Adiabatic microring resonators

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A class of whispering-gallery-mode resonators, herein referred to as adiabatic microring resonators, is proposed and numerically demonstrated. Adiabatic microrings enable electrical and mechanical contact to be made to the resonator without inducing radiation, while supporting only a single radial mode and therein achieving an uncorrupted free spectral range (FSR). Rigorous finite-difference time-domain simulations indicate that adiabatic microrings with outer diameters as small as 4 μm can achieve resonator quality factors (Qs) as high as $Q = 88{,}000$ and an FSR of 8.2 THz, despite large internal contacts.

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Microring and microdisk resonators have been used extensively in filtering [1,2], modulation [3,4], and sensing applications [5,6]. In active filtering applications (e.g., a resonant modulator or bandpass switch) where an electrical drive is required, or alternatively, sensing applications where a resonator may be suspended above a substrate [5–7], contact to the resonator is necessary. In all cases, it is highly desirable to maintain a high quality factor (Q) in the presence of the electrical or mechanical contact. Further, for many applications, it is desirable to simultaneously maximize the resonator free spectral range (FSR). In communication applications, the FSR determines the available optical bandwidth on a communication line. For sensing applications, the FSR can determine the pixel count in a wavelength-division-multiplexed sensor array [5]. Here, we introduce a class of whispering-gallery-mode resonators, adiabatic microring resonators (AMRs), that enable both a high Q and a large FSR in the presence of electrical or mechanical contact to the resonator.

In general, microdisks propagate modes with radial ($\hat{r}$), azithumal ($\hat{\theta}$), and axial ($\hat{z}$) mode numbers denoted by l, m, and n, respectively. As a rule, the Q of the mode increases with increasing azithumal mode number, m, and decreases with increasing radial, l, and axial, n, mode numbers due to radiation. For a nonzero azithumal mode number and low radial mode number, the modes are often referred to as whispering gallery modes, in reference to the acoustic whispering galleries of medieval churches and monasteries. Because these modes propagate at the outer radial boundary of the microdisk, contacting a microdisk in the center can be achieved without inducing radiation or impacting the resonator Q. However, microdisks propagate multiple higher-order radial modes (i.e., $l > 0$). These higher-order radial modes contribute spurious radial resonances with frequencies between the azithumal resonances of the lowest-order radial mode, thereby corrupting the resonator FSR. Moreover, higher-order radial modes contribute to coupling losses, leading to a reduction in the loaded Q of the resonator. The axially polarized magnetic field from a two-dimensional finite-difference time-domain (FDTD) simulation of a microdisk resonator is presented in Fig. 1(a). From the figure, it is clear that at least two radial modes are propagating, the lowest-order mode with radial wavenumber $l = 0$, and a spurious second-order mode with a radial wavenumber, $l = 1$. Further, a discrete Fourier transform (DFT) of the field at the output ports, plotted in Fig. 1(c), reveals the corresponding spurious resonances of the higher-order modes and their impact on the resonator FSR.

By adding an interior wall, higher-order modes of a microdisk can be effectively cut off, enabling microrings to propagate only the lowest-order radial mode. Yet, contacting a microring presents significant challenges. Figure 1(b) is a two-dimensional FDTD simulation of a directly contacted microring. The index perturbation caused by a direct contact to a microring induces radiation. The resonator Q, prior to contact, exceeded 10^6. However, as a result of the contact, the resonator Q has been reduced to 10^3 [see Fig. 2(b)]. To circumvent the problems of radiation and higher-order modes, previous electrically active microrings have utilized ridge waveguides to make electrical contact [3]. While ridge waveguides enable low-loss contact and cut off higher-order modes, they exhibit reduced field confinement and a corresponding larger minimum bend radii, resulting in a smaller FSR or available optical bandwidth than is otherwise possible in a microring with a hard outer wall but no contact [8].

Therefore, the challenge is to achieve the lossless contacts of a microdisk and the single-mode operation of a microring, in a tightly confined resonant structure. Such a structure could resemble a microdisk in the region of contact, and a microring in the region of coupling, so that the contact would not perturb the field and only a single mode would be available for coupling. The two regions of the structure could then, through the principle of mode evolution, be connected through an adiabatic transition. Mode evolution, that is, the change from one modal distribution to another via an adiabatic transition, has been used in numerous waveguide applications, including mode expanders, polarization splitters [2,9], and polarization rotators [2,10]. The theory of mode evolution dictates that an electromagnetic mode may be slowly transitioned from one distribution to another in a lossless manner, provided the transition is sufficiently slow [10,11]. The theory of mode evolution is well developed but translated here to cylindrical coordinates.

