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Single-photon all-optical switching using coupled microring resonators

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Abstract. We study the nonlinear phase response of a microring resonator coupled to a bus waveguide and the use of this nonlinear phase shift to store information in the microring resonator and enhance the switching characteristics of a Mach–Zehnder interferometer (MZI). By introducing coupling between adjacent microring resonators, the switching characteristics of the MZI can be exponentially enhanced as a function of the number of microring resonators, when compared to the linear enhancement for uncoupled resonators. With only a few moderate-finesse microring resonators, the switching power can be reduced to attowatt level, allowing for photonic switching devices that operate at single-photon level in ordinary optical waveguides.

Keywords. Microring resonator; single-photon switching.

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1. Introduction

The optical properties of a waveguide can be tailored using side-coupled microrings. Lossless microring resonators are generally used as phase equalizers or dispersion compensators in optical communication systems [1–4], add-drop filters for wavelength-division multiplexing [5], all-optical switching [6,7], wavelength-dependent delay lines [8], and to stop [9] and reverse [10] the light propagation using coherent effects. Lossy microring resonators, on the other hand, can be used for detecting biological pathogens sensitively [11] and for manipulating the speed of light propagation [12,13]. In this work, we discuss the applications of nonlinear microring resonators in information storage devices. We also demonstrate that the switching threshold power of a resonator-enhanced MZI can be exponentially reduced as a function of the number of coupled microrings. With only a few coupled microring resonators, the switching power can be reduced down to attowatt level, making the system to be an effective single-photon all-optical switching device.

2. Nonlinear phase response of a single microring resonator

The basic structure of an optically implemented single-stage microring resonator side-coupled to a bus waveguide is shown in figure 1a. One useful feature of a microring resonator is that the original power gets to build up in the microring and keeps circulating inside the ring cavity. The buildup factor B, which is defined as the ratio of the power circulating inside the ring resonator to the input power, is given by [6]

$$B = \frac{P_1}{P_0} = \frac{1 - r_1^2}{1 + r_1^2 a_1^2 - 2r_1 a_1 \cos\phi_0}, \tag{1}$$

where P_0 is the input power, P_1 is the average power inside the microring and r_1 is the self-coupling coefficient of the coupler. $a_1 = \exp(-\alpha_1 l_1/2)$ and $\phi_0 = \beta_1 l_1$ are the single-pass field transmission and linear phase shift in the ring, respectively. α_1 is the intensity attenuation coefficient, β_1 is the wave propagation constant associated with the fundamental mode supported by the ring waveguide, and l_1 is the circumference of the microring resonator. Under conditions that the incident light is on resonance with the microring resonator and the loss is negligible ($a_1 = 1$), the maximum value of the buildup factor $B_{\max} = (1 + r_1)/(1 - r_1)$. Thus, when r_1 is very close to unity, the power circulating inside the microring resonator becomes very high. This power buildup can induce nonlinear effects if the ring waveguide possesses an intensity-dependent nonlinear refractive index n_2 that results from the third-order susceptibility ($\chi^{(3)}$) of the material [6]. The nonlinear refractive index n_2 can be included in the single-pass phase shift as

$$\phi_1 = \phi_{\mathrm{L1}} + \phi_{\mathrm{NL1}} \cong \beta_1 l_1 + \gamma_1 L_{\mathrm{eff1}} P_1, \tag{2}$$

where $L_{\mathrm{eff1}} = [1 - \exp(-\alpha_1 l_1)]/\alpha_1$ is the effective interaction length due to the loss and γ_1 is the nonlinearity coefficient (related to n_2 by $\gamma_1 = 2\pi n_2/\lambda A_{\mathrm{eff}}$, where λ is the input wavelength and A_{eff} is the effective core area of the waveguide). ϕ_{L1} and ϕ_{NL1} are the single-pass linear and nonlinear phase shifts, respectively. In such a nonlinear case, ϕ_0 in eq. (1) should now be replaced by ϕ_1. Thus, by substituting

