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Emerging opportunities for ultra-high *Q* whispering gallery mode microcavities

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Whispering gallery modes (WGMs) were first discovered for sound waves in the whispering gallery of St Paul's Cathedral and explained by Rayleigh [1] in 1878. In 1961, Garrett et al. [2] applied the concept of WGMs to optical systems and realized stimulated emissions in Sm^{2+}-doped CaF_2 spheres. Since then, WGMs have been widely and intensively studied in a range of micro-sized systems, including microdroplets, microspheres, microtoroids, microdisks, and microtubes. In principle, WGM microcavity research can be categorized into two types. One type focuses on the non-Hermitian nature of microcavities and studies their internal wave dynamics, quantum chaos, tunneling process, and important phenomena around the exceptional points [3-5]. The other type mainly utilizes the ultrahigh-*Q* factors and directional output of WGM microcavities and explores their potential application in optical interconnects, frequency combs, optomechanics, sensors, quantum optics, and other nonlinear optics [6]. More than 7000 papers related to WGMs and optical microcavities have been published, and they cover all the above research fields in detail. In this perspective, we will mainly focus on the recent important developments in ultrahigh-*Q* WGM microcavities and discuss their new opportunities in practical applications.

In the past few years, the rapid progresses in micro- and nano-fabrication technologies have triggered intensive research into different types of WGM microcavities. The reflow techniques have drastically reduced surface roughness and increased the *Q* factors of silica-based microspheres (Figure 1(a)) [7] and microtoroids (Figure 1(b)) [8] to the order of $>10^9$. These high *Q* cavities have boosted the rapid progress in applications such as ultralow threshold lasers, nonlinear optics, and optical sensors. Recently, owing to developments in the etching process, the fabrication of silica microdisks has been revisited. *Q* factors $>10^8$ and full control of dispersion have also been demonstrated [9]. Microdisks and microrings (Figure 1(c)) [10] based on high index dielectrics, such as Si, Si_3N_4, and $LiNbO_3$, have also been quickly improved. By carefully optimizing the electron-beam lithography, reactive ion etching, and polishing of the top surface, the *Q* factors of Si_3N_4 ring resonators have also reached $\sim 3\times 10^7$; thus, a battery-operated integrated frequency comb has been experimentally demonstrated [11]. Recently, several interesting approaches, including the use of roll-up microtubular cavity, for fabricating WGM resonators have been demonstrated (Figure 1(d)) [12]. This cavity makes WGMs compatible with microfluidics and is suitable for integration with many liquid materials. The bottom-up synthesized microstructures can trap light via WGMs and form high *Q* factors (Figure 1(e)). These cavities are important complements to WGM microcavities and expand the possible microcavity material systems to include perovskites and two-dimensional materials. Such cavities can enhance

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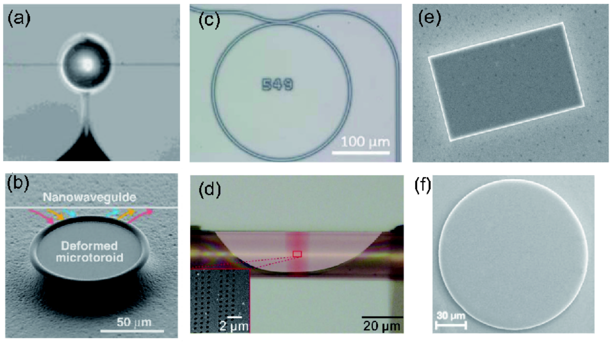

Figure 1 (Color online) Configurations of WGM optical microcavities. (a) Microsphere [7], (b) microtoroids [8], (c) microring [10], (d) microtube [12], (e) bottom-up polygon cavity, and (f) microdisk [13].

the light-matter interactions and are crucial to the study of pseudo-integrable systems and super-scars.

Owing to their excellent linear and nonlinear optical properties, microcavities fabricated from crystalline materials, such as $LiNbO_3$ (LN), CaF_2, MgF_2, and BBO, are another important branch of ultrahigh-Q cavities. Initially, the stable physical and chemical properties of crystals hindered their application in mass-manufacturable on-chip integrated systems, particularly for ultrahigh-Q WGM cavities. This obstacle was overcome by converting bulk crystals into films bonded to a material with a low refractive index and a high etching rate. Benefiting from the commercial production of lithium niobate on insulator (LNOI) films, the number of investigations into lithium niobate microcavities has seen an explosive increase. The quality factor of LN WGM microcavities on a chip was improved to 15 million (Figure 1(f)) [13], which is a little lower than the LN cavities of millimeter dimensions [14]. Periodically poled LN (PPLN) microdisks that can utilize the largest nonlinear coefficient d_{33} were also fabricated from a PPLN film (Figure 2) [15]. Various nonlinear optical effects, such as second harmonic generation, sum-frequency generation, and optical parametric oscillation, were demonstrated using several mW pump power. An electro-optical modulator with a modulation frequency >100 GHz and operating at CMOS-compatible voltages was also demonstrated herein. The excellent performance of LN microdisks makes LNOI attractive as a next-generation photonic platform.

