up of a triangular air hole photonic crystal slab with air hole radius of 0.25a and thickness of 0.4a (Nozaki et al. 2010, 2013). The wavelength of light in the structure is the one that typically used in optical communications. The waveguide width correctly defined (0.76 μm) to provide low reflection as well as good optical confinement in waveguide, also the waveguide will be remained proper for single mode operation. The parameters of the cavities are shown in Table 1.

3 Simulation and results

The structure is simulated numerically and theoretically by FDTD method and CMT. The FDTD parametes are considered as $\Delta x = 10$ fs and $\Delta t = 0.1$ fs. Considering the wavelength spectrum of cavities enables us to do some design works to get preferred transmission spectrum. CMT equations are developed in Eqs. (1)-(4) to model the coupled elements of the structure. This equations can be used to evaluate the behavior of the system by coupled ordinary differential equations (ODEs). In Fig. 3, the results of CMT model which is developed for symmetrized structure predicts the output spectrum. output shows huge increase in contrast and intensity after symmetrizing the structure (green plot) as we expected. Results of FDTD simulation and CMT are compared in Fig. 4.

Also by resizing the cavities, we found wavelength shift in spectra and someone could consider this shift for getting the best situations. Figure 5 shows the shifting behavior in wavelength when the size of the cavities are changed. To show the cavity size effect on the output spectrum, up cavity is modified by shifting two near holes by the value of 77 nm to 90 nm. The shifted spectra make it possible to achieve a sharper Fano spectrum. To have optimum fano resonance, it is essential that two resonances belong to the continuum and discrete states be close enough to each other. In this condition, maximum interaction between states will be happened. The waveguide is excited by Gaussian optical pulse which its central frequency is 192 THz (1.57 μm). For evaluating the

Table 1 Cavity sizes of modified structure

	S1	S2	S3
Cavity 1 (up)	85 nm	11.5 nm	0
Cavity 2(up)	92 nm	20 nm	92 nm
Cavity 1(down)	85 nm	11.5 nm	0
Cavity 2(down)	92 nm	20 nm	92 nm