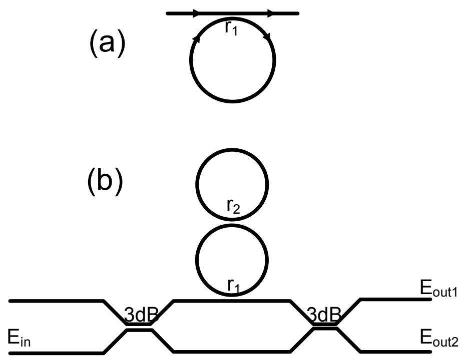

Figure 1. (**a**) Nonlinear microring resonator, (**b**) MZI with coupled nonlinear microring resonator in one of its arms.

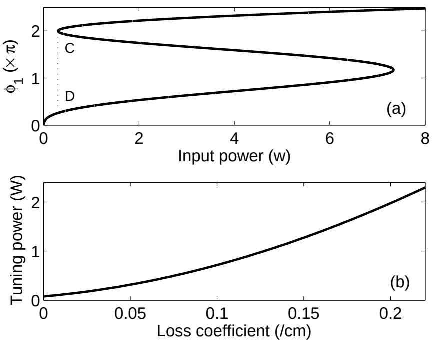

Figure 2. (**a**) Effective phase shift, (**b**) turning power as a function of loss coefficient. The parameters used in this calculation are $\gamma = 100\ \text{m}^{-1}\ \text{W}^{-1}$ (a typical value for air-clad GaAs waveguide [17]), $R = 1$ cm and $r = a = 0.86$.

eq. (1) into eq. (2), we get a transcendental equation for the single-pass phase shift as

$$\phi_1(P_0, \phi_{\text{L1}}) = \phi_{\text{L1}} + \gamma_1 L_{\text{eff1}} \frac{1 - r_1^2}{1 + r_1^2 a_1^2 - 2r_1 a_1 \cos\phi_1(P_0, \phi_{\text{L1}})} P_0. \tag{3}$$

Figure 2a plots the nonlinear phase shift as a function of input power assuming $\phi_{\text{L1}} = 0$. It shows an S-shaped curve, which is an indication of bistability in the system. This nonlinear phase shift can be converted to intensity change in different ways, leading to different potential applications. For example, one of the most straightforward applications would be to use the microring resonator as an information storage device. We look at point C in figure 2a, at which the nonlinear phase shift is 2π, resulting in a zero system transmissivity, at a finite input power level. Thus, all input optical power is trapped in the microring resonator and the signal cannot propagate through the waveguide. However, a slight decrease of the input power from C will make the nonlinear phase shift jump down to point D and the transmissivity of the system can quickly reach a high value (close to unity), thus the input signal can propagate efficiently through the system again. This property makes this device an ideal system for information storage or optical switch. By simply changing the input power near the turning point of the bistable curve, the system can totally 'store' or release the optical pulses through the waveguide.

However, there are certain issues or limitations that we need to mention regarding this single-microring information storage device. We notice that for a critically-coupled microring resonator ($r_1 = a_1$), optical pulses can be stored in the structure even without the help of the nonlinearity. At resonance the transmissivity is zero and the power circulates inside the microring cavity. Signal switching can be achieved by simply tuning the input wavelength or changing the linear refractive index of the ring waveguide. The disadvantages associated with such a linear scheme include difficulty in tuning the input wavelength or the index of the ring waveguide, and large value of required change for either wavelength or linear index. Second, the tuning power depends on system parameters and is normally quite high. Figure 2b shows the dependence of the turning power on the loss coefficient. As α_1 changes from 0 to 0.22 (corresponds to change of a_1 from 1 to 0.5 for $R = 1$ μm ring), the turning power increases from about 80 mW to above 2 W. Finally, as discussed before, due to the lossy nature of the microring resonator, the storage time is limited to sub-microsecond level. This limitation can be overcome by using coupled-resonator induced transparency (CRIT) [14,15], an analogy to electromagnetically-induced transparency (EIT) in atomic systems. By using CRIT, the information can circulate inside the microring resonators with a greatly reduced attenuation. Thus, the information storage time can be significantly longer and is ultimately limited by the two-photon absorption in the ring waveguides defined as $\alpha = A_2 I$, where A_2 is the two-photon absorption coefficient and I is the intensity inside the ring waveguide. For a typical value of the two-photon absorption coefficient of GaAs waveguide [16], the information storage time can reach millisecond time-scale with a moderate circulating power. However, to use CRIT, at least two microring resonators are required.