The optical fields circulating in a microresonator can enhance the interaction between the photons and the material. Due to the radiation pressure, photons coupled to the mechanical motion lead to remarkable nonlinear optical processes, which differ from the nonlinear effects, such as the Kerr effect as well as second and third harmonic generation. The optomechanical systems, which can be cooled to the ground state and produce strong coupling between the photons and mechanical motion, have stimulated strong interest in exploring the quantum behavior of otherwise classical, macroscopic mechanical systems, particularly in exploiting the mechanical degrees of freedom for applications in quantum information processing. The radiation-pressure-induced coupling between light and mechanical motion in traveling-wave resonators has been exploited to break the Lorentz reciprocity, enabling the development of non-reciprocal devices without magnetic materials [16]. The mechanically mediated conversion of optical fields between two opposite propagating lights of vastly different wavelengths can play a special role in a hybrid quantum network, enabling

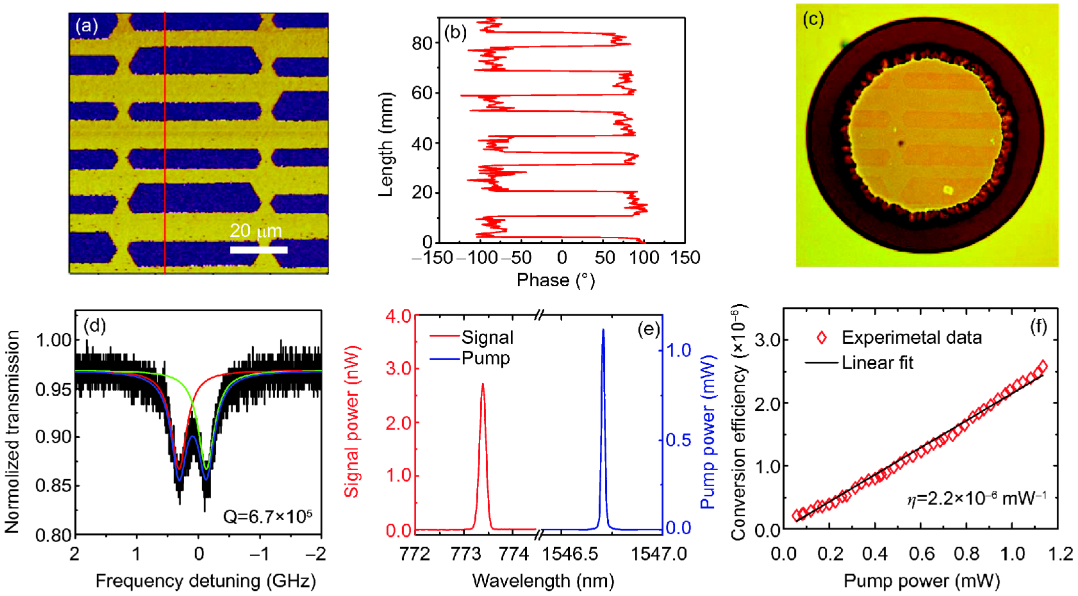

Figure 2 (Color online) $LiNbO_3$ microdisk [15]. (a), (b) Piezoelectric force images of PPLN film. (c) Optical image of a PPLN disk microcavity with a 40-μm radius. (d) Transmission spectrum of a PPLN microcavity with a quality factor of 6.7×10^5. (e) Second harmonic signal observed under a pump in 1550-nm band. (f) Second harmonic conversion efficiency with respect to pump power.

quantum communication between disparate quantum systems.

The study of the enhanced nonlinear optical processes in ultrahigh-Q microcavities is another area of great interest. Plenty of nonlinear optical processes have been extensively investigated both theoretically and experimentally, including second harmonic generation (SHG), third harmonic generation (THG), optical Kerr effect, stimulated Raman scattering, stimulated Brillouin scattering, and four-wave mixing. An important application is the phase-locked optical frequency comb, which shows great potential in terabit optical coherent communications, atomic clocks, ultrafast distance measurements, and dual-comb spectroscopy. Recently, novel phenomena and significant progress on nonlinear optical effects have been reported for ultrahigh-Q microcavities. To overcome the coupling problem of the nonlinear signals at multiple bands, Jiang et al. [8] proposed chaos-assisted broadband coupling in a deformed microcavity. Considering THG as an example in the experiment, the chaos-assisted mechanism improves the device conversion efficiency by ~5000-fold compared with the conventional coupling method. The second-order nonlinear effects in materials with inversion symmetry have also gained research interest (Figure 3) [17]. Contrary to the general rule that second-order nonlinearity is prohibited in centrosymmetric materials, Zhang et al. [17] reported nonlinear optics induced by symmetry breaking at the surface of an ultrahigh-Q silica microcavity under a submilliwatt continuous-wave pump. By dynamically coordinating the double-resonance phase matching assisted by thermal and optical Kerr effects, SHG is achieved with an unprecedented conversion efficiency of 0.049% W^{-1}, 14 orders of magnitude higher than that of the non-enhanced case.

