PHOTONICS Research

Optical Microresonators feature issue introduction

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We give an introduction to the feature issue composed of twelve articles on Optical Microresonators.

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Optical microresonators, which confine light in both the spatial and time domains, have advanced various research areas benefiting from significantly enhanced light–matter interactions, including integrated microlasers, nonlinear frequency conversion, Kerr frequency combs, and optomechanics. Over the past five years, the research interests in optical microresonators have rapidly expanded and combined with other disciplines, for example, optical chaos, non-Hermitian physics, and quantum materials. These cutting-edge research works have enabled the creation of optical microresonators with novel properties and capabilities. This special issue collects 12 articles that discuss the fundamental physics and emerging technologies in the field of microresonator photonics. The articles cover several fundamental research topics, such as higher-order exceptional points in waveguide-coupled microcavities [1], squeezed state preparation with optomechanical system [2], lasing in symmetry-breaking microcavities [3], nonlinear dynamics in such microcavity lasers [4], and high-quality microring resonators for mid-IR applications [5]. In addition, there are also the timely discussions about soliton microcombs and related nonlinear physics, including how to mitigate the fast thermal instability in soliton generation [6], frequency engineering via shifted grating multiple mode splitting for Kerr optical parametric oscillation [7], and the application of microcavities for photonic thermometer [8]. Further application-focused works include the characterization of microbubble cavities for optofluidic sensing [9], the combination of a microcavity with graphene for gas detection [10], a self-sensing boosted 4D microcavity for pollutant detection [11], and an encapsulated microprobe formed by a polymer microcavity and a U-shaped microfiber for ultrasound imaging [12].

Kullig *et al.* from Otto-von-Guericke-Universität Magdeburg, Germany consider N microresonators coupled via a common waveguide, and construct $2N$ higher-order exceptional points (EPs) through asymmetric backscattering [1]. With N microresonators, an EP-enhanced particle sensing is verified by the extraordinarily increased frequency splitting, and remarkably its performance is cavity-selective, enabling this system to function as an ideal platform to investigate the behaviors of higher-order EPs dependent on on-site perturbations. The scheme of waveguide-coupled microresonators is handy to implement, and the effective Hamiltonian approach enables an intuitive and insightful understanding of such systems at an EP of second and higher orders.

Zhu *et al.* from East China Normal University, China propose a method to deterministically generate photon number-squeezed states based on feedback control and bath engineering [2]. For practical implementation, a cavity optomechanical system is discussed in detail with realistic parameters. The quality of the prepared photon number-squeezed state is estimated theoretically, with the mean photon number and number fluctuation widely tunable thanks to the flexibility of the optomechanical system. The method does not require precise control of quantum dynamics and is tolerant to noisy environment, thus of significance to fundamental quantum research as well as application for quantum metrology.

Lee *et al.* from Kyungpook National University, Republic of Korea solve the problem of Q-degradation for rotational-symmetry-broken microcavities based on transformation optics and effective medium approximation, and report an integrated microlaser with spatially-varying distribution of nanoholes in an InGaAsP-based multi-quantum-well heterostructure [3]. The lasing threshold of their device is one-third of that of the same shaped homogeneous laser, and similar to that of a homogeneous microdisk laser. The approach is expected to benefit cutting-edge light sources for integrated photonic circuits and fundamental studies on optical chaos.

Li *et al.* from Institute of Semiconductors, Chinese Academy of Sciences, China report the observation of irregular pulse packets and self-chaos operation stemming from the interaction between near-degenerate modes within a circular-sided square microcavity [4]. A successive route from periodic to chaotic states is achieved by increasing the injection current, and the chaotic state is then realized with an effective bandwidth of 22.4 GHz and a power spectrum flatness of ±4 dB. The self-chaotic microlaser serves as an enriched platform for both fundamental research and practical applications, ranging from nonlinear dynamics in symmetry-breaking microcavity to secure optical communication.

Lim *et al.* from Korea Advanced Institute of Science and Technology, Republic of Korea develop the fabrication of Y_2O_3 buried oxide germanium-on-insulator (Ge-OI) platform, and experimentally demonstrate high-Q microresonators operating in the mid-IR region (∼4.2 μm) [5]. The microresonators have the loaded Q-factor of 94,500 and intrinsic Q-factor of 176,000, while also possessing high extinction ratio and low insertion loss. This first demonstration is a major step toward the mid-IR photonics based on the new Ge-OI platform using Y_2O_3, and would facilitate the implementation of multi-purpose devices such as sensors and switches by introducing other advanced structures.

