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Ultra-high-Q microfibre knot resonators: unlocking new frontiers in flexible photonics

Feng Li*

Abstract

Zhou et al. achieved a record-breaking quality factor (Q-factor) of 3.9×10^7 in microfibre knot resonators (MKRs) through optimised environmental control and coupling tuning, enabling stable single-frequency lasing and establishing a foundation for advanced photonic applications.

Keywords: Microcavity, Microfibre, Whispering gallery mode

Optical microcavities are fundamental to modern photonics and widely used in nonlinear optics, quantum information, and high-sensitivity sensing[1–3]. Microcavities supporting whispering-gallery-modes (WGMs), such as on-chip microtoroids and microspheres, are widely recognised for their ultra-high quality factors (Q-factors) (exceeding 10^8) and compatibility with miniaturised systems[4,5]. These structures rely on circular or polygonal geometries to confine light through total internal reflection, making them ideal for low-threshold lasing and cavity quantum electrodynamics studies. However, the rigid design of these on-chip microcavities may limit their seamless integration with flexible materials and fibre-based networks.

Before the advent of microcavities, macroscale fibre ring lasers were established as a major application of ring-cavity structures, leveraging the inherent low loss of optical fibre and fibre system compatibility for broad applications[6]. Because these fibre ring lasers operate on centimetre-to-meter scales, they were developed for reliability and ease of use, rather than for miniaturization. The subsequent advent of microfibres tapered to subwavelengths or micrometre diameters has changed the scenario. Integrating the flexibility of traditional fibres with the evanescent field enhancement of nanophotonic structures, microfibres have enabled applications ranging from wearable health sensors to evanescent chemical detectors[7–9]. For researchers working on microcavities, this progress has enabled the fabrication of WGM-like microcavities using microfibres, which combines the miniaturisation of WGM structures with the compatibility of the fibres and flexibility of the macroscale fibre rings[10]. Microfibre knot resonators (MKRs), which are formed by tying a microfibre into a knot, where evanescent coupling between overlapping segments creates a closed resonant cavity, have emerged as the most straightforward and promising realisation of this concept[9,11–13]. However, the use of MKRs has been restricted to low-performance scenarios owing to their low Q-factors, with experimental values of approximately 10^4–10^5 (far below the 10^9 theoretical limit), resulting from uneven microfibre stress caused by unstable fabrication environments and imprecise control of knot-region coupling.

Zhou et al. addressed this issue by first identifying the root causes of MKR performance limitations before developing targeted solutions[14]. Their key insight is that microfibre quality and knot coupling control are not independent factors; poor microfibre uniformity (e.g., stress concentrations and surface defects) undermines even

Correspondence: Feng Li (felix831204@xjtu.edu.cn)
Key Laboratory for Physical Electronics and Devices of the Ministry of Education and Shaanxi Key Lab of Information Photonic Technique, School of Electronic Science and Engineering, Faculty of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an 710049, China

the most precise coupling tuning, whereas imprecise coupling limits the performance potential of high-quality microfibres. To resolve microfibre quality issues, the team focused on environmental parameters during fabrication. Using an oxyhydrogen flame to taper standard single-mode fibres they found that temperature fluctuations and humidity variations disrupt the thermal field of the flame, leading to uneven silica melting and residual stress in the resulting microfibres. By maintaining constant humidity (with fluctuations <1%) and targeting a specific temperature-humidity baseline, they produced microfibres with uniform cross-sectional diameter (~3 μm at the waist), smooth surfaces, and balanced stress. These were observed through fracture tests, which exhibited breakage exclusively at the thinnest waist region, a sign of minimal internal stress concentrations. This consideration of the microfibre quality is a critical distinction from previous works, which generally overlooked environmental stability in favour of post-fabrication tuning.

For coupling control, the team considered beyond empirical adjustments and developed a theoretical framework based on the coupled mode theory to design the experiments. They modelled the MKR as two adjacent microfibre waveguides in the knot region, where the evanescent field overlap enabled periodic energy transfer between the segments. The key parameter was the coupling length L_c, the distance over which light is fully transferred from one waveguide to the other, and its relationship with the knot coupling region length L_k. Simulations revealed that L_c scaled with the microfibre diameter, underpinning a key mechanistic behaviour: the quality factor (Q-factor) of the resonator exhibited periodic oscillations with L_k, with the oscillation periods varying systematically across different microfibre diameters. Consequently, thinner fibres (1 μm) exhibited more frequent high-Q peaks; however, the narrow linewidth of these peaks required sub-micron tuning precision (beyond typical experimental setups). Thicker fibres (5 μm) required impractically short L_k (< 100 μm) to reach high Q. The team's choice of 3 μm microfibre diameter provided a critical balance: L_c was sufficiently long to allow tuning with standard stepper motors (10 μm resolution), whereas the high-Q peaks were sufficiently broad to be reliably accessible. This theoretical-experimental synergy is another contribution of this work, which ensures that the Q-factor breakthrough is not a one-time result, but a reproducible method that is critical for future adoption.