3. Enhanced all-optical switching

Another important application of such a nonlinear phase shift in microring resonator is to enhance all-optical switching in a Mach–Zehnder interferometer (MZI). It has been shown that by introducing a single microring resonator into one arm of the MZI, the switching threshold is reduced by a factor of $(2/\pi^2)F_1^2$, where $F_1 \equiv \frac{\pi}{2}\frac{1+r_1 a_1}{1-r_1 a_1}$ is the resonator finesse [6]. For a standard MZI with two 3 dB couplers and an arm-length difference ΔL, the switching threshold power is found to be $P_{\mathrm{th}} = 2\pi/\gamma_M \Delta L$, where γ_M is the the nonlinear coefficient of the MZI waveguide [18]. For a typical value of $\gamma_M = 100$ m^{-1} W^{-1} [17] and $\Delta L = 10\pi$ μm, the switching power is as high as 2 kW. For the single-resonator-enhanced MZI with a ring radius of 5 μm (so that its circumference equals to ΔL mentioned above) and a reflectivity of $r_1 = 0.99$, its switching power reduces to only about 100 mW, resulting in a compact milliwatt level all-optical switching device. Such finesse-squared reduction in switching threshold is due to enhanced power dependence of the accumulated nonlinear phase shift.

While single microring resonator can reduce the switching threshold significantly to milliwatt level, numerous applications require the switching threshold to be reduced further. For the ultimate goal of single-photon all-optical switching in such a waveguide system, the switching power needs to be reduced all the way down to attowatt (10^{-18} W) level. For such ultra-low-power all-optical switching, either single microring resonator with extremely high finesse (10^{10}, to get attowatt switching power) or multiple microring resonators must be used. Finesse values larger than 10^6 have been reported in the resonance feature associated with the whispering-gallery mode of a microresonator [19]. In addition to technical challenges in manufacturing high-finesse resonators, there is an intrinsic disadvantage in using microring resonators with a very high finesse value. Due to the small value of the cross amplitude transmission coefficient, it takes longer for the power to build up in the microring resonator. Thus, the lowering of the cut-off frequency (inversely proportional to $\mathcal{F}$) will accordingly limit the frequency response of the device [6]. For a multi-microring scheme, the simplest structure is to use multiple independent microring resonators. In such a case, the reduction of the switching threshold power is linearly proportional to the number of independent microring resonators. This reduction rate is too slow for achieving single-photon-level all-optical switching applications. Also, it will be hard to keep uniformity for such large number of microring resonators in the fabrication process.

We propose a new design scheme in which coupled microring resonators are introduced into one arm of the MZI, as shown in figure 1b. From the previous discussion, we know that a microring resonator side-coupled to a bus waveguide can quadratically enhance the phase sensitivity with respect to its input power [6]. The basic idea of our proposed design scheme is to further couple another microring resonator to this resonator. The phase sensitivity of the newly-added microring resonator is itself enhanced quadratically, and with proper design, the phase sensitivity of the whole system (MZI with two coupled microring resonators) is enhanced by the fourth power of finesse. For simplicity, in the following discussions we assume both microrings to be lossless ($a_1 = a_2 = 1$). First, we consider the power buildup in the outer microring resonator and derive the resonance conditions. Using field transfer characteristics of couplers and waveguides, and after some algebra, the electrical field in the outer microring resonator is found to be

