Vortex microlaser with ultrafast tunability

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Abstract: Based on the concepts of spin-orbit interaction, angular momentum conservation and transient optical gain controlled non-Hermitian symmetry breaking, we demonstrate an ultrafast-tunable vortex microlaser, providing emissions with controlled integer (fractional) OAM charge.

1. Introduction

In addition to phase, amplitude and frequency, the full-vector nature of light provides another information dimension, namely, the angular momentum (AM) which includes both orbital angular momentum (OAM) and spin angular momentum (SAM) [1]. Moreover, optical beams can carry a *fractional* orbital angular momentum (FOAM) [2], as a result of superposition of multiple spatially variant fields of different vorticity. This full AM dimension of light holds a great promise for multi-dimensional high capacity data multiplexing and modulation, meeting the ever-increasing demands for information. Conventional bulk optics such as spiral phase plate, spatial light modulators and recently developed planner optics such as metasurfaces, ring resonators require additional light sources, vortex microlasers offer a more compact and robust solution for on-chip integration. However, the demonstrated miniaturized vortex lasers at telecommunication wavelengths so far lack reconfigurability. Development of a dynamically tunable OAM light source on a chip is a critical step in the utilization of the full AM space. Here, we use the transverse spin and OAM interaction, total angular momentum conservation and ultrafast-controlled non-Hermitian symmetry breaking induced by transient optical gain to achieve the ultrafast-tunable vortex microlaser [3,4].

2. Design and Results

To achieve ultrafast-tunable vortex microlaser, we consider a microring resonator and an external coupling loop with two control arms, all made of InGaAsP multiple quantum wells (MQWs) and embedded in a Si_3N_4 substrate (Fig. 1A&B). The microring resonator supports two chiral modes: counterclockwise (↺) and clockwise (↻) whispering gallery modes (WGMs) that are indirectly coupled by the external loop. OAM emissions are extracted by an angular grating with M equidistant scatters at the inner side wall of the microring. We designed the microring resonator to support WGMs of order $N = 34$ around 1500 nm, which, alongside the order of the angular grating of M, yields a total angular momentum of $J = \pm(N - M)$ for extracted emissions from the ↺ and ↻ modes, respectively. The polarization of the emitted light is a superposition of two spin states in general. Therefore, the microlaser emissions, including the 4 SAM-OAM locked states, can be described as:

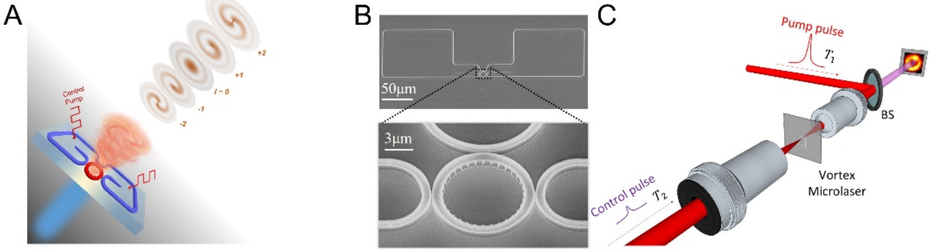

Figure 1. Ultrafast-tunable vortex microlaser. (A) Schematic of the ultrafast-tunable vortex microlaser on an III-V semiconductor platform. (B) The scanning electron microscope image of the vortex microlaser. (C) Schematic of the experimental setup for ultrafast characterization.

$$I_{out} = I_{\boldsymbol{L},N-M-1} + I_{\boldsymbol{R},N-M+1} + I_{\boldsymbol{L},M-N-1} + I_{\boldsymbol{R},M-N+1} \propto p_{\circlearrowleft}\sigma^2 + p_{\circlearrowleft}(1-\sigma^2) + p_{\circlearrowright}(1-\sigma^2) + p_{\circlearrowright}\sigma^2 \qquad (1)$$

where $\boldsymbol{L}/\boldsymbol{R}$ indicates the left/right-handed circular polarization, $p_{\circlearrowleft}/p_{\circlearrowright}$ denotes the power associated with the ↺/↻ mode inside the cavity, respectively, and σ is the absolute value of the transverse spin angular momentum charge. The (fractional)OAM charge is calculated by integrating the OAM flux across the whole vector beam, given no spin-orbit coupling at the paraxial limit. The weighting between the two chiral modes (i.e. $p_{\circlearrowleft}/\ p_{\circlearrowright}$) can be controlled through the external loops (Fig.1A&B) with optical pumping from completely symmetric (Hermitian) to unidirectional (exceptional point), depending on the gain-loss contrast between the two control arms.

