

Tunable topological charge vortex microlaser with ultrafast controllability

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Abstract— By harnessing the synergy of total momentum conservation, spin-orbit interaction, optical non-Hermitian symmetry breaking and transient optical gain dynamics, we demonstrate an (fractional) OAM-tunable vortex microlaser, providing ultrafast reconfigurable chiral light emission with desired topological charge at a single telecom wavelength.

Keywords—orbital angular momentum, fractional orbital angular momentum, ultrafast, optical vortex, non-Hermitian photonics

I. INTRODUCTION

The vectorial nature of light empowers a full control of topological features with spatially phase-variant fields, revealing vortex beams carrying the orbital angular momentum (OAM) and spin angular momentum (SAM) in addition to the well-known linear momentum [1]. In addition, optical beams can carry a *fractional* orbital angular momentum (FOAM) which may take any value between multiple integer numbers of quanta, as a result of superposition of multiple spatially variant fields of different vorticity and is especially useful in optical communications. The generation and control of vortex emission mainly rely on conventional bulk optics such as spiral phase plate, spatial light modulators, planar optics such as metasurfaces, ring resonators and recently developed vortex lasers which are either static or slow in performance [2]. Nevertheless, high-speed control and flexible reconfigurability of vortex light is demanding in optical communication and computation applications [3], which is not yet accessible by state-of-the-art microscale devices. Development of a fast tunable vortex light source on a chip is a critical step in the utilization of the full angular momentum (AM) space. Here, we use the transverse spin and OAM interaction, total angular momentum conservation and ultrafast optical controlled non-Hermitian symmetry breaking to control the vortex emission from a microlaser in an ultrafast fashion.

II. DESIGN AND RESULTS

We consider a microring resonator supporting the two degenerate clockwise (\cup) and counter clockwise (\oslash) whispering gallery modes (WGMs) on a III-V semiconductor platform, coupled with an additional bus waveguide of InGaAsP with two control arms which enables the indirect coupling between the two modes (Fig. 1A). The AM carried by N^{th} order WGM inside the resonator is extracted into free space by introducing M periodic angular scatters inside the inner sidewall (Fig.1A). The polarization state of

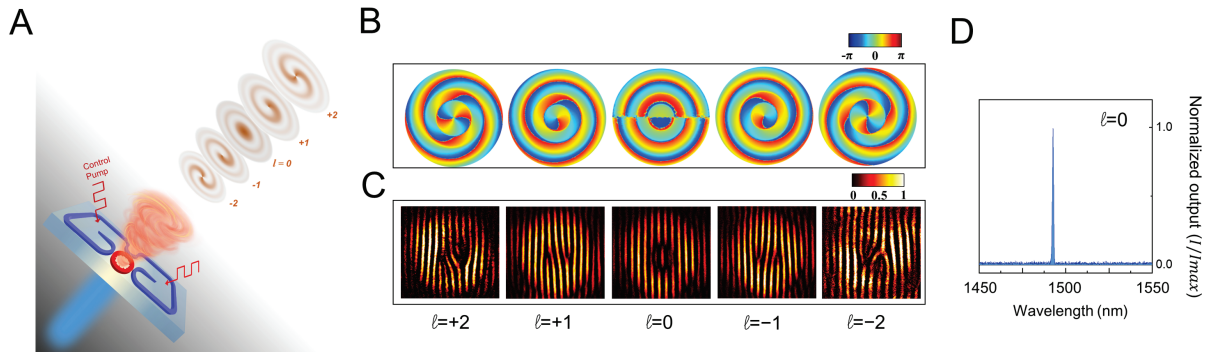


Fig.1 Vortex emission from the tunable vortex microlaser. (A) Schematic of the tunable vortex microlaser on InGaAsP platform embedded in SiN substrate. (B) Simulate phase distribution of 5 different OAM states showing helical phase winds $2l\pi$ around the center. (C) Off-center self-interference results. While no significant fringe mismatch was observed for $l=0$ state, a pair of inverted forks were observed for all other non-zero OAMs. (D) Lasing spectrum of $l=0$ state, all five states share the same lasing wavelength.

extracted fields in general is a superposition of two transverse SAM with their amplitudes dependent on the dimensions of the microring. Therefore, the microlaser emissions corresponding to the 4 SAM-OAM locked states, described as:

$$I_{out} = p_{\mathcal{U}}\sigma^2|L, N - M - 1\rangle + p_{\mathcal{U}}(1 - \sigma^2)|R, N - M + 1\rangle + p_{\mathcal{V}}(1 - \sigma^2)|L, M - N - 1\rangle + p_{\mathcal{V}}\sigma^2|R, M - N + 1\rangle \quad (1)$$

where, $p_{\mathcal{U}}/p_{\mathcal{V}}$ denotes the scattered power associated with the \mathcal{U}/\mathcal{V} mode, respectively; σ is the purity of the transverse spin; and L/R indicates left/right-handed circular polarization, respectively. The OAM/FOAM charge is calculated by integrating the OAM flux across the whole vector beam, given no spin-orbit coupling at the paraxial limit. By optically pumping one of the waveguide arms to create gain (generated through pumping) and loss (intrinsic material loss without pumping) contrast, an effective asymmetric coupling between the counter-propagating WGMs in the microring is obtained. Therefore, the weighting between the two chiral modes can be controlled from completely symmetric (Hermitian) to unidirectional (exceptional point).

