Finesse enhancement in silicon-on-insulator two-ring resonator system

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We demonstrate experimentally the finesse enhancement in a pair of mutually coupled ring resonators coupled to two buses fabricated in silicon-on-insulator technology, as proposed theoretically in an earlier paper. A finesse close to 100 (or $Q=30\,000$) is obtained in a two-ring system, with the outer ring double the size of the inner ring, and an external coupling coefficient of 34%. The maximum finesse enhancement relative to the single-ring structure is 14 times, in good agreement with the theoretical prediction. © *2008 American Institute of Physics*.
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Microring resonator has been extensively explored as filtering, switching, and sensing devices because of its small size and highly resonant behavior.[1] The ring cavity is normally excited by evanescent coupling from one or two waveguides and is functionally identical to a Fabry–Pérot cavity, with the coupling coefficient and the ring circumference corresponding to the mirror transmittivity and the cavity length, respectively. The performance of a resonator filter can be primarily characterized by the resonance amplitude (D_{max}) and the finesse (F), where D_{max} is the maximum amplitude in the "drop" output and finesse is a measure of the sharpness of the resonance. In order to achieve both high finesse and D_{max}, the coupling factor needs to be several times larger than the cavity round-trip loss while both are kept small, as the achievable finesse is limited by the intrinsic loss.[2] The best microring resonators have demonstrated round-trip losses less than 1% in various material platforms.[3–5] This would suggest a best-case finesse of around 100 in a single-ring system. Previously, we have theoretically proposed a two-ring structure, in which the two rings are mutually coupled, that is able to achieve a finesse higher by two orders of magnitude compared to the single-ring system.[6] The high-finesse resonance is associated with strong photon localization in the second ring, which is further and effectively shielded from the external bus by the first ring, especially when the latter is antiresonant. In this letter, we present the experimental verification of such finesse enhancement in silicon-on-insulator (SOI) technology using deep-uv complementary metal-oxide semiconductor process.[7] The finesse enhancement is measured to be one order of magnitude larger than the corresponding one-ring structure and in a good agreement with the theoretical prediction.

The schematic structure and fabricated device of the two-ring resonator system are shown in Fig. 1. The thickness of the SOI waveguide is 220 nm and the width is 440 nm. The gap between the waveguides is about 167 nm. Racetracks with lengths L_{C1} and L_{C2} are used to control the coupling between the bus waveguide and R1, and between R1 and $R2$. Typical design values are $L_{C1}=5.3\ \mu$m and $L_{C2}=3\ \mu$m, which yield rather strong coupling so that the individual rings would have only moderate finesse. The two rings may have different cavity lengths and the ratio $\gamma=L_2/L_1$ is an important device parameter. The radius of R1 is fixed at 15 μm, while the radius of $R2$ is adjusted to give the desired γ value, which is varied from $\gamma=1$ to $\gamma=2$. To facilitate fiber coupling, a second-order grating is integrated with the device. The fiber is butt-coupled to the grating 10° off vertical. The coupling efficiency has a Gaussian spectral profile with a bandwidth of about 30 nm. The device is excited with a broadband source with wavelength ranging from 1.42 μm to 1.61 μm. The output power is then passed through a 90:10 splitter, where 10% power goes to a fiber power meter for alignment purpose and the rest goes to an optical spectrum analyzer for normalization with the input spectrum.

Theoretically, the through (τ) and drop (d) transmittances of the two-ring system are given by[6]

$$\tau \equiv \frac{E_T}{E_{IN}} = r_1 \frac{1 - a_1\tau_{21}\exp(-i\delta_1)}{1 - a_1 r_1^2 \tau_{21}\exp(-i\delta_1)},$$
$$d \equiv \frac{E_D}{E_{IN}} = -\frac{\sqrt{a_1}\tau_{21}(1-r_1^2)\exp(-i\delta_1/2)}{1 - a_1 r_1^2 \tau_{21}\exp(-i\delta_1)}. \quad (1)$$

Note that these expressions are similar to those of the single-ring system, except for the factor $\tau_{21}=[r_2-a_2\times\exp(-i\delta_2)]/[1-a_2r_2\exp(-i\delta_2)]$, which embodies the load-

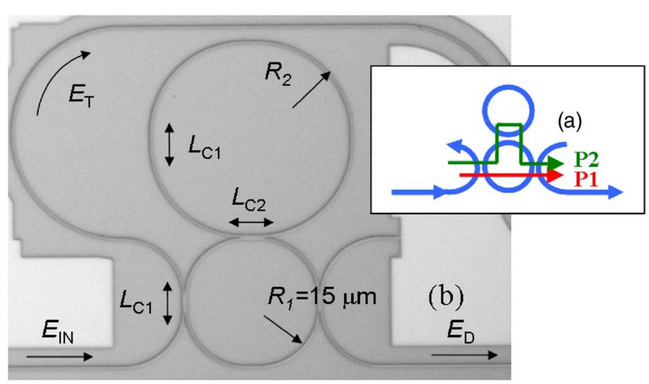

FIG. 1. (Color online) Schematic structure (a) and microscope image of the fabricated device (b) of the two-ring resonator system. E_T is the E field in the through port, and E_D that in the drop port.