$$\left|\frac{E_2}{E_{\text{in}}}\right| = \left|\frac{\sqrt{(1-r_1^2)(1-r_2^2)}}{\sqrt{2}[1 - r_2 \mathrm{e}^{i\Phi_{r_2}} + r_1 \mathrm{e}^{i\Phi_{r_1}}(\mathrm{e}^{i\Phi_{r_2}} - r_2)]}\right|, \tag{4}$$

where E_2 is the electrical field in the outer resonator, r_1 and r_2 are the through amplitude transmission coefficients for the directional couplers between MZI and the inner microring resonator, and between the two microring resonators, respectively. Φ_{r_1} and Φ_{r_2} are the single-pass phase shifts for the two microring resonators. Similar to the single-resonator structure, we expect that, on resonance, the power will build up in the outer resonator. For the coupled-resonator structure, the power buildup factor is expected to be proportional to

$$\left|\frac{E_2}{E_{\text{in}}}\right|^2 \propto \frac{(1+r_1)(1+r_2)}{(1-r_1)(1-r_2)}. \tag{5}$$

This condition can be satisfied as long as the single-pass phase shifts of the two rings fulfill the following resonance conditions: $\Phi_{r_1} = \pi$ and $\Phi_{r_2} = 0$, i.e., the inner resonator is on anti-resonance while the outer resonator is on resonance. Under this condition, the power buildup factor in the inner resonator is found to be $|(E_1/E_{\text{in}})|^2 = \frac{1}{2}\frac{1+r_1}{1-r_1}$. This buildup factor is much smaller than the one for the outer resonator. Thus, we only need to consider the nonlinear effect in the outer resonator and assume that the single-pass phase shift of the inner resonator is a constant.

Next, we consider the additional enhancement due to the effective phase shift for the whole device. The amplitude transmission coefficient of the output port can be written as

$$\frac{E_{\text{out}_2}}{E_{\text{in}}} = \frac{i}{2}\left[\mathrm{e}^{i\Phi_2} + \mathrm{e}^{i\Phi_1}\frac{\mathrm{e}^{i\Phi_{r_1}}\mathrm{e}^{i\Phi_{r_2}} + r_1 - r_2\mathrm{e}^{i\Phi_{r_1}} - r_1 r_2 \mathrm{e}^{i\Phi_{r_2}}}{1 + r_1\mathrm{e}^{i\Phi_{r_1}}\mathrm{e}^{i\Phi_{r_2}} - r_2\mathrm{e}^{i\Phi_{r_2}} - r_1 r_2 \mathrm{e}^{i\Phi_{r_1}}}\right]. \tag{6}$$

The effective phase shift of the device is the phase argument of the field transmission coefficient, which is the phase shift acquired by light in crossing from input port to output port. It is straightforward to obtain the following formula for the effective phase shift:

$$\Phi_{\text{eff}} = -\tan^{-1}\left[\frac{\cos\frac{\Delta_1+\phi_{r_2}}{2} + r_1\cos\frac{\Delta_2-\phi_{r_2}}{2} - r_2\cos\frac{\Delta_1-\phi_{r_2}}{2} - r_1 r_2\cos\frac{\Delta_2+\phi_{r_2}}{2}}{\sin\frac{\Delta_1+\phi_{r_2}}{2} + r_1\sin\frac{\Delta_2-\phi_{r_2}}{2} - r_2\sin\frac{\Delta_1-\phi_{r_2}}{2} - r_1 r_2\sin\frac{\Delta_2+\phi_{r_2}}{2}}\right], \tag{7}$$

where $\Delta_1 \equiv \phi_1 + \phi_2 + \phi_{r_1}$ and $\Delta_2 \equiv \phi_1 + \phi_2 - \phi_{r_1}$ are introduced for simplicity, and ϕ_1 and ϕ_2 are the phase shifts of the two MZI arms, respectively. At near resonance the effective phase shift becomes sensitively dependent on the single-pass phase shift ϕ_{r_2}. A measure of this phase sensitivity is obtained by differentiation of the effective phase shift with respect to ϕ_{r_2}. Under the resonance condition and assuming $\phi_1 = \phi_2 = 0$, we get

$$\frac{\mathrm{d}\Phi_{\text{eff}}}{\mathrm{d}\phi_{r_2}} = \frac{1}{2}\frac{(1+r_1)(1+r_2)}{(1-r_1)(1-r_2)}. \tag{8}$$