A key visualisation of this achievement is shown in Fig. 1 (adapted from Zhou et al.). The resulting UHQ-MKRs (ultra-high-Q-MKRs) not only achieved a record Q-factor of 3.9×10^7 but also demonstrated comprehensive performance that validates their practical potential. Long-term stability tests demonstrated that the devices maintained Q-factors higher than 10^7 for 96 hours, even with minor laboratory temperature changes. This is particularly impressive considering that MKRs rely solely on mechanical knotting for structure, with no external packaging. Thermal characterisation revealed clear bistability, an effect where increasing input power induces a thermo-optic feedback loop, shifting the resonance wavelength, and polarisation-dependent transmission, which are hallmarks of high optical finesse. The team further translated this performance to a real application by integrating the UHQ-MKR into an all-fibre laser system as

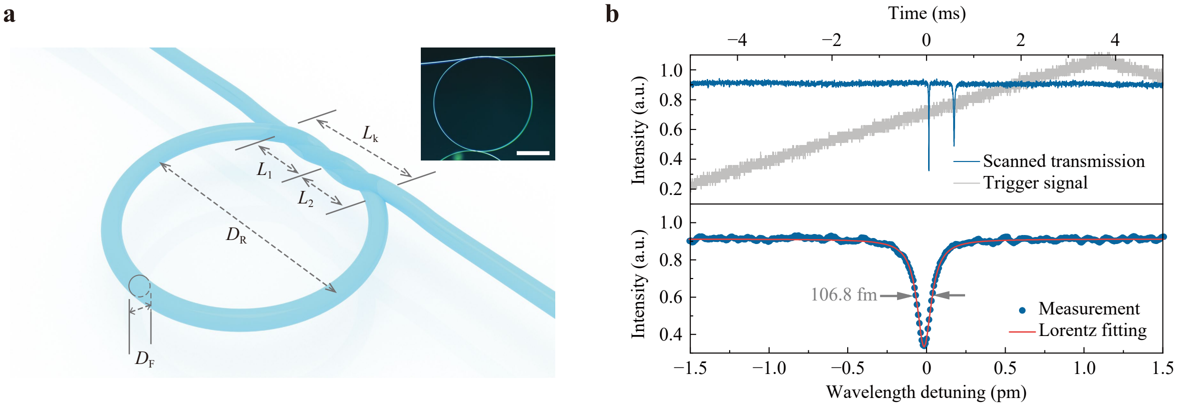

Fig. 1 Schematic and performance of the ultra-high-Q microfibre knot resonator (MKR). **a** Schematic of the MKR, defining key structural parameters: ring section diameter (DR), microfibre cross-section diameter (DF), knot coupling region length (L_k), and sub-knot area lengths (L_1/L_2). The inset shows a micrograph of a fabricated MKR (scale bar: 500 μm), demonstrating its smooth and stable structure. **b** Fine transmission spectrum obtained via wavelength detuning scan; the zoomed-in lower plot displays a Lorentz resonance at ~1560 nm with a Q-factor > 1.4×10^7. Adapted from Zhou et al.[14]

a mode selector. In contrast to traditional MKRs (with Q = 10^4), which cannot suppress multilongitudinal modes, the narrow resonance linewidth (< 20 MHz) of the UHQ-MKR enabled single-frequency lasing with a linewidth of approximately 20.26 kHz and an optical signal-to-noise ratio greater than 52.4 dB. This observation is pivotal, as it bridges the gap between MKR performance and real-world needs, demonstrating that UHQ-MKRs are not only lab curiosities, but also functional components for photonic systems.

Notably, this work is the first technical breakthrough in resolving the fabrication and coupling challenges of MKRs. This milestone opened two complementary paths for practical applications and fundamental research. On the practical side, the current laboratory-scale workflow can be refined for large-scale production by automating environmental controls and coupling tuning, which are critical for industrial adoption. The team also noted that packaging strategies (e.g., high-thermal-conductivity substrates to mitigate thermal bistability and flexible polymers to enhance mechanical robustness) could extend the utility of UHQ-MKRs in wearable sensors, underwater acoustics, implantable biosensors, and applications where the rigidity or bulkiness of traditional microcavities is a barrier.

On the fundamental research front, the unique synergy of ultra-high Q-factor, mechanical flexibility, and fibre compatibility in UHQ-MKRs establishes them as a versatile platform for exploring phenomena inaccessible to low-Q MKRs or rigid microcavities. For instance, coupling UHQ-MKRs to semiconductor microcavities can drastically modulate the intrinsic properties and propagation dynamics of cavity exciton-polaritons, including extending the polariton coherence lifetimes and enabling reconfigurable propagation pathways[15–16]. Notably, ion-doped (e.g., rare-earth ion-doped) MKRs can facilitate the integration of excitonic nonlinearity from semiconductor systems into fibre-based platforms via hybrid photonic modes, while allowing the precise tuning of the light-matter interaction strength. In addition to polariton physics, the structural flexibility of MKRs provides robust experimental platforms for investigating topological and non-Hermitian physics. Integrating optical anisotropy into nanofibres can induce geometric phase accumulation within resonant circulation loops, thereby enabling the engineering of artificial gauge fields and polarisation-tailored topologically nontrivial structures[17–18]. Additionally, engineering a dynamically tunable gain-loss landscape through multi-knot-coupled MKRs facilitates the exploration of non-Hermitian phenomena with the potential to realise non-reciprocal optical behaviour[19].

The study of Zhou et al. marked a significant breakthrough for MKRs, elevating them from niche, moderate-performance devices to competitive UHQ microcavities. By resolving long-standing technical challenges using a combination of environmental control, theoretical modelling, and rigorous characterisation, they not only expanded the practical utility of MKRs but also created a versatile platform for fundamental photonics research. As researchers build on this foundation, optimise for scale, and explore new physics, MKRs enable integration of ultrahigh-performance photonics with real-world applications, from wearable technology to quantum photonics.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The author declares no conflict of interests.

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