S1–S3 are shifting vectors

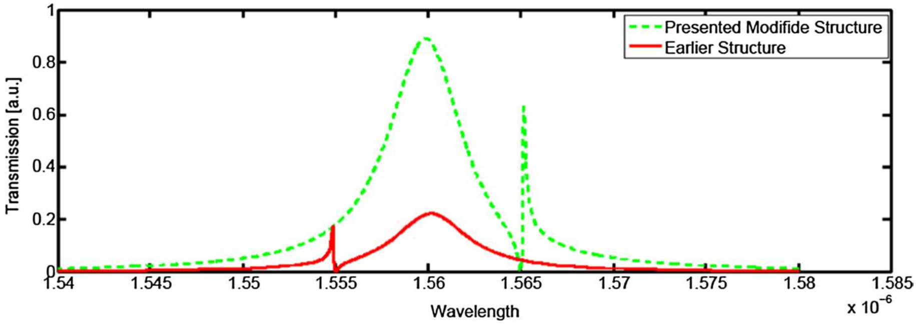


Fig. 3 The results from CMT model of both structures

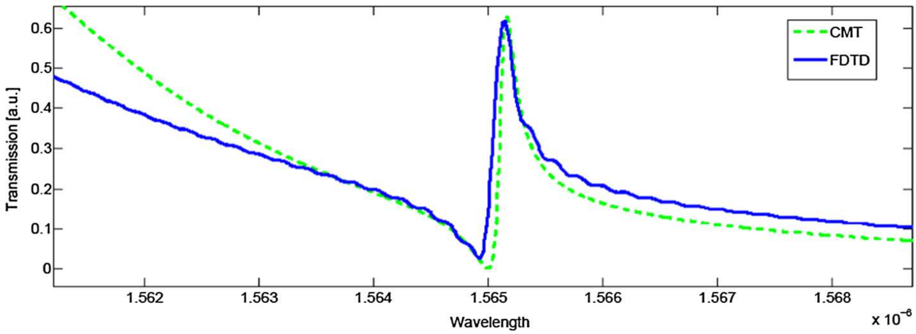


Fig. 4 Comparing the FDTD and CMT results

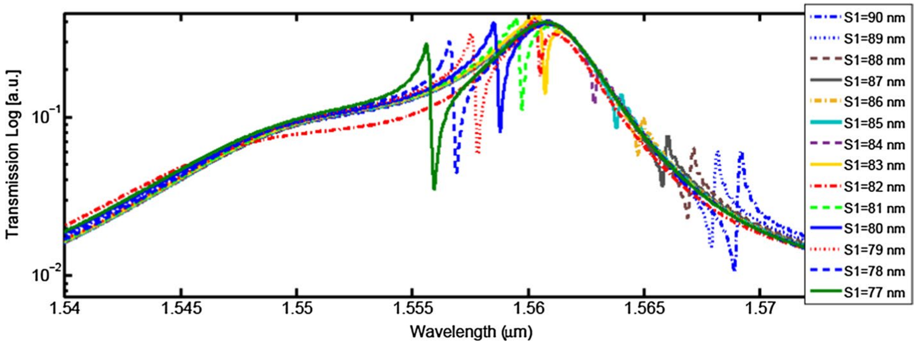


Fig. 5 Output spectrum. The size of cavity2 (up cavity in the structure) is changed by changing the S1 from 77 nm to 90 nm

results of modified structure and simple structure reported in literature (Nozaki et al. 2013), the CMT equations (Little et al. 1997) for modified structure is derived.

The dynamic behavior of the up cavities are modeled by eq (1) and (2) and also the down cavities by Eqs. (3) and (4). It should be noted that, the two sets of equations which describes the up and down cavities are completely similar to each other, because the cavities have the same physical structure.

$$\frac{da_1}{dt} = \left(j\omega_1 - \frac{1}{\tau_{t1}}\right)a_1 - j\mu_1 a_2 - j\mu_{CC}S_i/2 \tag{1}$$

$$\frac{da_2}{dt} = \left(j\omega_2 - \frac{1}{\tau_{t2}}\right)a_2 - j\mu_1 a_1 \tag{2}$$

$$\frac{da_3}{dt} = \left(j\omega_1 - \frac{1}{\tau_{t3}}\right)a_3 - j\mu_1 a_4 - j\mu_{CC}S_i/2 \tag{3}$$

$$\frac{da_4}{dt} = \left(j\omega_2 - \frac{1}{\tau_{t4}}\right)a_4 - j\mu_1 a_3 \tag{4}$$

In Eqs. (1)–(4), the resonance frequencies of continuum state cavities are at the same value and equal to ω_1 and the resonance frequencies of the both discrete state cavities are equal to ω_2. Which a_1 and a_3 are the field amplitude of the near cavities to waveguide and responsible for continuum while a_2 and a_4 are field amplitude of cavities responsible for discrete states, also μ_1 is coupling coefficient between first cavity and waveguide which has the same value in both up and down sections, $S_i/2$ is amplitude of half of light that couples to each section and τ_{ti} is electric field decay rate. Due to the similar cavities, $\tau_{t1}=\tau_{t3}$ and $\tau_{t2}= \tau_{t4}$, and are calculated as:

$$\tau_{t1}^{-1} = \tau_{t2}^{-1} = \tau_{int}^{-1} + \tau_{cpl}^{-1} + \tau_{abs}^{-1} \tag{5}$$

where τ_{int} is intrinsic decay rate of the cavity, τ_{cpl} is coupling decay rate and τ_{abs} is absorption decay rate which is proportional to bulk material absorption. Also by considering S_{1+} as incoming light, S_{1-} as reflecting light and S_{2-} as transmitted light while the incoming light from output is considered zero, the relation between in and out waves will be:

$$\mathrm{S}_{1-} = \mathrm{S}_{1+} - \mu_1^* \mathrm{a}_1 \tag{6}$$

$$\mathrm{S}_{2-} = -\mu_2^* \mathrm{a}_1 \tag{7}$$

where $\mu_1=\sqrt{2/\tau_{cpl}}e^{j\theta_1}$, $\mu_2 = \sqrt{2/\tau_{cpl}}e^{j\theta_2}$ and $\mu_{CC} = 2/\tau_{CC}$. θ_1 and θ_2 are either 0 or π depending on the symmetric or antisymmetric property of the cavity mode profile and τ_{CC} can be calculated from $Q = \omega\tau/2$ which Q_{CC} is the quality factor due to each two cavities coupling.

