PHOTONICS Research

Optical microcavities: new understandings and developments

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Optical microcavities have attracted tremendous interest in both fundamental and applied research in the past few decades, thanks to their small footprint, easy integrability, and high quality factors. Using total internal reflection from a dielectric interface or a photonic band gap in a periodic system, these photonic structures do not rely on conventional metal-coated mirrors to confine light in small volumes, which have brought forth new developments in both classical and quantum optics. This focus issue showcases several such developments and related findings, which may pave the way for the next generation of on-chip photonic devices based on microcavities.

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Optical microcavities is a fast growing field thanks to their unique appeals. On the fundamental research side, they offer a convenient and tractable platform for the studies of wave chaos and non-Hermiticity. On the practical side, they can be used for a wide range of applications including lasers, filters, optical diodes, comb generation, and sensing. This special issue aims to provide a glimpse of some exciting developments in this field, with the theoretical and experimental fronts put on an equal footing.

To analyze the modes of a microcavity and its wave transport, one approach is to construct its scattering matrix, which connects all the incident channels to the outgoing channels. Although there are several methods to construct the scattering matrix for an optical microcavity, they all have different drawbacks and limitations. For example, one of them is the modal expansion method, which was originally developed in nuclear physics and typically referred to as the R-matrix method. Its implementation introduces an artifactual discontinuity of the fields' normal derivative, which affects the analysis of light intensity near the cavity boundary, for example, in sensing applications. The article by Ge [1] proposes a numerical scheme to overcome this issue, which has the form of a non-local boundary value problem. But in contrast to the boundary integral method, this scheme does not involve the normal derivative of the fields and can treat continuous variation of the refractive index, which may come from a localized thermal source or a modulated optical gain and loss profile.

Two other theoretical studies in this special issue address the question of chirality, in microring [2] and quadrupole-deformed microcavity [3] lasers respectively. Being a fundamental symmetry of nature, chirality has profound influences in many fields of physics. While optical chirality can refer to the polarization direction of light, a more important aspect in an optical cavity is the balance between two counter-propagating modes as in the Sagnac effect. In the picture of geometric optics, a closed trajectory can support a pair of degenerate counter-propagating modes, e.g., a clockwise (CW) one and a counterclockwise (CCW) one, which have the same frequency. As a result, any linear superposition of them is still an eigenmode of the system. The question then arises: what determines the chirality of the corresponding lasing mode? There have been several studies of the question in microring lasers, which are uniform along the perimeter of the ring (see, for example, Ref. [4]). In the presence of a delicately modulated gain and loss configuration in the azimuthal direction however, the degeneracy becomes a non-Hermitian one, and both modes become traveling waves in the same direction. Longhi and Feng [2] show that this "unidirectional" operation of a microring laser is stable, even when the non-Hermitian degeneracy is perturbed. Kawashima *et al.* [3] study a more complicated microcavity, which is often referred as a quadrupole cavity. One set of modes in this microcavity has the shape of a hexagram, consisting of two overlapping triangles. Previously it has been shown that by shaping the spatial pump profile, the laser mode can be enforced to be on one of the triangles [5], with the benefit of reducing the laser threshold and increasing the output power. The time-dependent simulation of the Maxwell–Bloch equations now suggests that the lasing mode again has unbalanced CW and CCW components, similar to the finding in the circular ring geometry.

While chirality in optical cavities may involve only the coupling of two degenerate counter-propagation modes, the effect of multimode coupling can also become significant under certain conditions. One scenario has been found experimentally in a stadium-shaped microcavity formed by a rectangle sandwiched by two half disks. With continuous-wave pumping and above a certain threshold, multiple lasing peaks have been observed to merge into a single one [6]. The same authors now propose a theoretical understanding of this behavior [7]. If its validity is verified in microcavities of different shapes, we may have a new universal route towards single-mode lasing using wave-chaotic microcavities.

