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Analytical Study of Optical Bi-Stability of a Single-Bus Resonator Based on InGaAs Micro-Ring Array

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ABSTRACT

In this paper, for the first time to our knowledge, we investigate the optical bi-stability in a compact parallel array of micro- ring resonators with 5µm radius, induced by optical nonlinearity. Due to the nature of perfect light confinement, resonance and accumulation process in a ring resonator, optical nonlinear effects, even at small optical power of a few milliwatts in this structure are observable. Different optical applications such as: all-optical switching, memory, logic gates and modulators, due to optical bi-stability in a ring resonator are possible. By using of compound semiconductors, instead of silicon that have weakly nonlinear optical properties, we improve the performance of ring-resonator based devices. Also by using of a polymer cladding layer with negative thermo-optic coefficient, we have eliminate the temperature created nonlinearity which is a very slow process, so the switching speed of a few MHz increases to several tens of GHz. With plotting the transfer function of the resonator, a hysteresis loop in a few milliwatts is observed, that by using of ring resonator array, although the bandwidth is reduced, but the width of the hysteresis loop and resolution between both steady state increases.

KEYWORDS: Optical Bi-stability, Nonlinear Optic, Ring Resonator Array, Resonance Wavelength, Hysteresis Loop

1. INTRODUCTION

In recent years, micro-ring resonators, because of its extremely compact dimensions, horizontal light coupling, selective and tuneable spectral response, low cost and simple design has been a Noteworthy configuration in fabrication of variety of optical devices such as detectors, modulators, filters, and wavelength converters. Also because of resonance and accumulation process, ring resonators have a special place in nonlinear optics, so that even at small optical powers of a few milliwatts, nonlinear effects appear markedly. In active all-optical silicon devices, where the light is controlled by light, due to the weak nonlinear optical properties of Si, to achieve optical bi-stability, the change in refractive index and shift in resonance wavelength due to temperature nonlinearity is used. Si has a high thermo-optic coefficient, however, since the phenomenon of warming is a time consuming process, frequency response of devices based on thermo-optic effect will be much lower (about a few tens of megahertz) [1-2]. For this reason, for a device with a very rapid response, the compound semiconductor materials with excellent optical properties are used [3-4].

In references [5-8] optical bi-stability in silicon micro-ring resonators, in both single and two straight waveguide case, based on refractive index changes due to thermo – optic effect, have been investigated. In addition the optical bi-stability, based on compound semiconductor materials in a variety of optical devices such as semiconductor optical amplifier (SOA) has been shown [9].

In this paper, for the first time to our knowledge, we have investigate the optical bi-stability in a compact parallel array of InGaAs micro- ring resonators with 5μm radius, which is horizontally coupled to a straight wave guide, induced by optical nonlinearity and simultaneously, the high bandwidth and large hysteresis loop width, only with a few milliwatts of optical power, have been achieved.

Ring waveguide width and absorption region thickness respectively 500 and 200 nm are considered. In small input optical powers, optical field enters into the straight waveguide, if the wavelength of the input beam is matched with resonance wavelength of the ring, maximum amount of light in critical coupling condition, are coupled and absorbed into micro-rings. In this case, the output optical field from straight waveguide is in low state. But if the input beam wavelength and micro-ring resonance wavelength, is not equal, light field without being absorbed in 1st ring, goes to second ring and finally moved to output of the straight waveguide, and so the output status changes to high value.

With increasing input power because of the nonlinear Kerr, Free Carrier Absorption, Free Carrier Dispersion and Two Photon Absorption Effects and since the n_2 and σ_r coefficients (nonlinear refractive index and refractive volume coefficients) , for InGaAs in less than two micron wavelength is negative, ring resonance wavelength shifts towards shorter wavelengths that called “Blue Shift” [10].Resonance wavelength modifying, leads the structure to the outside of the critical coupling condition and so the output logic state change to other level.

Using an array of micro-rings, due to increasing absorption of light in the similar rings, the difference between the two states has been increased and also because of the wider spectral response width in ring array, the hysteresis loop width is increased. But in this case, due to increased delays in the passage of light from the multi ring structure, bandwidth decreased.

2. THEORY

To investigate the relationship between the input optical beam (E_{in}),circulating field in the rings (E_r) and straight waveguide output field (E_{th}), in the ring resonator array, with assuming uni-directional propagation mode, we used the model[11] proposed in figure 1, for double ring-resonator array.