In this method, the diffraction is considered and is added to CMT model to show the effect of light diffraction after collision of traveling light with centered holes. The fitted transmission plots by CMT method are shown in Fig. 3. Where the quality factors are considered as the same as experimental results, i.e. $\mathrm{Q_{cc}}=1800$, $\mathrm{Q_{cpl}}=3000$, $\mathrm{Q_{abs}}=34{,}700$, and $\mathrm{Q_{int}}=10{,}500$ (Nozaki et al. 2013). Spectrums are plotted by solving Eqs. (1)–(4) similar to equations solved in (Nozaki et al. 2013) for just two cavities. According to results, the total intensity and also transmission contrast is improved after modifying the structure.

Another improving work on theoretical model has been done by modeling new type of cavity as discrete state of Fano resonance. As discussed before, this cavity type is made by shifting 6 holes instead of just four nearby holes surrounding the main cavity to make a stronger light trapping in the structure, this effect could be introduced to CMT model just by assuming another cavity exactly in place of before cavity, so we have two cavities in same location; in fact one of them is not a real cavity and could be considered as virtual cavity (Fig. 6). Therefore, the new virtual cavity which is added to CMT model, has the same coupling coefficient as the second cavity (because it is assumed that they are at the same location) and this assumption which is phenomenological interpretation of unloaded Q factor, could be considered as new second cavity equation in CMT model,

$$\frac{da_1}{dt} = \left(j\omega_1 - \frac{1}{\tau_{t1}}\right)a_1 + j\mu_1 a_2 + j\mu_{CC}S_i \tag{8}$$

$$\frac{da_2}{dt} = j\omega_2 a_2 + j\mu_2 a_3 + j\mu_1 a_1 \tag{9}$$

$$\frac{da_3}{dt} = \left(j\omega_3 - \frac{1}{\tau_{t3}}\right)a_3 + j\mu_2 a_2 \tag{10}$$

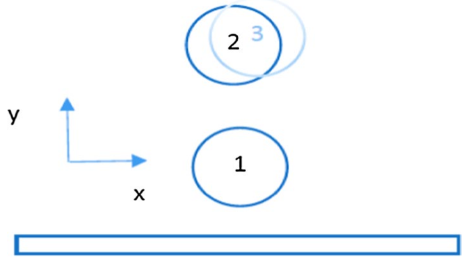
The output spectrum of the switch can be obtained by solving the Eqs. (8)–(10). Because of the enhanced frequency rejection by the modified cavity, Q factor will be increased two orders of magnitude.

4 Discussion

In Fig. 1b, the mode profile of the NTT's structure (Nozaki et al. 2013), shows the dissipation of light after collision. In the improved structure shown in Fig. 2a as the first result of this paper, dissipated light is guided to the output waveguide.

The spectrum of up cavity (up section) is modulated on down cavity and because of their contrast in line width, clearly an abrupt change has been occurred. By changing the size of each cavity, the designer can shift the cavities spectra to have proper Fano shape in terms of contrast and sharpness, in respect to its application as shown in Fig. 5. Also, when the up cavity spectrum reaches its peak, the down cavity will experience abrupt change and this will be reflect to the output spectrum. This describes what exactly happened when Fano shape emerged in output. We hope to use the proposed idea to improve the future device characteristics. Also, with proper design, even someone may have a better Fano shape in terms of contrast and sharpness, because in this symetrized structure, two Fano shapes (one due to the region under the waveguide and another due to region above the waveguide) are interfere independently in output port and so tiny deviation of

Fig. 6 Representation of virtual cavity



two Fano shapes from each other, could lead to a 2nd order Fano shaping in output port but in ideal situations. As a result, the sharpest Fano spectrum is achieved. In fact what exactly happened is that, after adding the same structure to the region under the waveguide, two improvements occur, first of all, the dissipated light, comes back to output waveguide and leads to higher intensity in output which this increase in intensity is crucial in optical long-haul communication, and as a second result, the light transmitted to the output port through the region under the waveguide, completely is collected and transmitted but after getting the shape of Fano. Therefore Fano shaping for the second time is achieved which means interference for second time and leads to sharper Fano spectrum.