Ultrahigh-Q WGM cavities can also be used as a platform to study cavity quantum electrodynamics (CQED) [18]. Single-photon switching devices based on the weak coupling between WGMs and quantum emitters have been demonstrated [19]. To enhance the interaction between the WGMs and the quantum emitters and thereby realize strong coupling, a small cavity mode volume and large oscillator strength are required. By combining both the large oscillator strength of quantum dots (QDs) and the small mode volume of a microdisk several micrometers in diameter, strong coupling has been realized [20]. Therefore, the coupled systems between WGMs and QDs have great potential for future CQED experiments and applications in quantum computation, communication, and metrology. Furthermore, the coupled systems connected by a waveguide or fiber could perhaps transfer quantum information from and to the building blocks and are promising for the development of integrated photonic networks [21].

In summary, significant progress has recently been achieved in ultrahigh-Q WGM microcavities. In the past few years, as the Q factors gradually approach the material limits, this research field will witness groundbreaking innovations. New understanding of physics and its principles must be developed to break the fundamental barriers in microcavity-based gyroscopes, ultrahigh-Q factor in nano-systems, and new coupling mechanisms between waveguides and cavities [22]. New functional materials, such as TiO_2, perovskites, and two-dimensional materials, must also be explored for ultrahigh-Q and hybrid cavities. In addition, most ultrahigh-

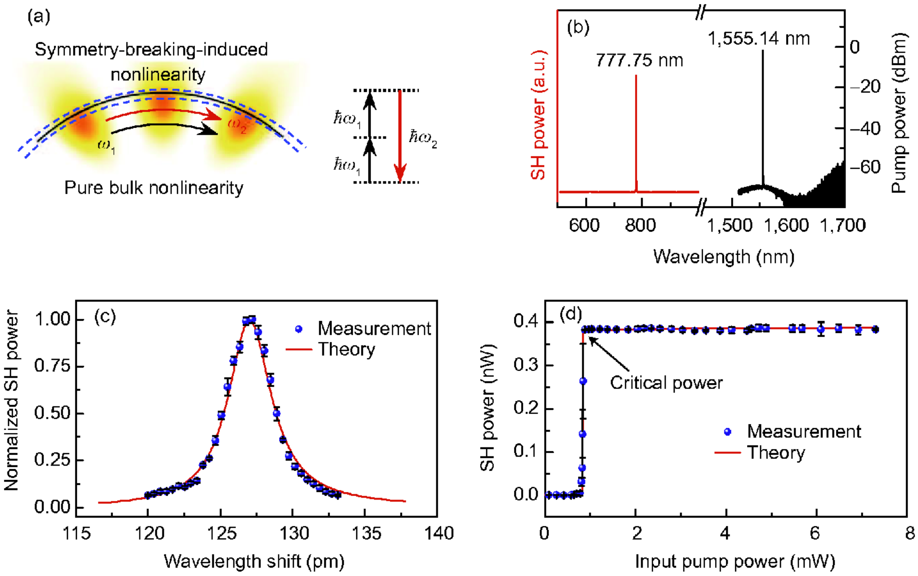

Figure 3 (Color online) Symmetry-breaking-induced nonlinear process at the surface of a microcavity [17]. (a) Second harmonic is generated from both the symmetry-breaking-induced nonlinearity at the cavity surface and the electric multipole response in the bulk. (b) Measured SH spectrum (red) and the corresponding pump (black). (c) SH power versus pump wavelength shift within the dynamical phase-matching process. (d) Dependence of maximum SH power on the input power for the same pump mode.

Q cavities are still closely related to a circular cavity and the advantages of chaotic motions and quantum chaos have not been fully exploited yet [8,23]. Most importantly, in addition to individual devices, it is essential and urgent to develop high-density, on-chip integrated ultrahigh-*Q* WGM cavities based on optoelectronic networks. In such systems, other recent developments in areas such as parity-time symmetry, topological photonics, spin-orbital coupling, time-reversal processes, non-reciprocity, and the bound state in continuum can be implemented to further improve performance, thereby accelerating the related research [4,8,16,22].

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