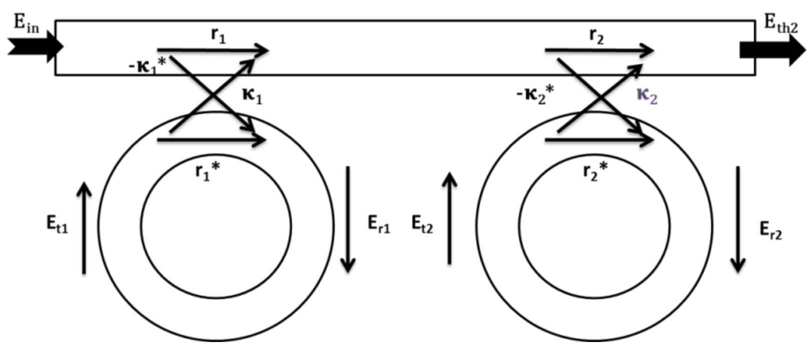

Fig.1. Double Ring-Resonator Array Simulation Model

The mutual relations between optical fields in the n^{th} ring are calculated from the following equations [10]:

$$E_{r_n}(t) = r_n E_{t_n}(t)$$
$$-i\kappa_n e^{i\beta_{w(n-1)}\Lambda_{(n-1)}} E_{th_{(n-1)}}(t) \qquad (1)$$

$$E_{th_n}(t) = r_n e^{i\beta_{w(n-1)}\Lambda_{(n-1)}} E_{th_{(n-1)}}(t)$$
$$-i\kappa_n E_{t_n}(t) \qquad (2)$$

And circulating field after one round-trip in the n^{th} ring is:

$$E_{t_n}(t) = E_{r_n}(t-\tau) e^{i\beta_n L r_n} e^{-\Gamma \alpha_{0n} L r_n} \qquad (3)$$

The relation between transmission and coupling coefficient in n^{th}ringwith assuming lossless coupling is equal to:

$$|r_n|^2 + |\kappa_n|^2 = 1 \qquad (4)$$

In these relations, n Ͽ {2, 3,4,…,∞} is the ring number,κ is field coupling coefficient, r is transmission coefficients between the straight and ring waveguides, Λ is space between two adjacent ring, β_w is propagation constant in straight waveguide, R is ring radius,L_r=2πR is ring waveguide perimeter, $\beta = \frac{2\pi n_r}{\lambda}$ is constant in ring resonators, n_r is propagation ring refractive index,τ is propagation round trip time of the ring resonator, λ is propagation input light wavelength, Γ is confinement factor and α_0 is propagation loss inside the micro-ring in μm^{-1}.

Distribution of circulating beam inside the ring resonator, with considering of nonlinear effects that demonstrated in figure 2, is given by the following nonlinear Schrödinger equation [12]:

$$\frac{\partial E_{rn}(z,t)}{\partial z}+\frac{n_0}{c}\frac{\partial E_{rn}(z,t)}{\partial t} = -\frac{\alpha_0}{2}E_r(z,t)-\left(\frac{\alpha_2}{2}-in_2k_0\right)I_{rn}(z,t)E_{rn}(z,t)-\left(\frac{\Delta_{fc}}{2}-i\Delta n_{fc}k_{0n}\right)E_{rn}(z,t) \quad (5)$$

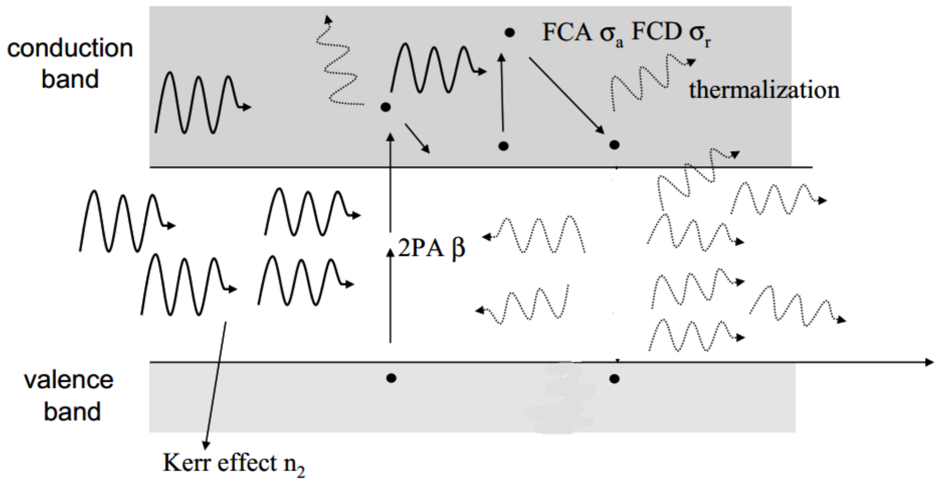

Fig.2. Optical Kerr, FCD, FCA and TPA effects in the InGaAs semiconductor [8]

