Light confinement in a low-refraction-index microcavity bonded on a silicon substrate

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The trapping of photons in low-refraction-index materials is thought to be prohibited in conventional photonic structures that employ total internal reflection. Specifically, the whispering gallery mode (WGM) microcavity, which is an important optical component, has to rely on a high contrast of the refraction index with the surrounding environment to manifest excellent light confinement. Here, we propose and demonstrate experimentally an optical microcavity structure consisting of a low-refraction-index silica microtoroid directly bonded on a high-refraction-index silicon substrate. The resonant structure supports high-Q fundamental WGMs in both visible and communication bands, while higher-order modes are suppressed significantly due to the strong leakage into the substrate at long wavelengths. The highest measured quality factor exceeds ten million and low-threshold microcavity Raman lasing is also realized. © 2016 Optical Society of America

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Whispering-gallery-mode (WGM) microcavities [1] confine light in a small volume for a long time, thus significantly enhancing the light–matter interaction. Recent efforts have demonstrated that they are an ideal platform for studies of fundamental and applied photonics, such as cavity quantum optomechanics [2], cavity quantum electrodynamics [3,4], and nonlinear optical processes [5]. Among the on-chip resonators, silicon-based microcavities usually have quality (Q) factors on the order of a million [13], and III–V semiconductor, such as GaAs, microcavities often support Q-factors around ten thousand [14]. The relatively low Q factors in these high-refraction-index materials become an obstacle to applications in the fields of on-chip nonlinearity and quantum manipulation, etc. Although the Q factor of the silicon microrings made by some research groups has increased to ten million, the employment of electron beam lithography technology incurs a high cost in the practical application [15]. In contrast, low-refraction-index materials have advantages in many aspects, especially in the fabrication of high-Q devices. With the aid of the reflow process, resonators with Q factors exceeding 100 million could be realized through photolithography [16,17]. However, traditional low-refraction-index devices are usually supported by a pedestal [16,18], introducing an extra air layer. Conventionally, these resonators have to be coupled by a tapered fiber, which makes for complications in using them for integrated photonics.

In this work, we propose and demonstrate experimentally a new method to achieve superior light confinement using a structure consisting of a low-refraction-index donut-shaped microcavity bonded on a substrate of a high-refraction-index material. High-Q fundamental modes are observed experimentally, while higher-order modes are suppressed due to a larger energy leakage into the substrate. The highest measured quality factor exceeds ten million, and subsequently low-threshold Raman lasing is demonstrated. The photonic resonant structure is illustrated in Fig. 1(a). A donut-shaped silica microcavity with a circular cross section is directly placed on the smooth silicon substrate. The refraction indices of silicon and silica are 3.48 (3.88), 1.44 (1.46), respectively, in 1550 nm (635 nm) wavelength band. The circular cross section of the microresonator remarkably reduces the electric field distribution area in the vertical direction compared with the traditional rectangular cross section, resulting in a better light confinement in the silica (see Supplement 1). Thus, the donut-shaped structure could support long-lived resonant modes mainly located in the low-refraction-index material, even though it is directly connected to the high-refraction-index substrate.

To gain a deeper understanding of the resonant modes in this photonic structure, we intend to vary the refraction index of the substrate $n_{\text{sub}}$, while keeping the refraction index of the silica microcavity unchanged. Figure 1(b) plots the imaginary part of the effective mode index $\text{Im}(n_{\text{eff}})$, which reflects the leakage rate depending on $n_{\text{sub}}$. It is noted that the leakage into the substrate...
Fig. 1. (a) Schematic representation of the donut-shaped silica microcavity bonded to the silicon substrate. One fourth of the device is cut off to show the cross-sectional geometry of the microcavity. The false-color diagrams mapped on the cross section show the electric distribution of the fundamental cavity mode. (b,c) The imaginary part and real part of the effective indices of transverse magnetic-polarized modes, respectively, versus the substrate refraction index $n_{sub}$. The refraction index of silica is 1.44 at a 1550 nm wavelength and the principal (minor) diameter is 8 μm. The values of Re$(n_{eff})$ are subtracted a constant number of 1.36180. The insets in (c) show the cross-sectional field distributions at $n_{sub} = 1.5$ and 3.5.

dominates the whole decay given that the radiation into the air is trivial for a large-sized WGM microcavity. In contrast to the intuitive understanding that more energy will leak into the substrate with larger $n_{sub}$, the numerical result shows that Im$(n_{eff})$ has a maximum value when $n_{sub}$ is around the refraction index of the silica microcavity. This phenomenon results from the trade-off between the density of states and leakage strength [19,20]. Figure 1(c) shows the real part of the effective mode index Re$(n_{eff})$, calculated by $\lambda/2\pi R$, which characterizes the mode resonance wavelength $\lambda$. It is found that Re$(n_{eff})$ relies on not only the ratio of energy distributed in the substrate to that in the cavity part, which is related to Im$(n_{eff})$, but also the location of the mode field in the substrate, which moves inward as $n_{sub}$ increases [insets of Fig. 1(c)]. The peak in Fig. 1(c) is the trade-off between these two factors (see Supplement 1).