As the second work in this paper, the role of new softening method applied to cavities for having better Fano shaping is investigated. By using of new cavities (Fig. 2b), the vertical radiation loss to clad (air) has been decreased. In fact by referring the total quality factor of every cavity, to its components of Q_{load} and Q_{unload} and $Q_{tot} = 1/(1/Q_{load} + 1/Q_{unload})$, which Q_{load} is due to in-plane Q factor and is related to coupling elements around the cavity and Q_{unload} is due to vertical Q factor and shows the vertical optical losses when just that cavity exists alone. Applying the new softening method improves the Q_{unload} of the targeted cavity. Higher Q contrast between two states of continuum and discrete leads to better Fano spectrum. In this work we have just make the up cavities in the symmetrized presented structure, more softened while down cavities unchanged. This new softening method increases the Q_{unload} of the cavity by reducing vertical optical losses as described in (Asano et al. 2010). In this method by shifting 6 around holes in the way shown in Fig. 2b, the optical losses due to sharp reflection at cavity walls has been reduced. The idea is from the form of modal electric field profile of the cavity. As discussed in (Asano et al. 2010), before applying new softening method, the envelop function of the electric field, assumed to have a triangular form, after applying these new hole shifts which make the cavity confined by a spatially distributed reflection, the modal electric field profile has been become in form of Gaussian shape. Since that abrupt change induced from triangular shape reforms to soft change in Gaussian, an optical loss reduction is expected. Therefore, the Fano resonance which is due to interference between two elements with high contrast between their quality factors, is enhanced when the Q factor of one of the elements with greater Q factor, increases by mentioned softening method. As a result, a Fano shape with so sharper and also higher contrast relative to later structures has been achieved. In Fig. 7, the spectral behavior of four cavity system with simple cavity and new proposed cavities are compared by earlier simple structure.

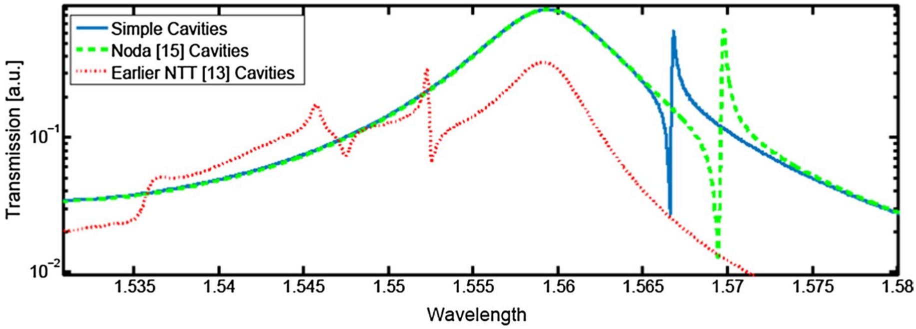


Fig. 7 Output spectra of the improved device in comparison to previous device with highest QF

5 Conclusion

In the designed switch, results show that the Q contrast between discrete state and continuum is highly important to have a sharp Fano shaped spectrum. By increasing the Q factor of the 2nd cavity which has the higher value, the sharpness and contrast of the Fano spectrum is enhanced. Here both types of load and unload Q factors has been improved in two stages, first with symmetrization of the earlier structure, the higher load Q factor has been achieved and second by shifting the third holes around the discrete cavities, the unload Q factor has been increased which both leaded to steeper and sharper Fano shape. The contrast of the designed switch is better than the previously reported structure, besides, $\Delta\lambda_{peak-peak}$ of the Fano spectrum is decreased which leads to much less energy consumption. According to the results, the switching performance is sensitive to the shifting values of the holes (S3) about more than 1 nm. Also, the differences between the sizes of the cavities should not be more than 13 nm to have strong interference between cavity modes. However, it is found that there is an important tradeoff between sharpness and contrast, but here, because the device, has been reached to its maximum structural capacitance due to so high Q factor elements which is existed in the structure, the tradeoff has been vanished. Therefore, by resizing the up cavity, only contrast has been changed which it could be useful to design stable devices. Besides, by modifying the structure, the output intensity is absolutely enhanced.

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