In this relation, 1st, 2nd, 3rd and 4th term are due to Linear Absorption, Two Photon Absorption, Free Carrier Absorption and Free Carrier Dispersion respectively. $\Delta\alpha_{fc}$ and Δn_{fc} are the changes in the absorption and refractive index induced by free carriers generated from the TPA and Linear absorption processes, which are proportional to the free-carrier density, N_{fc}, via $\Delta\alpha_{fc}=\sigma_a N_{fc}$ and $\Delta n_{fc} = \sigma_r N_{fc}$. n_2 is the nonlinear refractive index and σ_r is refractive volume parameter, which based on the results of experimental investigations, both of them are negative for InGaAs [4] and σ_a is the Free Carrier Absorption Cross Section.

The free-carrier density generated by TPA and Linear absorption processes with considering heat losses evolves according to:

$$\frac{dN_{fc}}{dt}=\frac{\alpha_0 I}{h\nu}+\frac{\alpha_2 I^2}{2h\nu}-\frac{N_{fc}}{\tau_{fc}} \quad (6)$$

In this relation, α_n, τ_{fc}, h and $\nu$are TPA coefficient, free carrier life time, plank constant and input light frequency respectively and"I" represent the circulating beam intensity and related to the circulating field by the following equation:

$$I_r(z,t) = \frac{1}{2}\varepsilon_0 n_0 c|E_r(z,t)|^2 \qquad (7)$$

Critical coupling condition for maximum coupling of light into the micro ring, in the n^{th} ring is [10]:

$$r_n = e^{-\Gamma\alpha_0 L r_n} \qquad (8)$$

We solve equations (1-8) numerically with Crank-Nicolson method and the parameters used for simulation is illustrated in table 1.

TABLE1. The Parameters Used in Simulation

sign	quantity	value
L_a	Absorption Layer Thickness	**0.2µm**
W_r	Ring Waveguide Width	**0.5 µm**
R_{eff}	Rings Radius	**5 µm**
τ_{fc}	Free Carrier Life Time	**50 ps**
σ_r	Refractive Volume	**-10^{-8}µm^3**
σ_a	Absorption Cross Section	**2×10^{-8}µm^2**
n	Refractive Index	**3.45**
α_0	Linear Absorption Coeff.	**.007 µm^{-1}**
Λ	Space between two Ring	**50 µm**

3. DISCUSSION

In figure 3, the output spectral response of single-ring resonator structure, in critical coupling and in the absence of nonlinear effects for 0.1 mw input power is plotted. As observed in this curve, one of the resonance wavelengths of the ring is 1550.9 nm, and just the input beams with opposite wavelength in regard to ring resonance wavelength has ability to crossing from straight waveguide to the output without absorbing in ring.

Normalized circulating Spectral Response of single-ring resonator, for different input powers and in the presence of nonlinear effects in critical coupling condition, is illustrated in fig.4. According to equations (1-6), nonlinear Kerr and FCD Effects, proportional to circulating beam intensity (I_r) andI_r^2respectively, so with increasing input power, nonlinear effects and so as can be seen in figure 4, resonance wavelength blue shift, increased. Therefore the critical coupling condition is no longer true. In other words,a smaller portion of the light is coupled into ring and so the amplitude of circulating spectral response decreased.