The evolution of a waveguide induces coupling amongst the modes, extracting power from the initially

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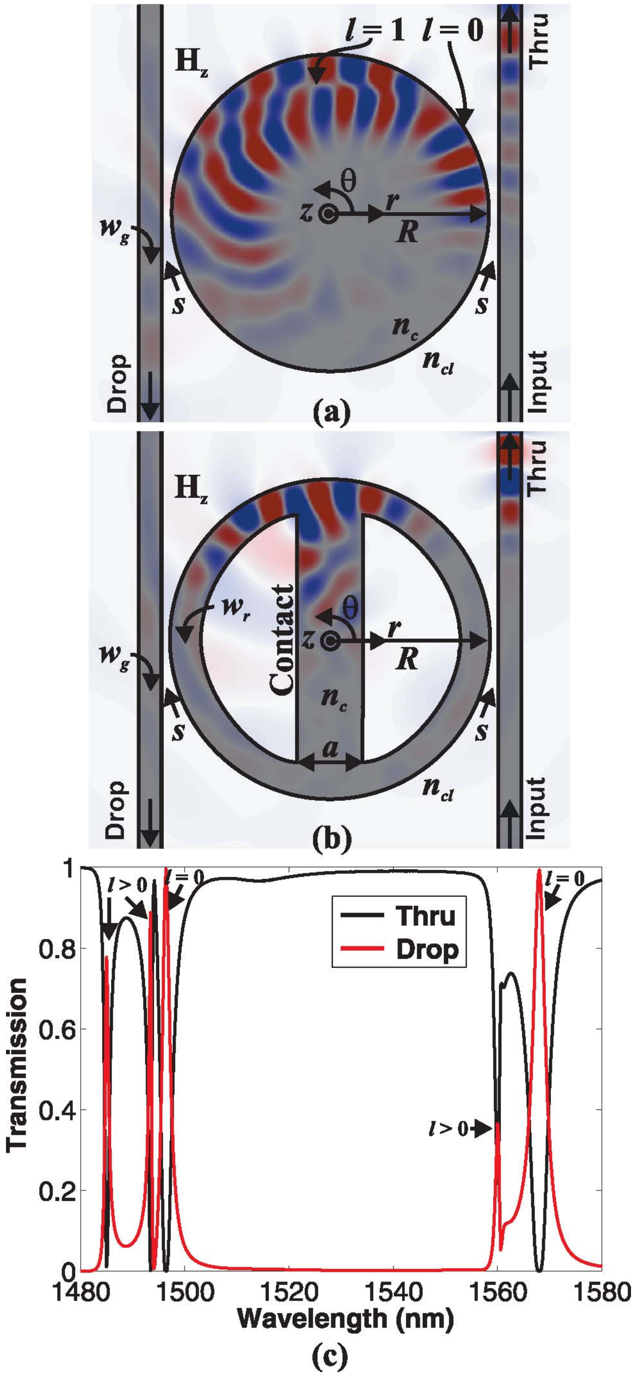

Fig. 1. (Color online) (a) 2D FDTD simulation of a microdisk resonator with $w_g = 0.3$ μm, $R = 2$ μm, $n_c = 3$, $n_{cl} = 1$, and $s = 0.1$ μm. Microdisks provide natural contacts from the interior of the resonator but support high-order radial modes. (b) 2D FDTD simulation of a directly contacted microring resonator ($w_r = 0.4$ μm and $a = 0.8$ μm). The microring supports only a single radial mode, but the contact induces scattering and radiation thereby degrading the Q [see Fig. 2(b)]. (c) DFT outputs for the through and drop ports of the microdisk. Higher-order modes corrupt the available FSR.

excited mode. The mode amplitudes $b_m(\theta)$ can be described by the coupled local mode equations:

$$\frac{\mathrm{d}b_m}{\mathrm{d}\theta} + j\beta_m(\theta)b_m(\theta) = \sum_n \kappa_{mn}(\theta)b_n(\theta), \qquad (1)$$

where $\beta_m(\theta)$ is the local propagation constant of mode m and $\kappa_{mn}(\theta)$ is the local coupling coefficient between modes m and n given by

$$\kappa_{mn}(\theta) = \frac{\omega}{4\delta\beta(\theta)} \int \mathbf{e}_m^*(r,\theta,z) \cdot \mathbf{e}_n(r,\theta,z) \frac{\mathrm{d}}{\mathrm{d}\theta}\epsilon(\theta)\mathrm{d}A. \quad (2)$$

