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EDITORIAL

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Monolithic microcavity-metalens interfaces: bridging performance and complexity in quantum light sources

Simon Betzold[1] and Sven Höfling[1*]

Abstract
A hybrid quantum photonic platform integrates cavity-enhanced single-photon emission with metasurface-enabled wavefront control, pointing toward scalable sources of high-dimensional quantum light.

The generation of quantum light that is simultaneously bright, coherent, and structurally complex remains a central challenge in photonic quantum technologies. Single photons underpin applications ranging from secure communication to quantum computing, yet practical implementations demand more than just high-quality emission: future systems will require access to multiple photonic degrees of freedom within compact and scalable platforms [1]. Achieving this combination of performance and functionality remains an outstanding goal, as scalable quantum photonic architectures ultimately require both high source quality and access to multiple encoding degrees of freedom. Solid-state emitters, particularly semiconductor quantum dots, have emerged as leading candidates for deterministic single-photon generation [2]. When embedded in optical microcavities, these systems benefit from Purcell-enhanced emission, enabling high brightness and near-unity indistinguishability [3–5]. However, such devices typically emit photons in simple Gaussian modes, limiting their usefulness for high-dimensional encoding involving, for example, orbital angular momentum (OAM) or structured polarization [2]. In parallel, metasurfaces have enabled unprecedented control over the amplitude, phase, and polarization of light with subwavelength resolution [6–8]. More recently, these concepts have entered the quantum domain, where metasurfaces provide powerful tools for manipulating quantum states and enabling high-dimensional encoding [9, 10]. Yet metasurface-based quantum light sources generally offer weaker emission enhancement compared to cavity-based systems, limiting brightness and photon indistinguishability due to weaker emission-rate enhancement. This fundamental trade-off between source performance and state complexity is illustrated schematically in Fig. 1.

Writing in *eLight*, Ma et al. address this long-standing tension by combining both approaches within a single monolithic architecture [11]. Their device integrates a quantum-dot micropillar cavity with a multifunctional metalens fabricated on opposite sides of a semiconductor chip (Fig. 1c). This design separates photon generation from state manipulation at the functional level while preserving efficient optical coupling between the two, thereby mitigating a long-standing trade-off between source performance and state complexity that arises from the incompatibility between narrowband cavity resonances and broadband metasurface functionality. The micropillar cavity serves as a high-performance single-photon source, enhancing emission and directing photons into a well-defined spatial mode. Crucially, this

[†]S.B. and S.H. prepared and revised the manuscript.

*Correspondence:
Sven Höfling
sven.hoefling@uni-wuerzburg.de
[1] Lehrstuhl für Technische Physik and Würzburg-Dresden Cluster of Excellence ctd.qmat, Julius-Maximilians-Universität Würzburg, 97074 Würzburg, Germany