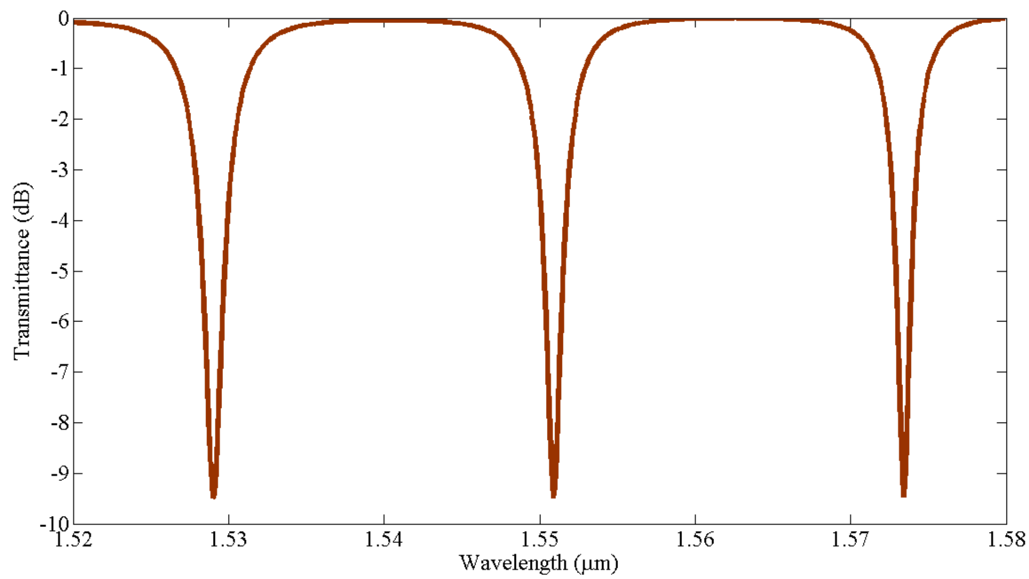

Fig. 3. Output Spectral Response of a single-ring Resonator (R=5μm)

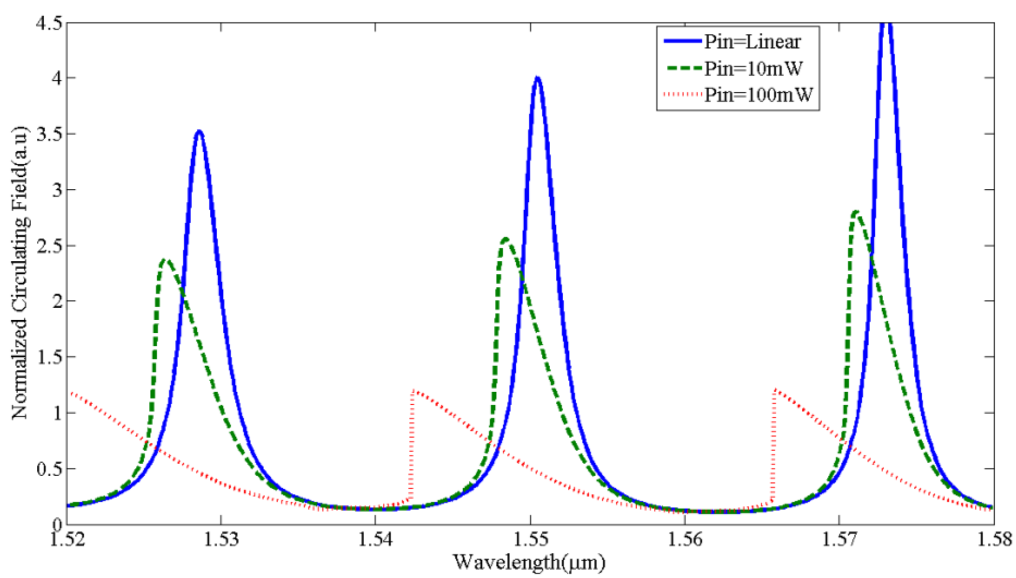

Fig.4. Circulating Spectral Response of a single-ring Resonator for Different input power (normalized to input power)

Also because of increasing FCA effect in high input powers, a part of input beam absorbed by free carriers and converted to heat, which further reduces the amplitude of the circulating field in high input powers.

In figure 5, the output spectral response of a single-ring resonator in presence of nonlinear effects and for different input powers is demonstrated. In fact because of this drastic change in ring resonance wavelength, bi-stability in the ring is possible.