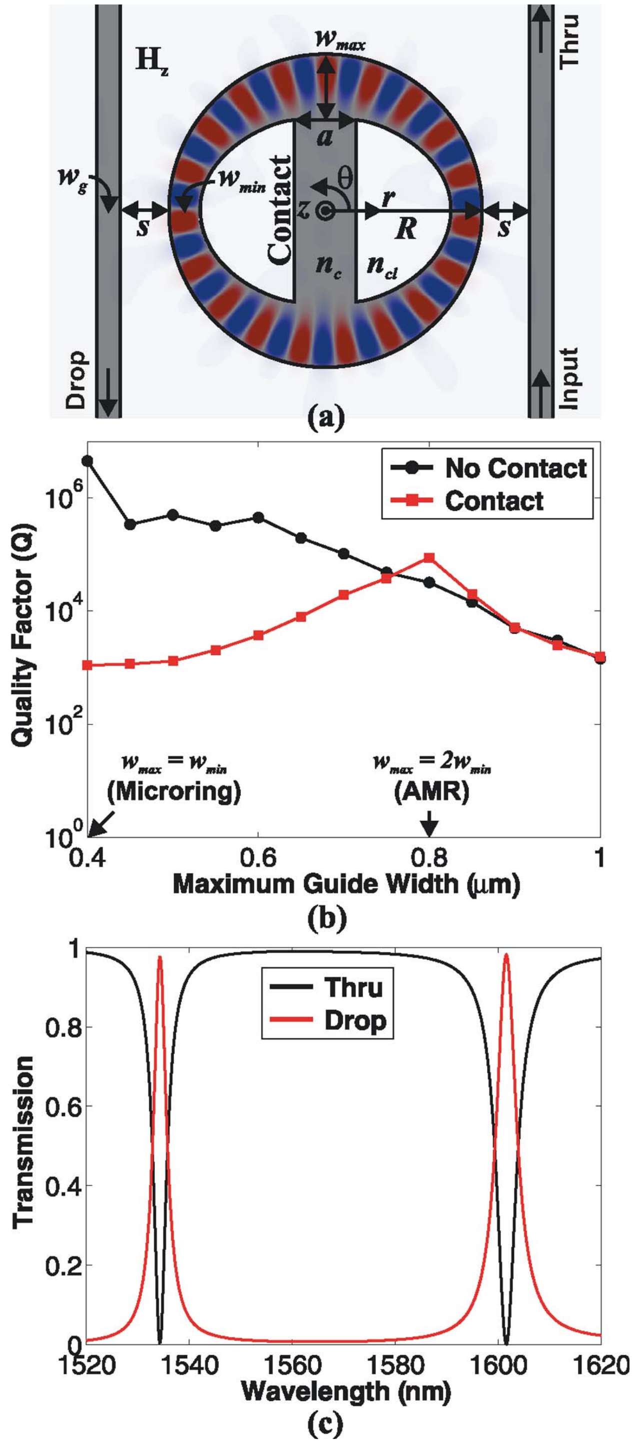

Fig. 2. (Color online) (a) 2D FDTD simulation of an AMR with $w_g = 0.3$ μm, $w_{\min} = 0.4$ μm, $R = 2$ μm, $a = 0.8$ μm, $n_c = 3$, and $n_{cl} = 1$. (b) Results of a cavity ringdown simulations, Q versus maximum guide width, $w_{\max}$, showing an internal Q of 88,000 for the resonator ($w_{\max} = 0.8$ μm). (c) Spectrum of the adiabatic microring obtained from DFTs of the output ports ($s = 0.1$ μm and $w_{\max} = 0.8$ μm), revealing an 8.2 THz FSR.

Here $\delta\beta(\theta) = \beta_m(\theta) - \beta_n(\theta)$ and $\mathbf{e}_m(r, \theta, z)$ represents the power normalized local vector electric field of mode m, and for purposes of normalization and orthogonality, the modes have been assumed to be lossless, generally a good approximation. In the limit of weak coupling, the higher-order terms $\sum_{n\neq k} \kappa_{mn} b_n$, where mode k is the initially excited mode, can be dropped. The coupling to a mode m is then determined to be

$$b_m(\theta) = b_k(0) \exp\left[-j \int_0^\theta \beta_m(\theta')\mathrm{d}\theta'\right] \times \int_0^\theta \kappa_{mk}(\theta') \exp[-j\overline{\delta\beta}(\theta)\theta']\mathrm{d}\theta', \qquad (3)$$