To characterize the reconfigurability for *integer* OAM states, the microlaser is designed to support a WGM of order $N = 34$ at the wavelength around 1500 nm, scatter number $M = 32$ and $\sigma = 1$. According to (1), the extracted emission carries OAM of $l = 0, \pm 1$ and SAM of $\sigma = 0, \pm 1$ for $\mathcal{U} + \mathcal{V}/\mathcal{U}/\mathcal{V}$ modes, respectively. Additional tunability of the OAM charge $l = \pm 2$ was demonstrated through the conservation of the total angular momentum in the spin-to-orbit conversion using a radial polarizer that preserves the rotational symmetry of the emitted laser beam. Five spiral phase maps showing the corresponding topological charges from +2 to -2 were clearly observed in the numerical simulations (Fig.1B). The corresponding self-interference interferograms were captured to analyze the vortex reconfiguration of the emitted beams (Fig.1C), showing good agreement with theoretical prediction. Notably, the lasing of all these 5 OAM states occurred at a ‘single’ wavelength at 1492.6 nm (Fig. 1C), potentially providing 5 spatial channels for information modulation.

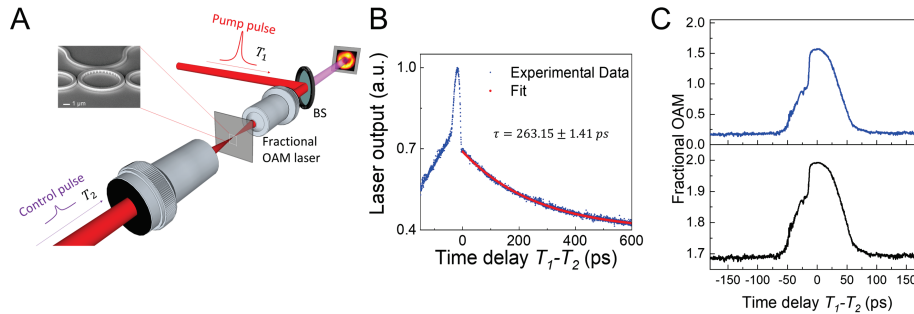


Fig.2 Ultrafast control of vortex emission from the tunable vortex microlaser. (A) Schematic of the experimental setup. Inset shows the scanning electron microscope image of the tunable vortex microlaser. (B) The measured and fitted temporal evolution of laser emissions, showing ultrafast gain dynamics in the InGaAsP multiple quantum wells with a carrier lifetime of 263.15 ± 1.41 ps. (C) Measured FOAM charge of laser emissions tuned from 0.18 to 1.57 (upper panel) and from 1.68 to 2 after filtering out the cross-spin component (lower panel) in 100 ps.

To achieve the ultrafast control, additional microlaser is designed with scatter number $M = 35$ and $\sigma = 0.9$ with the same WGMs order. We apply two synchronized femtosecond pulses from the same pump laser (~ 140 fs): a main pump pulse above the lasing threshold at T_1 to enable the lasing in the microlaser and a control pulse below the lasing threshold at T_2 to excite gain carriers in one of the two arms (Fig.2A). As the excited carriers relax in time, the associated gain also decays, resulting in the non-Hermitian-controlled indirect coupling varies as a function of time, from unidirectional to symmetric. Hence, the weighting between the two chiral modes in the microring and thus the weighting of different OAM components in (1) can be controlled as a function of time. The transient carrier dynamics as a function of $T_1 - T_2$ was measured and fitted to be $\tau = 263.15 \pm 1.41$ ps in the MQWs, demonstrating the potential towards the ultrafast dynamical control (Fig.2B). The power associated with all 4 spin-OAM components in (1) can be evaluated by their spatial distributions and polarization states. For instance, $|R, 0\rangle$ and $|L, 0\rangle$ states are located at the center as marked in the inset of Fig. 2A. Similarly, the temporally varying power associated with $|R, +2\rangle$ and $|L, -2\rangle$ can be measured. Altogether, by counting the power average of all 4 integer OAM components, we conducted dynamical sweeping of the FOAM charge of the vector beam with a picosecond resolution, where the fractional charge can rapidly vary from 0.18 to 1.57 within 100 ps (Fig. 2C upper panel). The tuning range can be expanded if the cross-spin components are filtered. By selecting only the right-handed polarized components ($|R, +2\rangle$ and $|R, 0\rangle$), the FOAM charge varies in a range from 1.68 to 2 (Fig. 2C lower panel).

III. CONCLUSION

Our tunable vortex microlaser is capable of emitting and sweeping vortex beams of both OAMs (5 states) and FOAMs (from 0 to +2) with ultrafast reconfigurability within 100ps. The ultrafast non-Hermitian manipulation of chiral spin-orbit interaction offers fundamentally new functionality of controllable vortex light emission in a scalable way. The toolbox of generating and controlling various vortex light at a single wavelength holds the promise for future development of multi-dimensional OAM-SAM-wavelength division multiplexing and mutli-level OAM keying for high-density data transmission in classical and quantum regimes.

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