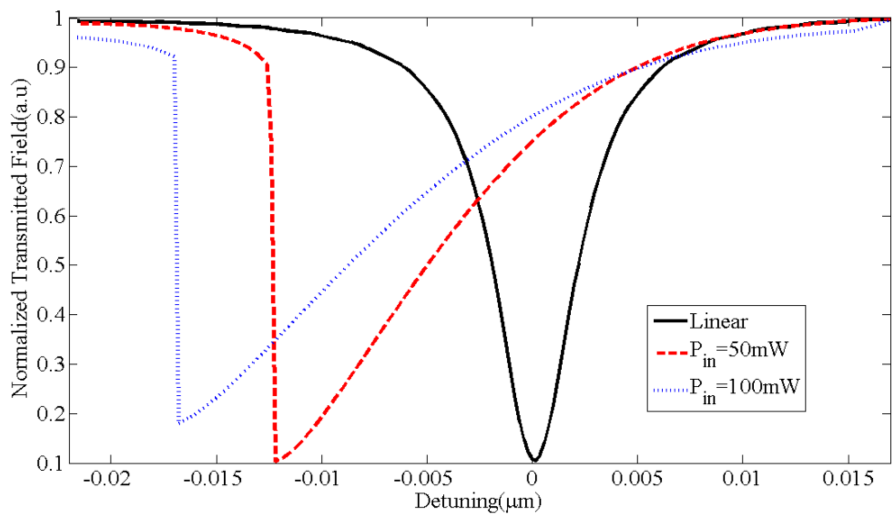

Fig.5. Output Spectral Response of a single-ring Resonator for Different input power (normalized to input power)

In figure 6, the blue shift of ring resonance wavelength is plotted for different optical powers. As can be seen, detuning from resonance wavelength toward smaller wavelength (blue shift), increased with increasing optical input power.

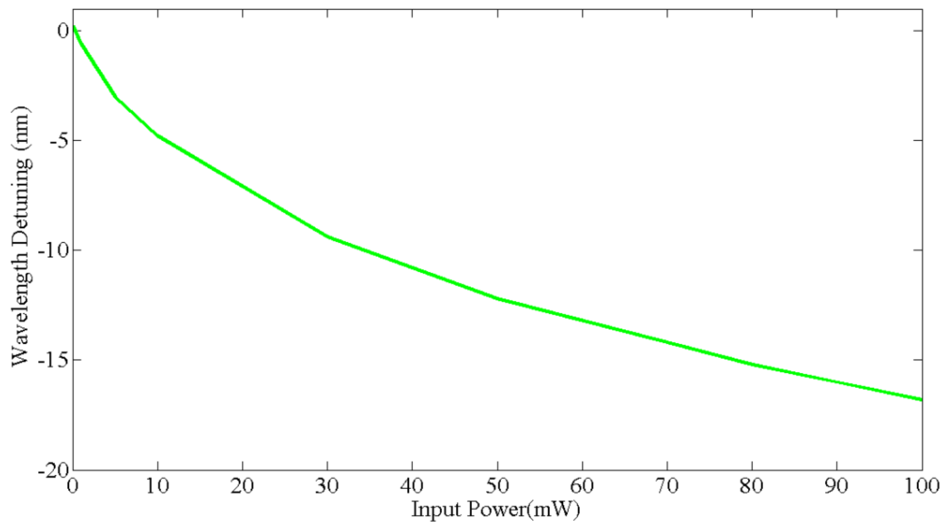

Fig.6. Resonance Wavelength Blue shift as a function of the input optical power

As mentioned before, in high input powers nonlinear FCD and FCA effects in compare with nonlinear Kerr and TPA effects, are dominant, because they are proportional to the square of the field intensity. This is clearly evident in figure 7, which plot the change of refractive index and absorption coefficient, for different optical powers, in the presence of any of nonlinear effects.

For investigating the optical bistability, we assume that the wavelength of the input beam, 0.9 nm is smaller than the ring resonance wavelength. Thus as shown in figure 8, at first by increasing the optical power, the straight waveguide output, due to approaching to the critical coupling condition is reduced, so that in 0.9 nm blue shift in resonance wavelength, the maximum part of beam is coupled to the ring , thus the minimum output occurs.