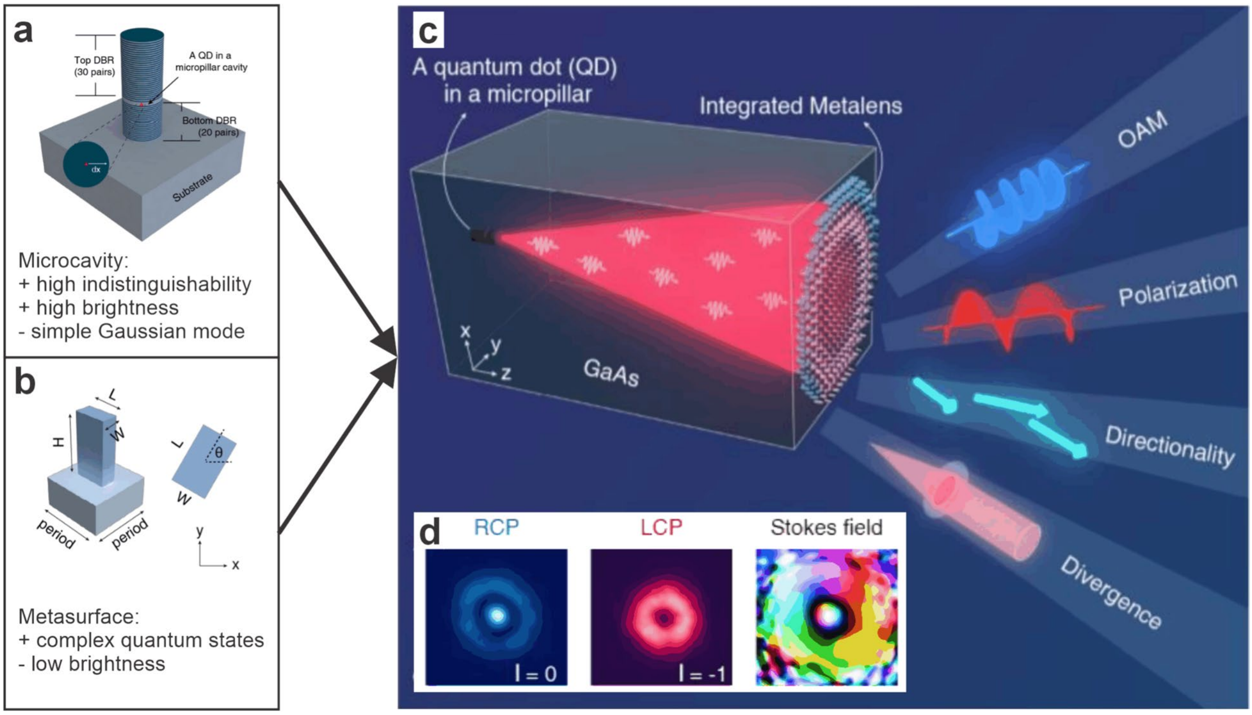

Fig. 1 Bridging performance and complexity in quantum light sources. **a** Quantum-dot micropillar cavities provide high brightness and photon indistinguishability via Purcell enhancement, but emit predominantly Gaussian modes. **b** Metasurfaces enable versatile wavefront shaping and access to multiple photonic degrees of freedom, but typically suffer from reduced emission efficiency. **c** Monolithic integration of a micropillar cavity with a multifunctional metalens combines both functionalities, enabling simultaneous high-performance photon generation and multidimensional state engineering. **d** Example output states including polarization-dependent orbital angular momentum modes and optical skyrmions characterized by spatially structured polarization fields. Adapted from Ref. [11]

functionality is achieved without relying on external bulk optics, which is essential for scalable integration. The reported device achieves an extraction efficiency of 35.7% and a Hong–Ou–Mandel visibility of 0.736, representing a notable balance between brightness, purity, and indistinguishability in an integrated system. While these figures do not yet reach the very best cavity-based sources [3–5], they demonstrate that a substantial fraction of the performance can be preserved even after adding functionality, placing the device in an intermediate regime between high-performance cavity sources and highly versatile metasurface-based approaches. On the opposite side of the chip, the metalens enables versatile manipulation of the emitted photons. By engineering the geometric phase of subwavelength meta-atoms, the device independently controls different polarization channels and shapes the wavefront accordingly, enabling simultaneous control over emission direction, divergence, and phase front [6, 7]. This effectively extends a high-quality photon source into a multidimensional state generator.

A key advance is the ability to engineer multiple photonic degrees of freedom at once. The authors demonstrate single photons carrying well-defined OAM states, with different topological charges encoded in orthogonal polarization channels [11]. This directly enables polarization-OAM entanglement, a key resource for high-dimensional quantum information processing. Quantum state tomography reveals a fidelity approaching 0.9, confirming the high quality of the generated quantum states. Beyond entanglement, the platform enables the generation of optical skyrmions, photonic states with nontrivial topological textures (Fig. 1d) that have recently attracted considerable interest [12–14]. Notably, these states exhibit robustness under atmospheric turbulence, suggesting a potential pathway towards more robust high-dimensional quantum communication in realistic propagation environments, where conventional structured light is often fragile. This work comes amid rapid progress in quantum meta-optics. Quantum metasurfaces have been shown to mediate multiphoton interference and enable quantum state reconstruction, highlighting their potential for scalable quantum photonic processing [15]. Meanwhile, resonant metasurfaces exploiting bound states in the continuum promise enhanced nonlinear interactions and more efficient quantum light generation [10]. In a complementary direction, nanophotonic platforms such as Mie-void resonators have demonstrated strong field confinement in low-index environments, pointing toward new hybrid quantum emitter architectures [16]. Against this backdrop, the microcavity-metalens interface stands out by unifying high-performance photon generation with versatile state engineering within a single chip-scale device. Nevertheless, important challenges remain. While the observed indistinguishability represents a notable achievement for an integrated platform, it remains significantly below the near-unity regime required for scalable multi-photon interference [3–5]. This suggests that integrating metasurface functionality may introduce additional constraints, for example through fabrication-induced disorder or imperfect mode matching between cavity and metalens. As the number of interfering photons increases, even small deviations from perfect indistinguishability accumulate, leading to a rapid degradation of interference fidelity. In addition, operation at cryogenic temperatures and the requirement for deterministic emitter positioning continue to complicate large-scale integration.

Looking ahead, several directions could further enhance this platform. Incorporating high-Q resonant metasurfaces may allow simultaneous optimization of light-matter interaction via Purcell enhancement and wavefront control [10]. Active or tunable meta-atoms could enable dynamic reconfiguration of photonic quantum states, while hybrid integration with emerging material platforms, such as two-dimensional semiconductors or Mie-void structures, may extend operation to new wavelength regimes [16]. Machine-learning-assisted inverse design may also accelerate the development of increasingly complex multifunctional devices. More broadly, the convergence of quantum photonics and meta-optics is beginning to reshape how quantum light is generated and controlled. In this context, the work of Ma et al. represents a conceptual step towards integrating photon generation and state engineering within a single platform. Rather than representing a mere combination of two established concepts, it points towards a broader paradigm in which photon generation and state engineering are co-designed within a unified architecture. This demonstrates that high-performance photon sources and high-dimensional state engineering need not be separate functionalities, but can instead be realized within a single integrated platform, bringing scalable quantum light sources a significant step closer to practical implementation.

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