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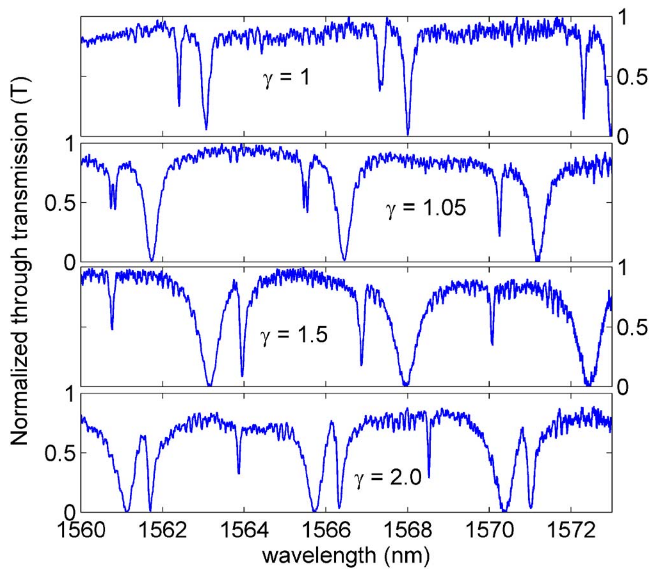

FIG. 2. (Color online) The measured through transmission for various γ. Note the fact that the resonance order is large (>300), the Vernier effect is apparent in $\gamma=1$, where there are two distinct resonances instead of resonance splitting.

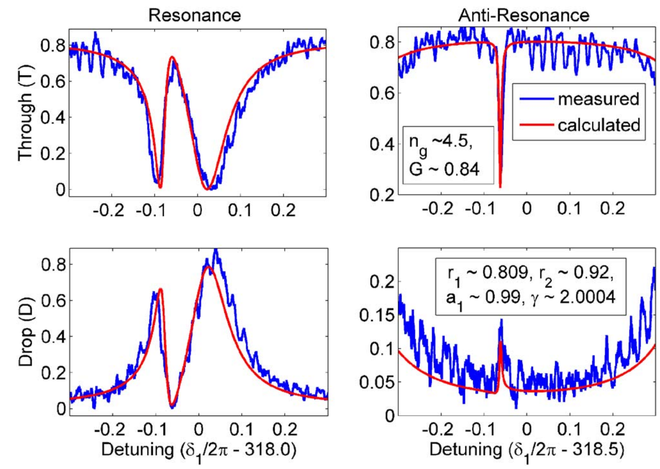

FIG. 3. (Color online) The measured transmission (blue) and the theoretical fit (red) as a function of δ_1. Note that the narrow resonance (right) is slightly offset from the antiresonance of R1.

ing effect of $R2$ on R1. In Eq. (1), $\delta_m = \omega n L_m / c$ and $a_m = \exp(-\alpha L_m/2)$ are the round-trip phase and loss, respectively, of the mth ring of cavity length L_m and effective index n, r_1 is the coupling coefficient between R1 and the bus waveguides, and r_2 is the coupling coefficient between the two rings. In the single-ring picture, by writing $\tau_{21} = |\tau_{21}|\exp(i\theta_{21})$, it can be seen that the effect of $R2$ is to introduce an additional loss and phase, so that the effective round-trip loss in R1 is modified to $a = a_1|\tau_{21}|$ and the effective round-trip phase becomes $\delta = \delta_1 - \theta_{21}$. The first term in δ represents the pathway resonating in R1, while the second term, which is significant only when $R2$ is resonant, represents the pathway resonating in $R2$, as shown in Fig. 1. The two pathways interfere constructively (giving rise to the maximum in d and the minimum in τ) when δ/π is even and destructively when δ/π is odd.