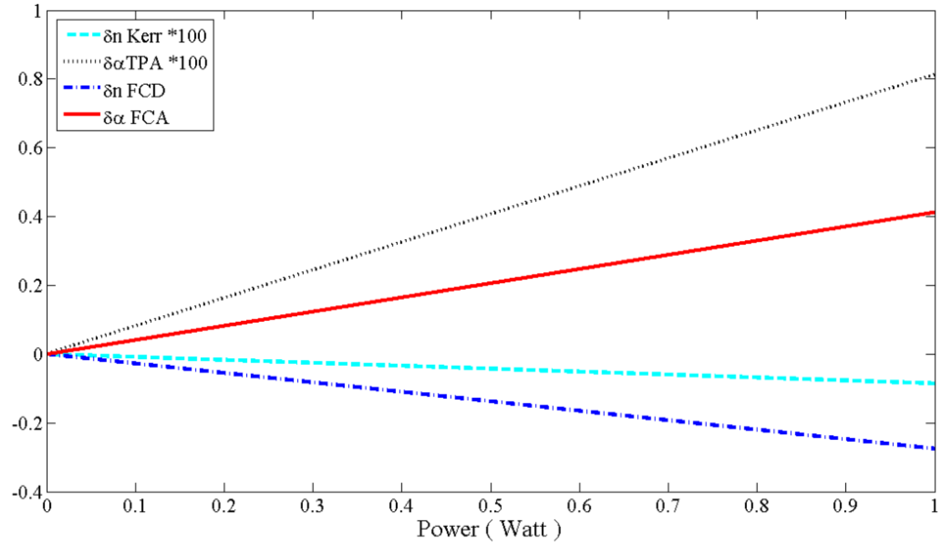

Fig.7. Change of refractive index and absorption coefficient for different optical power for considering any of nonlinear effects

But again with further increasing the input power, the wavelength blue shift increased and again the critical coupling condition not satisfied, so the output signal increased.

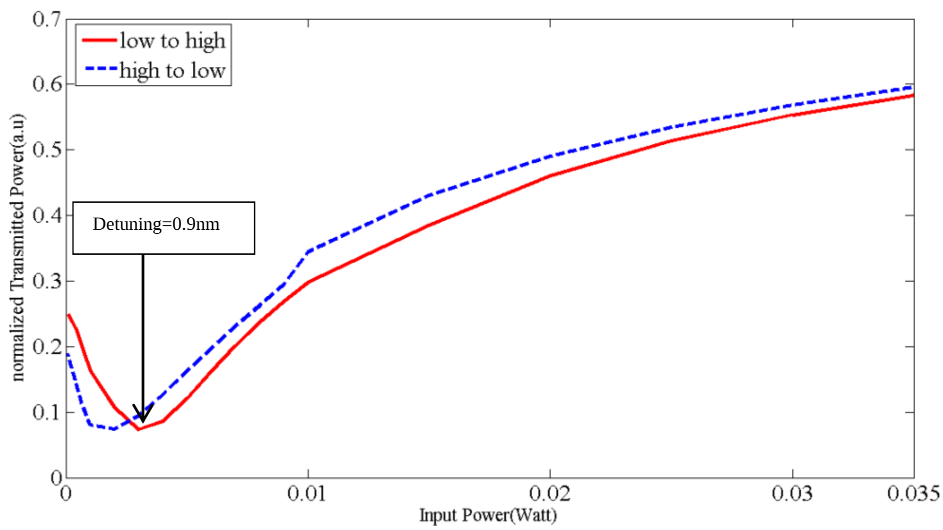

Fig.8. Single-Ring Resonator Hysteresis Loop (λ_r=1550.9,λ_{in}=1550 nm)

However when we reduce the input power from its maximum value, due to the presence of high concentration of free carriers, nonlinear effects will be there in smaller input powers. So the minimum output, will occur in smaller input power in regard to the case that we increase the input power from low to high. This difference between the two switching modes creates a loop which is known as “Hysteresis Loop”. Until the input optical power is within this loop, the straight waveguide output signal will not change their status.

With increasing the number of rings, due to increased effective absorption of light, the extinction ratio is increased up to 4 times. And also in the ring resonator parallel array, due to the increase of spectral response Full Width at Half Maximum (FWHM), according to Figure 9, the width of hysteresis loop, as demonstrated in figure 10, increases.