Liu *et al.* from Tsinghua University, China mitigate the transient thermal instability that prevents the stabilization of soliton microcombs [6]. The different thermal relaxation processes in an AlN microcavity are characterized, and two protocols with engineered laser sweep waveforms are proposed accordingly. Both are verified by experimental measurements and explicitly discussed by numerical simulations. The techniques relax the requirement of laser sweep speed and can reduce the noise transduction from the drive to the pump frequency, paving the way for visible soliton generation.

Lu *et al.* from National Institute of Standards and Technology, USA propose a single-period shifted grating on the inner boundary of the microring that creates a rotational asymmetry and can split multiple adjacent cavity modes [7]. With this approach, powerful multi-frequency engineering functionality is enabled for nonlinear optics. As an example, they demonstrate optical parametric oscillation (OPO) across a wide range of pump wavelengths in a normal-dispersion device where OPO is otherwise missing. This approach is simple and easy to implement, meanwhile providing additional control for nonlinear optical processes if combined with other multiple-mode splitting techniques.

Zhang *et al.* from National Institute of Metrology, China demonstrate an integrated photonic thermometer with an ultrahigh temperature resolution of 58 μK and a broad range of 45 K [8]. The capabilities are achieved by using a soliton microcomb as a broadband frequency reference and rely on a feedback loop to resolve the ambiguity of beat note signal between sensing microresonator and the microcomb. The proof-of-concept device holds suitability for industrial applications, and also showcases the vast prospects for the practical applications of optical microcombs.

Jalaludeen *et al.* from Okinawa Institute of Science and Technology Graduate University, Japan characterize the structure of a thin-walled microbubble cavity utilizing focused ion beam milling and scanning electron microscopy imaging [9]. A theoretical model based on the optical waveguide approach is also proposed to identify the whispering gallery modes and validated by numerical simulations. Both the structural characterization and theoretical model serve as powerful tools to accurately predict the optical responses of hollow microbubbles for optofluidic sensing applications, and are readily adaptable for other wavelength-scaled photonic devices.

Wang *et al.* from University of Electronic Science and Technology of China, China combine a fiber microcavity with graphene to generate degeneracy breaking modes with orthogonal polarization, and take advantage of a heterodyne beat note signal to cancel the optical common mode noise [10]. Gas detection is demonstrated with a detection limit down to 2 pmol/L in vacuum and 0.01 ppb (parts per billion) in air for NH_3, and is universally applicable for other gas components with polar bonds. This paradigm paves a way to realize a label-free, low-power-consumption and simple-operation tool to realize quantitative gas molecule detection and *in-situ* chemical sensing.

Saetchnikov *et al.* from Ruhr University Bochum, Germany report a high-performance optical sensor based on a microcavity for per- and polyfluoroalkyl substances (PFAS) detection [11]. With hundreds of simultaneously interrogated 4D microcavities that boost the self-sensing, i.e., the material reaction on the external medium, the detection of the PFAS at the level of down to 1 ppb is demonstrated. This technique provides an integrated approach to detecting the contamination of the aqueous environments and is potentially feasible for efficient removal of low-concentration PFAS.

Sun *et al.* from Peking University, China demonstrate an ultrasound microprobe with the noise equivalent pressure of 1.07 mPa/$\sqrt{\text{Hz}}$, a record-high bandwidth of 150 MHz, and a large detection angle of 180 degrees [12]. Leveraging the superior comprehensive performance of the microprobe, high-quality *in-vivo* whole-body photoacoustic imaging of a zebrafish larva is demonstrated. This microprobe provides a new strategy to develop miniature ultrasound detectors and is easy to fabricate, meanwhile it holds great potential for applications like endoscopy.

In summary, this special issue offers great insight into the new physics and interesting phenomena of microresonator photonics, and showcases the useful applications of microresonators for novel light source generation, sensing, and optical metrology. We hope to drive further innovation and development in this area by sharing these new findings and advances with the broader photonics community.

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