In experiments, two synchronized pumping pulses are projected onto the sample: one pump pulse at T_1 triggers the lasing of the microlaser and one control pulse at T_2 excites the optical gain in one of the control arms (Fig.1C). 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 with a picosecond resolution. To demonstrate the dynamically tunability of *integer* OAM emissions, we designed the vortex microlaser with $M = 32$ and $\sigma = 1$. In addition, the two nanosecond pulses are completely synchronized (i.e. $T_1 - T_2 = 0$). The extracted light carries OAM of $l = 0, \pm 1$ and SAM of $s = 0, \pm 1$ for ↺ +↻,↺ and ↻ mode in the microlaser, respectively. Based on the concept of total angular momentum conservation, a radial polarizer is used to convert the SAM into OAM realizing additional OAM tunability of $l = \pm 2$. Five numerical simulated patterns clearly shows the twist phase distribution from OAM -2 to +2 (upper panel of Fig.2A). Off-center self-interference characterization is carried on verifying the vortex nature of the emission and shows a pair of inverted forks with non-zero OAM emissions (lower panel of Fig.2A). Notably, all lasing happens at the same wavelength of 1492.6nm which makes it compatible with wavelength division multiplexing. To demonstrate the ultrafast tunability of *fractional* OAM emissions, we designed the vortex microlaser with $M = 35$ and $\sigma = 0.9$. Hence, all four spin-orbit locked states as descried in (1) are expected and their weighting will vary as a function of time delay of two femtosecond pulses (i.e. $T_1 - T_2$). By measuring the power average of all four states, we sweep the fractional OAM emission from 0.18 to 1.57 in less than 100 ps as shown in the upper panel of Fig.2B. Moreover, by filtering out the cross-spin components we extended up limit of sweep range to 2.00 as shown in the lower panel of Fig.2B.

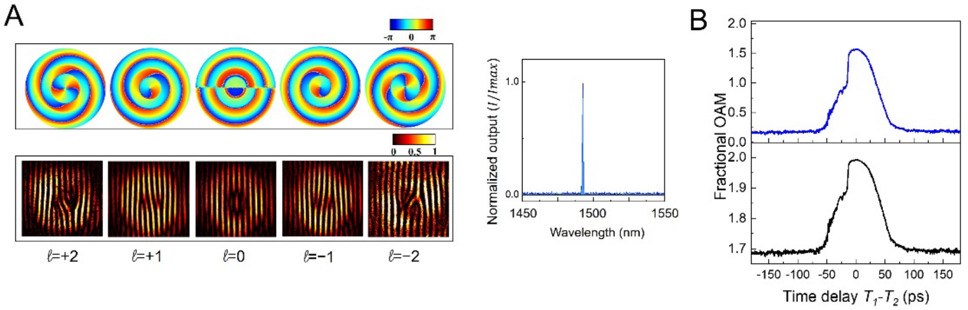

Figure 2. Characterization of the dynamical tunability of vortex microlaser emissions. (A) Upper panel: Simulated phase distribution of 5 different OAM states showing helical patterns. Lower panel: Experimental captured off-center self-interference images. A pair of inverted forks were observed for all other non-zero OAMs. Right panel: All five states share the same lasing wavelength. (B) Experimental measured fractional OAM emissions sweeping from 0.18 to 1.57 (upper panel) and from 1.68 to 2.00 (lower panel) in 100 ps.

3. Conclusion

To conclude, we have experimentally demonstrated both integer (up to 5) and fractional (0 to 2) OAM emissions from a vortex microlaser, harnessing the fast transient carrier dynamics of the semiconductor optical gain in conjunction with non-Hermitian-controlled spin-orbital interactions of light. Our scheme, compatible with other modulation schemes in polarization, amplitude, frequency, etc., could be of potential relevance for the next generation of ultrahigh-speed optical communication systems offering a feasible route to further enhancing the communication bandwidth based on OAM-SAM-wavelength division multiplexing and multi-level OAM keying in optical communication.

4. References

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