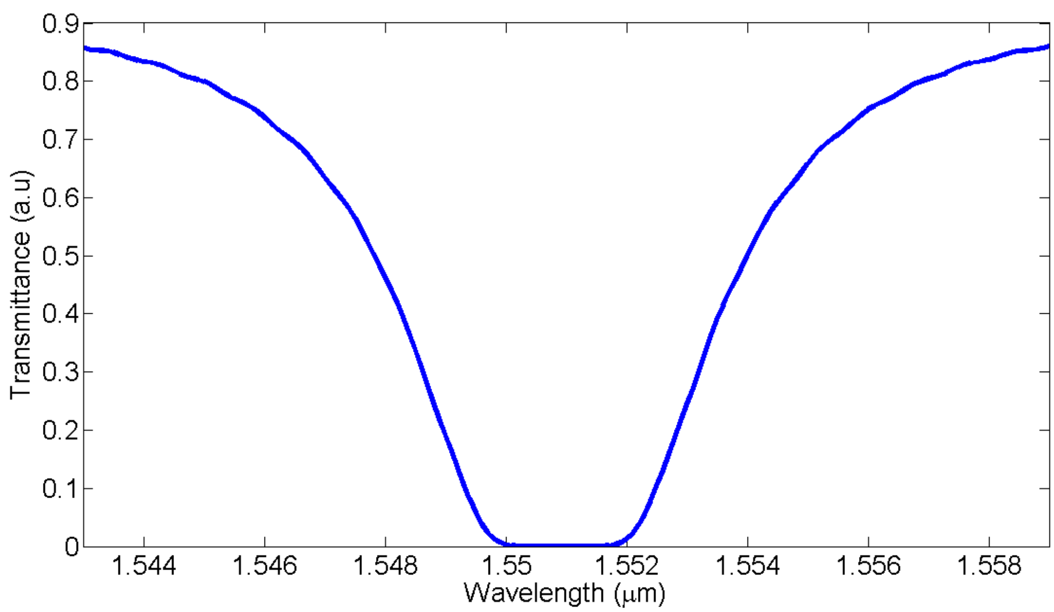

Fig.9. Spectral Response of 10 Ring Parallel Array in Critical Coupling Condition (R=5μ)

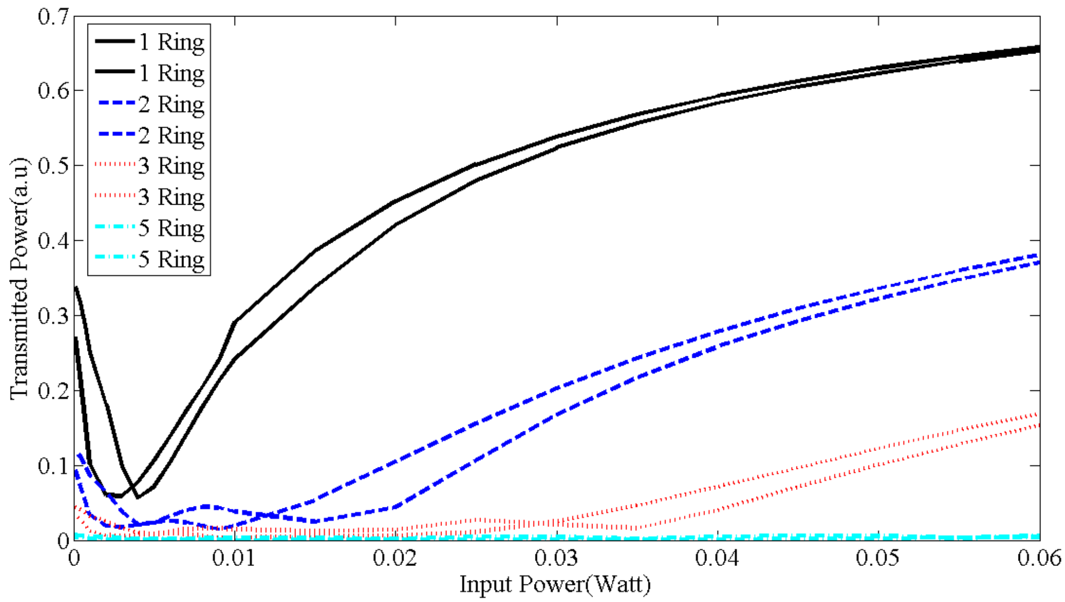

Fig.10. Resonator Transfer Curves for different number of rings in critical coupling Condition (λ_{in}=1550nm)

But it should be noted that, as demonstrated in Figure 10, if we increase the number of rings more than 2 or 3 rings, due to complete absorption of light, the bi-stability will disappear. The reason of this issue is that the blue shift of resonance wavelength is proportional to the ring input optical field, thus because the optical field at the first ring is high, the maximum blue shift is occur in the 1st ring and light cannot be absorbed in that, but in the next rings, this blue shift become minimum and light completely absorbed in several rings.

Increasing the number of rings, increases the extinction ration and width of hysteresis loop, however, due to increase delay in the passage of light from the multi ring structure, the bandwidth of multi ring based devices decreased. In figure 11, the frequency response of multi ring resonator structures in critical coupling condition, for input power of 100mW is plotted.

