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News & Views

Optical microcavity: from fundamental physics to functional photonics devices

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Optical microcavities have attracted strong research interests, for their unique property of confining photons for a long time in small volumes, which significantly enhances light–matter interaction [1]. In recent decades, various fabrication techniques of microcavities with higher quality factors (Q) and smaller mode volumes (V_m) have been developed, pushing forward studies from fundamental physics to functional photonics devices. Microcavity optomechanics provides an ideal platform for exploring the quantum nature of macroscopic objects [2], quantum information processing and precision measurement [3]. Microcavities with deformed boundaries can act as an open billiard system, allowing for the study of classical and quantum chaos and directional lasing [4]. The enhanced light–matter interaction characterized by the figure of merit Q/V_m enables ultrahigh sensitive optical sensors with the detection limit down to single nanoscale particles [5]. Researchers in China have participated extensively in this area and made tremendous achievements.

Previously, people used photolithograph, etching or high-temperature fusion to make the widely investigated microcavities including microdisks, microtoroids, microspheres, microrings and microbubbles, all of which can support high-Q whispering-gallery modes (WGMs). Recently, Xu et al. [6] have summarized a newly developed fabrication technique of three-dimensional microcavities using femtosecond lasers. The femtosecond laser processing features with high fabrication resolution. When hit by a femtosecond laser pulses, the material responses nonlinearly to the light intensity. Thus, the volume of the material where two- or multi-photons are absorbed is much smaller than the linear light–matter interactive volume, resulting in fabrication resolution down to tens of nanometers and beyond the optical diffraction limit. Using the femtosecond laser, Lin et al. [7] fabricated lithium niobate microdisk cavities with the record Q-factor $\sim 2 \times 10^6$, and the conversion of the second harmonic generation is measured to be 1.35×10^5 mW^{-1} with a CW pump laser. These results shed light on new development of the fabrication of microcavity and other micro- and nano-structures.

Variations of the surrounding medium of a microcavity, such as changing the refractive index and attaching nanoparticles to the cavity surface, can alter the electric field distribution of the whispering-gallery modes and may reflect the WGM characteristics in mode shift [8], mode broadening [9] or mode splitting [10, 11]. By monitoring the WGMs, the properties of the surrounding medium can be obtained, which is the physical principal of the microcavities acting as sensors. Recent efforts which aimed at lowering the detection limit of the microcavity sensor include employing surface plasmon resonance (SPR)-enhanced WGM, microcavity lasing and noise suppression [5]. Besides sensing the surrounding medium, Zhou et al. [12] demonstrated that the WGMs can also reflect the applied forces due to cavity deformation. They applied strain to the microcavity to tune the resonant frequency of WGMs. The polydimethylsiloxane (PDMS) was chosen as the material to fabricate microsphere cavities, since much smaller stretching force is required to accomplish the WGM frequency tuning. The microsphere was supported at the center of two collimating fiber stems, with one of the stems connected to the piezoelectric stage to apply the

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stretching force to the microcavity. The experiments demonstrate that the tuning range is over 50 nm, limited by the tunable laser and predicted to be greater than 300 nm. In the tests of the microsphere as a force sensor, a high sensitivity of ~19.7 pm/μN was reported, which can be a promising candidate for weak force sensing.

Another significant application of microcavities is the microlaser with ultralow threshold. Fluorescent materials, such as quantum dots and rare earth ions, are usually doped to the microcavities to act as the gain medium. Fan et al. [13] reported thulium (Tm^{3+})-doped and thulium–holmium (Ho^{3+})-codoped microtoroid laser fabricated by silica sol–gel synthesis process. Since the emission bands of the rare earth ions Tm^{3+} and Ho^{3+} extend from 1750 to 2200 nm, the microlaser wavelength can reach as long as ~2 μm, and the lasing threshold can be as low as 2.7 μW for the Tm^{3+}/Ho^{3+}-codoped microcavity. To achieve high-speed modulation for microlasers, Long et al. [14] designed and demonstrated a microsquare laser with side length of 16 μm connected to a 2-μm-wide output waveguide, which has the threshold current of 5 mA. The *K*-factor of 0.22 nm can be obtained, implying a maximum intrinsic 3 dB bandwidth of 40 GHz.

Besides the WGM microcavities mentioned above, researchers are also seeking ultralow mode volume and high *Q*-factor in photonic crystals (PhC) microcavities with great endeavor. Gan and Li [15] presented a review about their recent works on PhC cavities. They discussed the theoretical background of the PhC slab cavities and several integrated photonics devices based on PhC cavities. Finite difference time domain simulation provides optimized design of PhC structures, of which the fabrication requires electron beam lithography, focused ion beam, inductively coupled plasma etching and other wet etching techniques and procedures. Different PhC cavities, including line defect cavity, waveguide-like parallel-hetero cavity, low-index nanobeam cavity and nonlinear cavity, were analyzed. They also showed the design of the PhC cavity applied in all-optical filter, optical switches and optical logic gates.

In summary, optical microcavities featuring large figure of merit Q/V_m hold unprecedented potential for a wide range of applications, such as microlasers with ultralow threshold, microsensors with high sensitivity, and are great platforms to explore fundamental physics. The chemical surface functionalization of the microcavities' surface also allows for label-free detection of specific bio-analyte and makes them good candidates for early-stage diagnostic and environment monitoring tools. The researches on optical microcavities have been developing fast in both China and other parts of the world, and significant progress is still anticipated to be achieved with more scientific groups entering this field.

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