Another article in this special issue proposes to achieve single-mode lasing via a completely different method [8]. Xie and collaborators study polymer microbottle cavities fabricated by transferring a microdroplet of R6G-doped epoxy resin solution from the tip of a tapered optical fiber to the middle of another suspended microfiber. Due to surface tension and mild heating at 60°, a spindle-shaped microbottle is formed, and its different cross sections host whispering-gallery modes (WGMs) of different angular momenta at almost the same frequency. A pumping fiber, which doubles as a loss sink, spoils the unwanted WGMs away from the waist of the microbottle. As a result, only the WGM right at the waist lases, which has been observed experimentally from both the lasing spectrum and the microscopic image of the microbottle cavity. The same group has also resorted to an optical pumping beam in the form of an interference pattern to excite the same WGM mode and achieve single-mode lasing.

Although optical pumping of a laser in modern times usually utilizes another laser at a shorter wavelength, it was certainly impossible for the first laser developed by Maiman in 1960. This ruby laser was pumped by a quartz flash tube, and shortly afterwards LEDs were widely adopted as the pumping source. With the advent of laser diodes in the 80's, LED pumping was gradually abandoned until the recent re-emergence of LEDs in commercial and residential lighting. Due to their vastly improved intensity, dramatically reduced price, and high performance at room temperature, a new wave of LED-pumped lasers have arrived in the last ten years. Herr and collaborators use an LED light source centered at 810 nm to pump a crystalline high-Q spheroidal WGM cavity [9]. The result is a lasing peak at 1064 nm, the threshold and intensity of which depends on the coupling strength between the microsphere and the outcoupling prism.

To confine light at the microscopic scale, all the optical microcavities mentioned in this introduction so far utilize total internal reflection. Another form of unconventional mirrors resorts to a photonic band gap, such as in vertical cavity surface emitting lasers (VCSELs) and defect photonic crystal cavities. Guided by genetic-algorithm optimization, Yu and collaborators design and fabricate an on-chip reflector with a small square footprint of about 2 μm on each side [10]. The structure is composed of randomly distributed pixels, and its reflectivity stays above 85% in the wavelength range of 1440–1640 nm and reaches as high as 95%. This performance is robust against the rounding of corners occurring in device fabrication. They further fabricate a Fabry–Perot cavity with an intrinsic quality factors as high as 4000, formed by two such reflectors and a waveguide in between. These numerically optimized reflectors may be used as a standard module in integrated photonic circuitry.

Integrating a laser monolithically on the Si platform has been a long pursued goal in silicon photonics. Chen and collaborators discuss the design and fabrication of suspended, tensile-strained Ge/SiGe multiple quantum well microdisk resonators [11]. They present an etch-stop technique in the Ge/SiGe system that eliminates defective buffer layers and maintains high material quality. Using photoluminescence and Raman spectroscopy, they investigate strains in microdisks with different sizes and achieve a transferred biaxial tensile strain as high as 0.88%, corresponding roughly to a 60 meV reduction of the energy separation between the Γ and L valleys. They expect a high net gain about 600 cm^{-1} for the TE mode in the C band of telecommunication, which makes their system a viable candidate for efficient Ge-based lasers on Si.

Last but not the least, an improved fabrication technique is introduced by Ma and collaborators to obtain large microtoroid cavities with a major axis on the order of millimeters and a high quality factor [12]. Although a Kerr frequency comb was first demonstrated in a microtoroid cavity, the bottleneck in fabrication has limited its application due to the relatively low quality factor ($\sim 10^7$) even with a diameter approaching 1 mm. Now by including a thick silica film that prevents the forming of corrugations on the disk plane, the authors are able to increase the quality factor of their microtoroid cavities by one order of magnitude. They further demonstrate a Kerr frequency comb with a repetition rate as low as 36 GHz. These characteristics are approaching the state of the art achieved using wedged microdisk cavities, which make microtoroid another feasible option for microcavity comb generation.

Due to the length limitation and a relatively short submission window, we have not included purely pedagogical articles or touched on other stimulating subjects of optical microcavities, including optical and optomechanical sensing as well as symmetry and topology protected states in a microcavity network. The readers are encouraged to explore the references given in the articles of this special issue, as well as recent reviews on various aspects of optical microcavities (for example, see Refs. [13–19]). It is our hope that this special issue can provide a glimpse of exciting developments in the field of optical microcavities, which may prompt students and researchers to enter and become more involved in this energized field.

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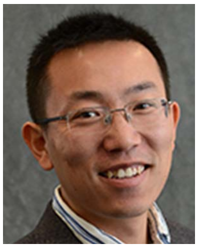

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