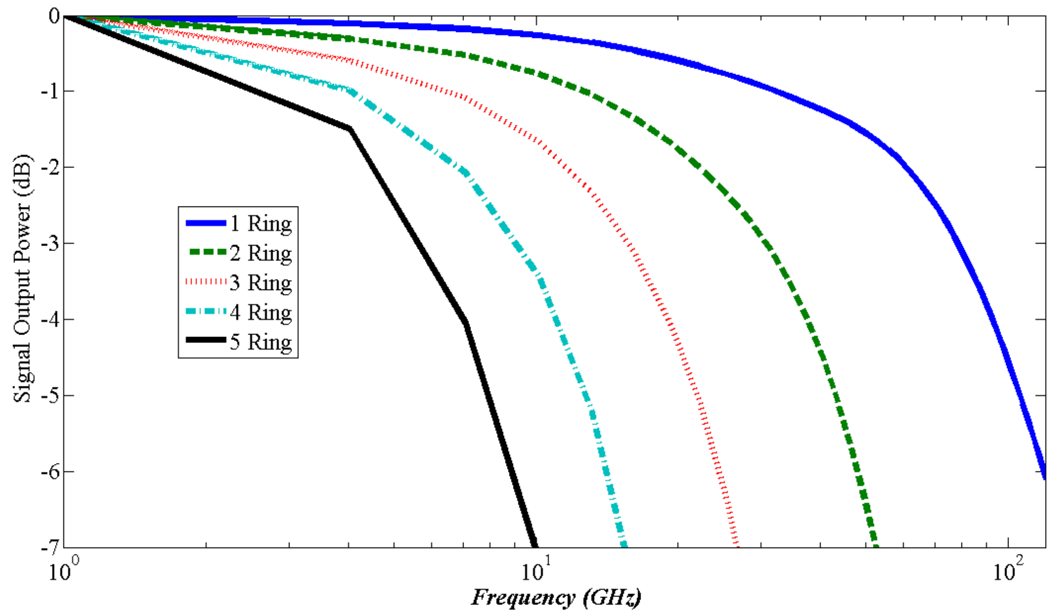

Fig.11. Frequency Response of Ring Resonator Array in Critical Coupling Condition for Different Number of Rings (λ_{in}=1550.9nm)

As can be seen, with increasing the number of rings, the 3dB cut off frequency decreased.

In figure 12, the difference between two steady states (Extinction Ratio), as a function of input optical power is demonstrated.

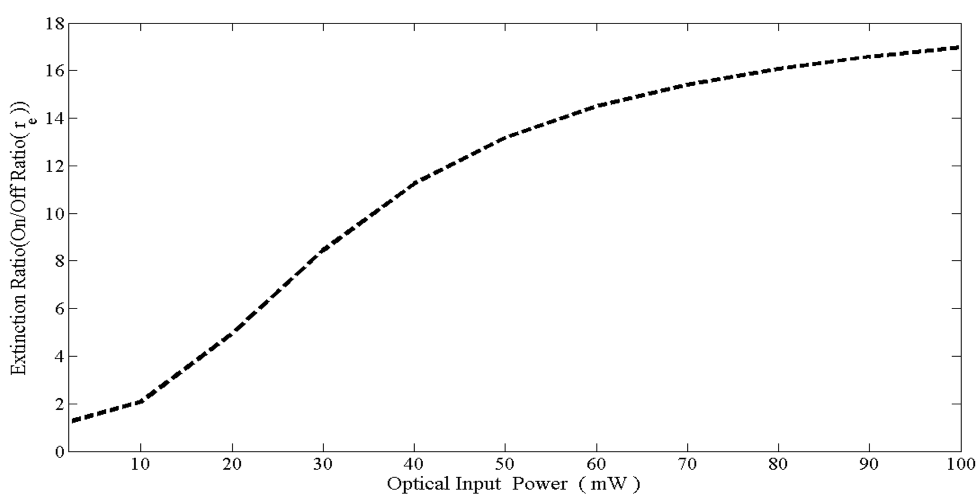

Fig.12. Two level Resolution vs. Different Input Optical Power

According to figure 12, as the amount of optical power increases, the extinction ratio will increase.

4. CONCLUSIONS

In this paper for the first time to our knowledge, the optical bi-stability in a compact parallel array of micro- ring resonators, basis on effective refractive index change, induced by some optical nonlinear effects such as: Kerr, FCA, FCD, TPA effects, is investigated. Due to ignoring the thermo-optic effect, the switching speed in this structure raised up to 100 GHz. Also we demonstrate that, with choosing an optimum ring array, with a small decrease in bandwidth, the hysteresis width and extinction ratio increased considerably. Based on our results, we expect, this bistable structure can be used in fabrication of different optical devices, such as: all-optical compact switches, optical memories, modulators, logic gates and so on.

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