We can see that the enhancement of phase sensitivity is also proportional to the multiplication of finesses of these two microring resonators. If the outer ring is allowed to possess a third-order nonlinearity, then the single-pass phase shift can be written as $\phi_{r_2} = \phi_{r_{20}} + \gamma_{r_2} L_{r_2} P_2$, where $\phi_{r_{20}}$ is a linear phase offset, and γ_{r_2} and L_{r_2} are the nonlinear coefficient and the length of outer microring, respectively. The derivative of the effective phase shift with respect to the input power gives a measure of the power-dependence of accumulated nonlinear phase. For the coupled two-ring structure, this derivative can be expressed as

$$\frac{\mathrm{d}\Phi_{\text{eff}}}{\mathrm{d}P_0} = \frac{\mathrm{d}\Phi_{\text{eff}}}{\mathrm{d}\phi_{r_2}}\frac{\mathrm{d}\phi_{r_2}}{\mathrm{d}P_2}\frac{\mathrm{d}P_2}{\mathrm{d}P_0} \xrightarrow{\phi_{r_1}=\pi,\phi_{r_2}=0} \gamma_{r_2} L_{r_2}\frac{1}{4}\left(\frac{1+r_1}{1-r_1}\right)^2\left(\frac{1+r_2}{1-r_2}\right)^2. \tag{9}$$

For microrings with the same r, we can see that the enhancement of phase sensitivity with respect to the input power is proportional to the fourth power of the resonator finesse, resulting in a reduction of MZI switching power proportional to the fourth power of the finesse. Figure 3 shows an example of the power transmission characteristics of the coupled-resonator-enhanced MZI of very low input power with a radius of 5 μm and reflectivities $r_1 = r_2 = 0.99$ for both rings. In the calculation, one arm length is biased and the input wavelength is detuned such that $\Delta = \phi_1 - \phi_2 = 1.2380$ and $\phi_{r_{20}} = -0.000036$, where Δ is the linear phase difference between two MZI arms. The single-pass phase shift in the inner resonator ϕ_{r_1} is kept to be π. The system transmission changes from 0 to 1 when the input power increases from 0 to a mere 5 μW. Thus, one can clearly see that with only two coupled microring resonators with moderate finesse, the switching power has been reduced to the microwatt level.

The above discussions are about the coupling of two microring resonators to the MZI. It is obvious that the proposed design scheme can be extended to more

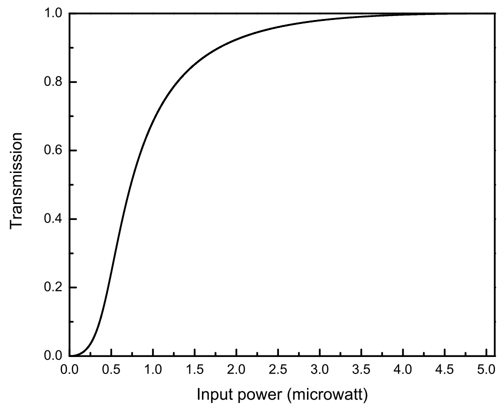

Figure 3. Transmission characteristics of resonator-enhanced MZI with two coupled microrings. Note that in order to get exponential reduction in switching power with perfect switching, the arm length needs to be properly biased and the input wavelength needs to be properly detuned.