Figure 2 shows the measured through transmission $T = |\tau|^2$ for various γ values. Theoretically, when $\gamma=1$, there should be an even resonance splitting corresponding to equal light localization in both rings. However, the measurement shows that there are two rather distinct resonances, instead of even splitting. This implies that γ is not exactly 1 due to fabrication variations. Simulations show that even a slight deviation of less than 1% in γ can shift one resonance from the other by much larger than the full width at half maximum linewidth due to the Vernier effect, which is important for large resonance orders (>300 for 15 μm radius ring). Furthermore, the mutual coupling between the rings may help to shift the resonances so as to make the ring slightly nonidentical.[8]

When $\gamma \neq 1$, the resonances of both rings do not coincide. The broad resonance corresponds to the resonance of R1 where the phase perturbation from the second ring is nearly absent, and the system behaves as a one-ring structure. On the other hand, the narrow resonance corresponds to the resonance of $R2$ (and off-resonance for R1) where the resonant phase perturbation from $R2$ (a sharp π phase step) changes the interference condition in δ from destructive to constructive in rapid succession, thus producing an asymmetric and narrow resonance. We address this resonance as the Fano resonance as it is associated with dominant light localization in $R2$.[6,9]

The sharpness of the Fano resonance is determined by the intensity buildup factor in $R2$ relative to R1. Light localization in $R2$ is expected to be maximum when $R2$ is resonant (δ_2/π=even) and R1 is antiresonant (δ_1/π=odd) at the same time. This implies that the general condition for maximum finesse is $\gamma = 2p/(2q+1)$, where p and q are integers. However, there is a narrow resonance at every resonance order only when γ is an even integer. The simplest case, $\gamma=2$, is shown in the last panel of Fig. 2, where a very narrow resonance is seen roughly in the middle between two broad, split resonances for every resonance order. The broad resonances are similar to those in the $\gamma=1$ case, and occurs when R1 and $R2$ are both resonant. However, in this case, light is localized in both rings in inverse proportion to the ring size, hence, the resonance splitting is narrower compared to the $\gamma=1$ case. Similarly, the narrow resonance occurs at the antiresonance of R1 and the resonance of $R2$. The antiresonance in R1 effectively shuts the escape pathway (and also increases the injection time) for light circulating in $R2$, resulting in a long photon cavity lifetime and, hence, higher finesse.

Note that a rather similar pattern is also observed near 1570 nm for the case where γ is near 1.5, suggesting that $\gamma = 2p/(2q+1)$ is satisfied at that particular resonance order. This is possible because of fabrication variations that slightly deviate the value of γ so as to match the general condition above.

To verify the theory, the measured through (T) and drop (D) transmissions for $\gamma=2$ are fitted with theory, as shown in Fig. 3, where the general good fit is evident, and the best-fit parameters are given by $a_1 \sim 0.99$, $r_1 \sim 0.809$, $r_2 \sim 0.92$, and $\gamma \sim 2.0004$. Note that $r_1 r_2$ is consistent with the fact that $L_{C1} L_{C2}$, and the best values of r_1 and r_2 are consistent with simulated results based on the supermode theory for directional coupling and the measured racetrack geometry. The round-trip loss of about 1% is verified independently by the drop transmission of a single ring of the same diameter coupled to two waveguide buses fabricated in the same sample [see Fig. 4], which shows no significant difference in the loss parameter. Finally, there is an $\sim$0.2% deviation from

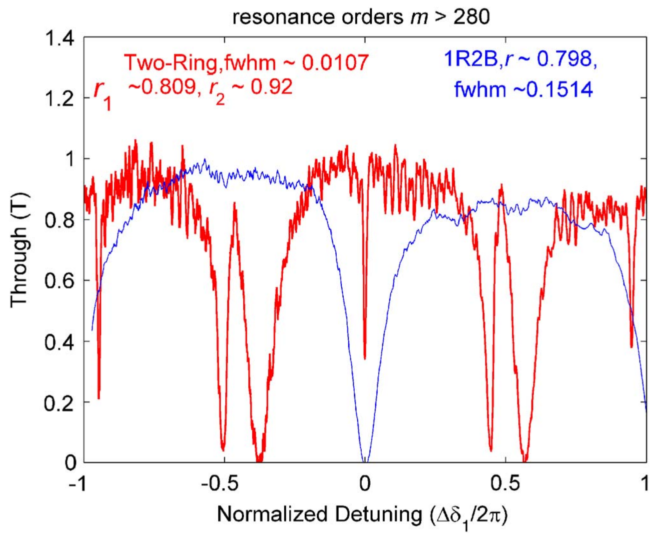

FIG. 4. (Color online) The comparison of two-ring and single-ring transmission spectra as a function of the relative normalized detuning from each resonance.

