Tunable orbital angular momentum microring laser

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***Abstract*—We demonstrate a microring laser generating vortex beams with topological charge. By implementing a chiral S-bend element inside the active ring and a second-order grating structure around the sidewall, this system could effectively down-convert the large order whispering gallery mode to on-demand OAM values.**

Keywords—laser resonator, microcavity devices, semiconductor lasers

I. Introduction

Vortex beams carrying orbital angular momentum (OAM) are of great importance in optics [1,2]. With a phase singularity and a twisted wavefront, in recent years, OAM beams have found numerous applications in a variety of scientific and technological settings, ranging from optical microscopy [3], to micromanipulation [4], and to fiber optics telecommunications [5]. One can transform an arbitrary wavefront into a vortex OAM beam by manipulating its transverse amplitude and phase distribution using specially designed phase plates (like spiral phase plates), spatial light modulators, computer generated holograms, or even metasurfaces [6]. Moreover, in fully integrated configurations, it is shown that a silicon microring resonator equipped with an appropriately designed second-order grating can radiate light with low order OAM when excited via an adjacent bus waveguide [7]. While such passive techniques are useful in many circumstances, in some applications, the direct generation of OAM vortex beams at the micro and nanoscale is greatly desired. So far, this has been accomplished by either implementing phase plates on top of VCSELs [8] or using grating structures that involve a large level of losses in order to establish an exceptional point [9]. Hence, of interest will be to identify an all-dielectric and compact OAM laser without inducing extra loss into the system. Here we propose a dented microring laser with an additional S-bend for directly generating OAM beams of arbitrary order.

A schematic of this OAM laser is presented in Fig. 1(a). In this design, the microring resonator has a radius of $3\,\mu m$, width of $500\,nm$, and overall height of $210\,nm$. The S-bend is located at a distance of $100\,nm$ at its closest proximity to the ring and square shaped protrusions with sides of $100\,nm$ are incorporated along the outermost sidewall of the ring resonator. In this system, the S-bend breaks the symmetry between the two counter-propagating modes and hence enforces the unidirectional power flow in the ring resonator, while the dented sidewall serves as a second-order grating, down-converting the large OAM values intrinsic to whispering gallery modes and facilitating vertical free-space emission of the generated vortex beam. The resulting vertical emission of the device has the angular momentum $\hbar l$ per photon associated with the difference between the orders of the WGM (p) and the number of periodic scatterers (q). Fig. 1(b) provides an SEM image of this structure. The modal response of the device (Fig. 1(c)), found using finite element methods (FEM), clearly indicates that the S-bend promotes lasing in a unidirectional fashion (CCW). Moreover, the phase evolution is provided in Fig. 1(d) of a ring with an $l = p - q = 2$. The ring is resonant at a wavelength $1540\,nm$ ($p = 30$) and has $q = 28$ scattering elements.

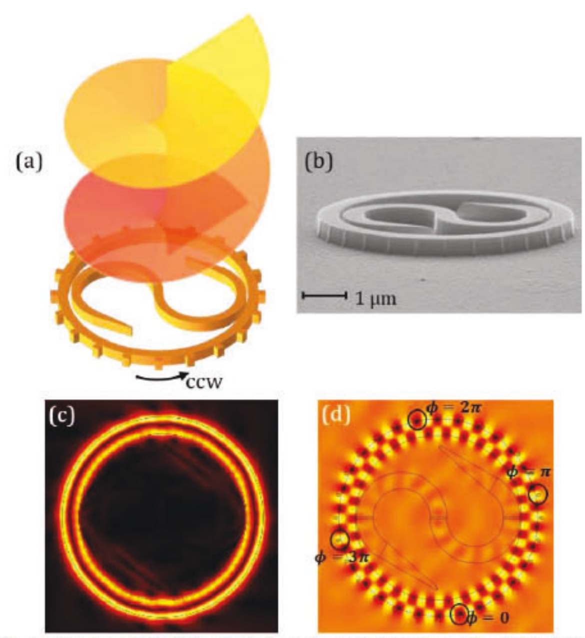

Fig. 1. Design of OAM microring laser. (a) Schematic of the OAM microring laser. The incorporated S-bend element enforces only the counter-clockwise wave propagates inside the ring resonator. (b) SEM image of a fabricated device. (c) Normalized amplitude of the azimuthal component of the E-field inside the structure. (d) Phase evolution of the scatterers located in the outer periphery of the device when $l = p - q = 2$.