than two microring resonators. By coupling one more microring to the outermost resonator, the phase sensitivity will be further enhanced by an additional factor of finesse squared of that resonator. Therefore, the total reduction in switching power for N microring resonators of the same finesses is proportional to $\prod_{i=1}^{N} F_i^2 = (F^2)^N$. Thus, by introducing coupling between adjacent microring resonators, the achievable reduction in switching power scales exponentially with the number of microring resonators instead of the linear dependence as in the uncoupled case. The resonance conditions for the coupled resonators with more than two microrings are that the single-pass phase shift for the outermost resonator is 0 while for all the inner resonators it is π. Thus, power eventually builds up in the outermost resonator. Figure 4 shows the switching power as a function of the number of coupled microring resonators. All resonators are assumed to have the same $r = 0.99$ and $R = 5$ μm. The solid line is for lossless resonators. The straight line in this semi-log plot clearly shows the exponential reduction in switching power as the number of microring resonators increases. With only five moderate-finesse resonators the switching power of the MZI has to be reduced to sub-attowatt level, making this device a promising candidate for single-photon all-optical switching applications.

4. Comments and conclusions

In the discussions of multi-ring structure so far, we have assumed that there is no loss in the ring waveguide. In reality, the losses in microring resonators will reduce the enhancement ability in switching power, as shown by the dashed line in figure 4, where the power attenuation coefficient of waveguide in each microring is assumed to be 6.4 cm^{-1} (corresponding to $a_i = 0.99$). Additional microrings are required to compensate for the waveguide losses. For microrings with radii larger than few micrometers, the dominant loss mechanism in microrings is due to surface-roughness scattering in the curved waveguides [20]. Typical value of propagation losses of

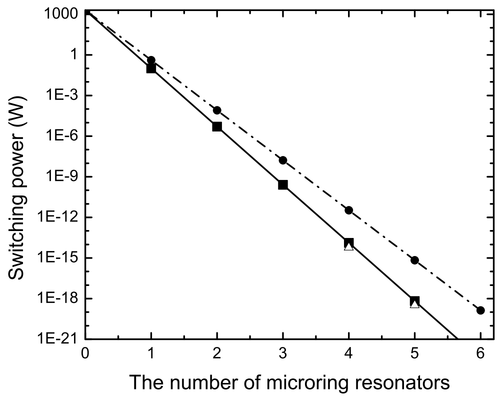

Figure 4. The switching power of MZI as a function of the number of coupled microring resonators. All resonators are assumed to be identical with $r = 0.99$, $\gamma = 100$, and $R = 5$ μm. The solid line is for lossless ($a_i = 1$) resonators while the dashed line is for $a_i = 0.99$. The empty triangles are the FDTD simulation results.

index-guided waveguides (such as GaAs-AlGaAs waveguide) can be made to be well below 1 cm^{-1}, making the loss effect to be negligible in microring resonators. Some applications require that different microrings posses different losses [14]. In this case, non-index-guided lossy waveguides with controllable loss coefficients can be used to make microrings. For example, by using anti-resonant reflecting optical waveguides (ARROW) with low-index gas or liquid cores and alternating high-index cladding layers, loss values as low as 0.26 cm^{-1} have been experimentally achieved and can be easily controlled by adjusting the cladding layer thicknesses [21]. We have carried out a finite difference time domain (FDTD) simulation on a real device consisting of MZI coupled with multiple microring resonators which are made by the solid-core ARROW waveguide. FDTD is a popular computational electrodynamics modeling technique used to solve Maxwell's equation in time domain [22]. A commercial FDTD package (OminSim© by Photon Design) was used to perform the real simulation. We used SiO_2 ($n = 1.46$) as the solid-core material. To save the calculation time, we chose $R = 5$ μm for all rings. The width of the ridge waveguide was set to 1 μm and the distance between different rings was carefully adjusted so that the coupling between adjacent ring reached $r = 0.99$. The waveguide material loss was set to 0.1/cm (corresponding to $a = 0.9999$). The device was excited by a mode exciter corresponding to the lowest order of the waveguide mode at the center wavelength of 800 nm. Near the device input and in the outermost ring, we put two sensors to detect the power level of the input and output pulse. Finally, we gradually increased input power level until the output power level could reach 95% of the input power. Under these conditions, the calculated switching powers for four- and five-ring structures are shown in figure 4 as empty triangle. As can be seen, the simulated value is even smaller than theoretically calculated value. This is because in FDTD simulation, we allowed for a 5% error in switching (i.e., we assumed it to be a perfect switching if the output power is 95% of the input power). A more strict theoretical calculation shows that the switching power can be further reduced by a factor of two if we allow for a 0.2% switching error, and by a factor of four for 4.5% switching error. Therefore, the FDTD simulation agrees well with our theoretical calculations presented here.