where $\overline{\delta\beta}(\theta) = (1/\theta) \int_0^\theta \delta\beta(\theta')\mathrm{d}\theta'$ is the average difference between the propagation constants. In evolving structures, the coupling coefficient varies slowly and can be replaced by its average outside the integral in Eq. (3). The power P_m, transferred to a spurious mode m, is then

$$P_m(\theta) = 2\left|\frac{\bar{\kappa}}{\overline{\delta\beta}}\right|^2 [1 - \cos(\overline{\delta\beta}\theta)], \qquad (4)$$

with the total power lost from the initially excited mode k given by $\sum_{m\neq k} P_m$. According to Eq. (4), the power lost to a given mode can be minimized by maximizing the ratio of $\overline{\delta\beta}$ to $\bar{\kappa}$ for each mode, allowing modes to dephase before substantial power exchange takes place.

The number of modes with propagation constants similar to the initially excited mode (i.e., guided modes) should therefore be minimized, and for modes that cannot be cut off, the difference in their rates of propagation ($\delta\beta$), maximized. In general, the slower the transition, the smaller the coupling [Eq. (2)], and the higher the index contrast, the larger the difference in rates of propagation between the relevant modes.

With these principles in mind, we now consider an adiabatic transition within a microring that enables single-mode coupling yet minimizes scattering losses at the region of electrical or mechanical contact. Such a resonator, herein referred to as an adiabatic microring resonator (AMR), is depicted in Fig. 2(a). The exterior wall of the resonator remains circular; however, the interior wall forms an ellipse. The ring waveguide is designed to be narrow and single mode in the coupling region and then adiabatically widens prior to contact. Contact can then be made where there is little electromagnetic field present. The 2D FDTD simulation in Fig. 2(a) illustrates this point. To demonstrate high-Q operation and to optimize the resonator Q in the presence of a contact, cavity ringdown simulations of unloaded adiabatic microrings were performed for different maximum guide widths [Fig. 2(b)]. As the maximum guide width is increased, the Q of the noncontacted AMR decreases while the Q of the contacted AMR increases, ultimately, a balance between minimizing scattering off the contact and maintaining an adiabatic transition is achieved. At $w_{\max} = 0.8$ μm, the simulations indicate that an internal Q = 88,000 or 2 orders of magnitude higher than the directly contacted microring resonator is possible. It is surprising, in fact, that the ring demonstrates such a high Q with only a 2 μm outer ring radius. The high index contrast results in a large difference in the azithumal mode numbers between the modes of interest, thereby ensuring a large ratio of $\delta\beta$ to κ despite the rapid transition. Finally, from DFTs taken at the output ports of the adiabatic microring [Fig. 2(c)], the output spectra were obtained, revealing a wide uncorrupted 8.2 THz FSR, indicating the elimination of the higher-order modes and spurious resonances that plague microdisks.

In summation, we have numerically demonstrated a class of whispering-gallery-mode resonators that allow for direct contact to be made to the resonator without sacrificing the resonator Q and while preserving a clean, uncorrupted FSR. In this manner, adiabatic microrings combine the best qualities of microring and microdisk resonators for applications requiring electrical or mechanical contact.

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References

1. B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J. P. Laine, J. Lightwave Technol. **15**, 998 (1997).
2. T. Barwicz, M. R. Watts, M. A. Popovic, P. T. Rakich, L. Socci, F. X. Kaertner, E. P. Ippen, and H. I. Smith, Nat. Photon. **1**, 57 (2007).
3. Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, Nature **435**, 325 (2005).
4. M. R. Watts, D. C. Trotter, R. W. Young, and A. L. Lentine, in *2008 5th IEEE International Conference on Group IV Photonics* (IEEE, 2008).
5. M. R. Watts, M. J. Shaw, and G. N. Nielson, Nat. Photon. **1**, 632 (2007).
6. A. M. Armani and K. J. Vahala, Opt. Lett. **31**, 1896 (2006).
7. D. K. Armani, T. J. Kippenberg, S. M. Spillane, and K. J. Vahala, Nature **421**, 925 (2003).
8. Q. Xu, D. Fattal, and R. G. Beausoleil, Opt. Express **16**, 4309 (2008).
9. M. R. Watts, H. A. Haus, and E. P. Ippen, Opt. Lett. **30**, 967 (2005).
10. M. R. Watts and H. A. Haus, Opt. Lett. **30**, 138 (2005).
11. A. W. Snyder, *Optical Waveguide Theory* (Chapman & Hall, 1983).