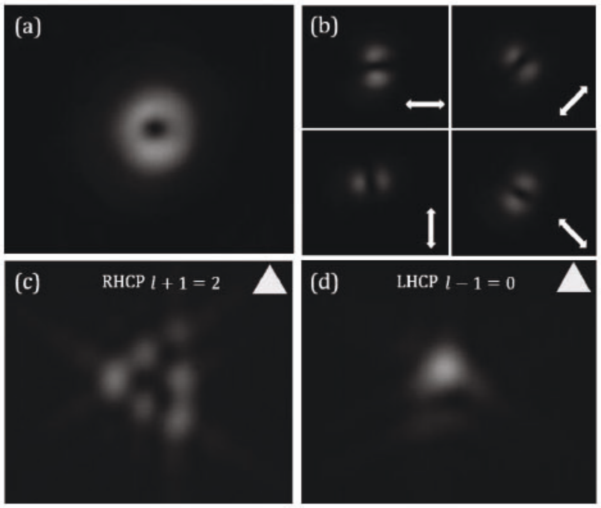

Fig. 2. Characterization of OAM lasing. (a) The near-field intensity profile of the microring laser (radius 3 μm), showing a doughnut-shaped beam. (b) Intensity distributions of the laser emission after passing through a linear polarizer, demonstratating an azimuthally polarized beam. The polarizer orientations are indicated by arrows. (c, d) The far-field diffraction after passing through a triangular aperture filtered for right-hand and left-hand circular polarizations, demonstrating a vortex beam with $l = +1$.

In our experiments, we characterized a unidirectional active microring vortex laser with the same dimensions mentioned above, supporting oscillations in the 27^{th} WGM (corresponding to 1529 nm) at room temperatures. In order to extract a vortex beam with an $l = 1$, the microring is fabricated with $q = 26$ scattering elements along its sidewall. The intensity profile presented in Fig. 2(a) displays the doughnut shape associated with a vortex beam. As expected, this emission is predominantly azimuthal polarized (Fig. 2(b)). Moreover, using the triangle technique [10], the

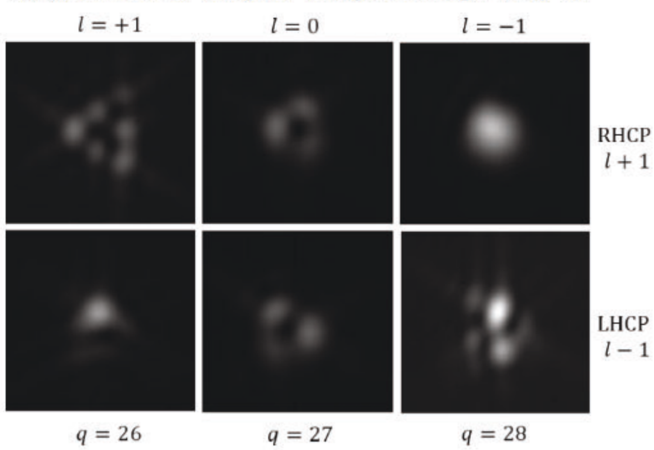

Fig. 3. The experimental results of the far-field diffraction patterns under two different polarizations: right- and left-handed circular polarization with respect to number of scatters $q = 26, 27, 28$, where these structures are lasing at the same order of longitudinal mode $p = 27$.

OAM measurement indicates a value of $l = 1$ (Fig. 2(c, d)). This is observed by filtering for either the left- or right-handed circular components of the polarization, thus obtaining a scalar beam with an associated topological charge of $l+1=2$ or $l-1=0$, respectively [7].

To further confirm our observation, next we fabricated a number of rings with the same radii (3 μm) but with varying number of periodic scattering elements ($q = 26$ to 28) in their peripheries. Consequently, the measurement results provided in Fig. 3 clearly confirm the decreasing of l from 1 to -1. In particular, one may notice that once the grating pitches and the resonator mode share the same order, the resulting beam offers no orbital angular momentum, while it remains an azimuthally polarized vortex beam.

In summary, we demonstrated a compact unidirectional microring laser that directly generates optical vortex beams with tunable OAM. The OAM microrings can readily be implemented in electrical pumping schemes and could help pave the way for a new generation of compact and integrated vortex beam emitters.

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