It is also well-known in filter theory that any performance enhancement increases exponentially with serially coupled rings. However, there are crucial problems with the serial coupled resonator schemes, such as exponentially increased losses, exponentially decreased bandwidth, and exponentially increased demanding on manufacturing tolerances. To make it practical, we need to carefully think about all these problems relating to our proposed multi-ring-enhanced all-optical switching devices.

First, let us look at the losses for coupled microrings. As mentioned earlier, the coupled microring resonators will not increase the total loss of the whole system exponentially. Instead, through CRIT, the whole system can become transparent even though the individual ring has loss [14,15]. Each additional microring resonator corresponds to an additional energy level in the atomic system. Waveguide with two coupled microring resonators is similar to a three-level Λ-type atomic system, which can lead to one dip in the middle of the absorption peak (EIT), while waveguide with three coupled microring resonators is similar to a four-level atomic system, which can lead to two dips in the absorption peak (double EIT), and so on. It is therefore obvious that by carefully selecting parameters, the whole system can be transparent or with low losses while still maintaining a high enhancement factor for the switching power.

Second, we consider the problem of manufacturing tolerances. For a multiple microring structure, the resonant conditions are $\phi = \pi$ for all inner rings and $\phi=0$ for the outermost ring. Due to the relatively flat response near the anti-resonant condition, the manufacturing tolerances of all inner rings are not very demanding, leading to relatively drift-tolerant all-optical devices.

Next, there is also an issue of quantum fluctuations at extremely low switching power levels. Typically such fluctuations will bring de-coherence and dissipation in the system which become important at attowatt power level. Also, at such low power levels we have both deterministic switching as well as occasional stochastic (fluctuations-induced) switching present in such systems. The latter is of spurious type and hence unwanted in practical systems, and can be avoided to a large extent by using squeezed light source in such devices so that the quantum fluctuations are reduced.

Finally, let us look at the most important question of exponentially reduced bandwidth for such coupled-resonator-enhanced MZI. This problem is intrinsic for all resonator-enhanced devices. The very early paper on this topic (ref. [6]) has clearly pointed out that the reduction of switching power scales with F^2, while the reduction of bandwidth scales with F for single-resonator-enhanced MZI. So with some tradeoff, devices with different requirements can be achieved theoretically. In the case of coupled resonators, due to the anti-resonant nature, the input power does not accumulate in any of the inner resonators and quickly builds up in the outmost microring resonator. Therefore, the bandwidth decrease of the system only scales with the overall system finesse F, which is the multiplication of the individual finesses F_i. Considering that the enhancement scales with the square of the overall finesse, the advantage of using such coupled resonators is still bigger than the disadvantages in this regard, or at least not worse than in the single microring case.

In conclusion, we have studied the nonlinear phase responses of the coupled microring resonators and used this nonlinear phase shift for optical information storage and enhanced all-optical switching in MZI. By introducing coupling between adjacent microring resonators, the switching power of the MZI becomes exponentially reduced as a function of the number of microring resonators, when compared with the linear reduction in the case of uncoupled resonators. We have also shown that with only a few microring resonators, the switching power can be reduced down to sub-attowatt level, allowing for photonic switching devices that operate at single-photon level in ordinary optical waveguides. Our proposed devices also possess some additional advantages in reducing total system losses in operation.

Acknowledgements

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