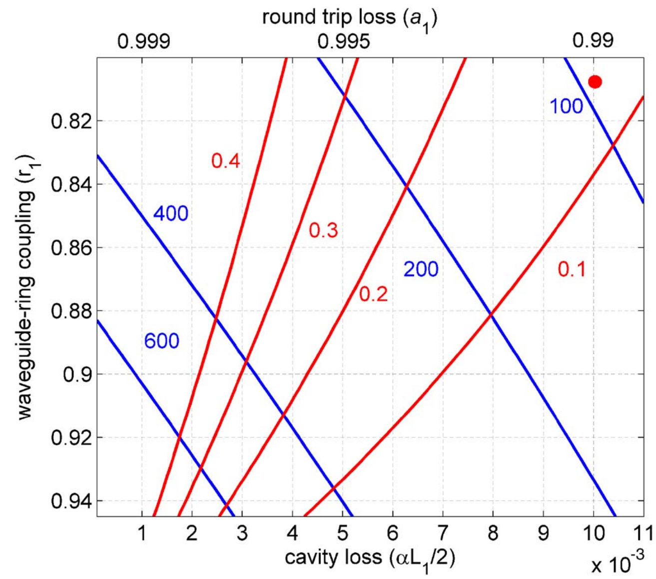

FIG. 5. (Color online) The measured device performance shown on the Finesse-$D_{\max}$ contour for the case $r_2 \sim 0.92$.

$\gamma=2$, which results in a shift of the narrow resonance by about 5% of the free spectra range. Such sensitivity is due to the large resonance order of 318 for R1 of 15 μm radius. Next, we briefly mention only some of the procedures used to extract these parameters. First, the wavelength is normalized with respect to $L_1=2\pi R_1+2L_{C1}+2L_{C2}$, to give δ_1 in such a way that the resonance splitting occurs near even values of δ_1/π. This yields a waveguide group index of about 4.5, which is in agreement with the reported values in literature.[10] Second, we use the theoretical resonance splitting for $\gamma=2$,[11] i.e.,$\Omega=2\cos^{-1}\left[\frac{1}{2}(1+r_2)\right]$ to derive an initial guess of r_2. Third, the grating factor G is adjusted to match the measured "through" transmission near the antiresonance (δ_1/π=odd), giving the value $G \sim 0.84$.

To study the finesse enhancement, we juxtapose in Fig. 4 the narrow resonance of the two-ring structure and the ordinary resonance of the single-ring structure fabricated in the same sample (as mentioned earlier) that have nearly the same waveguide-ring coupling (i.e., $r_1 \sim r$). The finesse of the single-ring structure is 6.6. This gives ~1% round-trip loss, when compared with the lossless case $\pi r_1/(1-r_1^2) \sim 7$, and, thus, in agreement with the best-fit value of $a_1 \sim 0.99$ in the two-ring system. The measured finesse for the two-ring structure is ~94, about 14 times larger than the single-ring value. From the drop spectrum in Fig. 3, the resonant amplitude $D_{\max}$ is about 0.12. These measured finesse and $D_{\max}$ values are in good agreement with the theory.

Figure 5 shows the calculated finesse-$D_{\max}$ contours as a function of r_1 and a_1 for a fixed r_2 (r_2=0.92), with the red dot coresponding to the best-fit values of (r_1, a_1) for the measured device. Note that the predicted finesse and $D_{\max}$ are close to the measured values. The contour plot gives guidelines on how to improve finesse and $D_{\max}$ using the present fabrication condition. We note that the resonator Q factor is given by the finesse multiplied by the resonance order, and $D_{\max}$ is the same as modulation depth (except the latter is given in decibel). For given r_1 and r_2, both finesse and $D_{\max}$ can be increased by reducing the round-trip loss. Using the fact that the bending loss is negligible for radius larger than 5 μm,[12] it is possible to reduce the round-trip loss to ~0.3% (or $a_1 \sim 0.997$) by decreasing L_1 by three times, in which case the finesse and $D_{\max}$ will be increased by about three to four times, respectively. If $D_{\max}$ is more important, then one can further decrease r_1 (by increasing L_{C1}) to achieve a larger $D_{\max}$ at the expense of finesse. In general, one can exploit the trade-off between finesse and $D_{\max}$ to achieve the desired combination.

In summary, we have demonstrated that a simple two-ring system can exhibit a finesse one order of magnitude larger than that achievable in a single-ring system, as theoretically predicted earlier in Ref. 6. A finesse close to 100 (associated with $Q=qF \sim 30\,000$) is obtained in a two-ring system that has an external coupling coefficient of 34% (r_1 ~0.809), the good agreement between experimental results and theory verifies the accuracy of the model used. Finally, it is shown that even larger finesse ranging from 300 to 500 and $D_{\max}$ from 0.2 to 0.4 can be realized by making the rings smaller or reducing the loss with improved fabrication. A larger $D_{\max}$ is important to make the device useful for practical applications.

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