According to the coupled-mode theory [21], the resonant mode, to the first approximation, can be given as a “superposition” of the WGM in the donut-shaped microcavity (free microcavity) and the “leaky mode” in the silicon substrate (without bonding to the microcavity),

$$\psi_{\pm}(d) = a_{\pm}(d)\psi_{WGM}(d) + b_{\pm}(d)\psi_{loa}(d),$$

where $a_{\pm}(d)$ and $b_{\pm}(d)$ are the amplitudes of the constituent WGM $\psi_{WGM}(d) = \{1, 0\}^T$ and leaky mode $\psi_{loa}(d) = \{0, 1\}^T$ basis respectively, $d$ is the minor diameter of the microcavity. The square modulus of the WGM amplitude $\vert a_{\pm}(d)\vert^2$ is a measure of the ‘character’ of the resonant mode, that is, the degree to which it is WGM-like:

$$\vert a_{\pm}(d)\vert^2 = \frac{n_{eff}(d) - n_{loa}(d)}{(n_{eff}(d) - n_{WGM}(d)) + (n_{eff}(d) - n_{loa}(d))}.$$
and polarized probe light, respectively. The scanning probe wavelength range $Q$ the (a,b) Normalized transmission spectra excited by TE- and TM-polarized light wavelength is in (a) 1550 nm and (b) 635 nm bands, respectively. Data with the same $d$ in (a) and (b) are measured in the same microcavity. Numerical simulated $Q$ factor exceeds the range of vertical axis in the 635 nm wavelength band, which is not shown in (b). Inset: scanning electron microscope image of the photonic microstructure and its zoom-in showing the scattering particle. It is an oblique view taken by an angle of 56° with the horizontal substrate. Scale bar: 20 μm.

Remarkably, the measured $Q$ factors in the 635 nm wavelength band are greater than that in the 1550 nm wavelength band, in particular for small $d$. This phenomenon is distinct from that in the conventional microtoroid supported by a tiny silica pillar, where the $Q$ factors of modes at shorter wavelength are lower due to stronger surface scattering effects. With regard to the effects of the principal diameter $p$ on characteristics of the microcavity, it is similar to the case of the microcavity with a supporting pillar. The free spectral range is inversely proportional to $p$ and the $Q$ factor is hardly affected by $p$ for large enough cavities with a $p$ of tens of micrometers.

Finally, we demonstrated microcavity Raman lasing [5] to show the potential of the resonant structure in the low-power-consumption integrated photonics. To this end, the tapered fiber is attached to the top of the toroidal part during the experiment, which is more stable and does not decrease the $Q$ factor too much. We performed the experiment in a cavity with principal (minor) diameter of 63.4 (9.7) μm. The pump cavity mode has an intrinsic $Q$ factor of about ten million and a loaded $Q$ factor of about six million. The pump laser is locked on the target mode while the pump power is increased to trigger stimulated Raman scattering. Figure 4 shows a typical Raman lasing spectrum of the microtoroid measured by an optical spectrum analyzer (OSA) with a resolution of 0.02 nm [see Fig. 4(a)]. The pump laser is around...
1550.8 nm and Raman lasing occurs at 1653.4 nm. The dependence of the Raman laser power, measured by the OSA, on the loading pump power is shown in Fig. 4(b), from which we can clearly see a Raman lasing threshold of about 56 mW. It should also be noted that when the pump power reaches about 58 mW, the pump-to-Raman conversion efficiency is suddenly reduced. This is due to the first-order Raman laser field acting as a secondary pump field for the generating second-order Raman laser, thus reducing the intensity of the first order Raman laser.

In summary, we have demonstrated experimentally excellent light confinement in low-refraction-index material by using a photonic microstructure consisting of a donut-shaped microcavity bonded on a high-refraction-index substrate. The resonant structure supports high-$Q$ fundamental whispering gallery modes in both visible and communication bands, and possesses weak energy leakage to the substrate, especially for short wavelength and large $d$. Low-threshold Raman lasing is also demonstrated in the microcavity with a $Q$ factor of ten million. This mechanism of light confinement in the photonic microstructure applies to various low-refraction-index materials besides silica, such as polymers. In practical applications, micromachining technology can be adopted to realize bath production instead of a transferring method of microcavity [24–26]. As for the attached coupling, a waveguide could be fabricated under the donut-shaped microcavity to replace the tapered fiber, which offers perfect stability and high efficiency without a large decrease of the $Q$ factor. Moreover, the resonant structure shows good tolerance to the geometry deformation of the toroidal cross section, which is particularly needed for industrial applications (see Supplement 1). The present work may open up new possibilities for the investigation of highly integrated photonics and applications in fields including on-chip nonlinearity and quantum manipulation.

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See Supplement 1 for the supporting content.

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