Supporting Information for

High-speed directly-modulated cylindrical vector beam lasers

Xiang Ma†, Shuang Zheng†, Quanan Chen, Su Tan, Pengfei Zhang, Qiaoyin Lu, Jian Wang*, and Weihua Guo*

†These authors contributed equally to this work.

*Correspondence to: guow@mail.hust.edu.cn, jwang@hust.edu.cn

1Wuhan National Laboratory for Optoelectronics and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China.

1. Device Design and Simulation

1.1 Normal microring cavity case

Figure S1. Typical distributions of the electric field components along the radial direction of the quasi-TE WGMs in a microring cavity. (a), (b). The distributions of radial field and azimuthal field components in the cross section of the microring cavity. (c). Comparison of the magnitude of the radial and azimuthal field components. Here, R =10 µm is the external radius of the microring cavity.
1.2 The microring cavity interacted with only the side grating case

When a second-order grating (side grating) with a symmetry plane (Fig. 1b) is etched on the periphery of the microring cavity, the two degenerate WGMs reorganize so as to have different symmetries, symmetrical mode or anti-symmetrical mode, relative to this symmetry plane as depicted in Figs. S2a and S2b. Here the symmetry properties are defined for the electric fields. When the azimuthal mode number \( m \) of the WGMs is equal to the period number of the side grating \( N \), the two degenerate WGMs split after reorganization. Since \( E_\psi \) is larger than \( E_r \) at the periphery of the microring cavity as shown in Fig. S1c, \( E_\psi \) is the main scattered field from the side grating. Remarkably, the symmetrical mode suffers little scattering loss due to a perfect cancellation of the scattered field component from \( E_\psi \), while the anti-symmetrical mode suffers the highest scattering loss mainly in the lateral direction due to the doubled scattering loss. The other WGMs \((m \neq N)\) are still degenerate and suffer serious loss mainly from \( E_\psi \). As a result, the side grating can select the symmetrical standing wave mode with \( m = N \) to be the lasing mode through the scattering cancellation mechanism [33]. However, the microring cavity interacted with only the side grating contributes less to the vertical emission and has very limited vertical emission efficiency even for the symmetrical mode.
1.3 The microring cavity interacted with only the top grating case

We then consider the microring cavity applied with only the top grating, which is etched on the top grating layer of the cavity. Similar to the interaction with the side grating, the WGMs are also reorganized to the symmetrical mode and anti-symmetrical mode, relative to the symmetry plane (Fig. 1b). However, the grating on the topside interacts mainly with $E_r$ enabling easy vertical emission, since $E_r$ exists as the main electric field component ($E_r$ is larger than $E_{\phi}$). In such case, the symmetrical mode suffers doubled scattering loss from $E_r$, while the anti-symmetrical mode suffers little scattering loss from $E_r$ (scattering cancellation). Hence, the symmetrical mode has the most efficient vertical emission ($E_r$ component), while the anti-symmetrical mode becomes the lasing mode with limited emission of $E_{\phi}$ component (doubled scattering from the top grating but small interaction with the top grating). In addition, $E_r$ behaves more like a fundamental mode and

Figure S2. Distributions of the (a) symmetrical mode and (b) anti-symmetrical mode relative to the symmetry plane.
$E_\phi$ is more like a high-order mode (Fig. S1). Thus the emitted anti-symmetrical mode ($E_\phi$ component) is not the preferred radially polarized vector beam ($E_r$).

1.4 Simulation results of the microring cavity interacted with gratings

When the cavity is added with only the top grating, the normalized upward emission intensity profiles of the symmetrical mode and anti-symmetrical mode are shown in Figs. S3(a) and S3(b), respectively. The scattered field of the symmetrical mode mainly in the vertical direction and from the $E_r$ component has an ideal emission pattern with almost perfect donut shape. The upward emission efficiency of the symmetrical mode and the anti-symmetrical mode is approaching 60% and 30%. Therefore, the symmetrical mode is preferable to be the lasing mode.

Figure S3. Simulated emission fields of the cavity with only the top grating. The normalized upward emission intensity profiles of the (a) symmetrical mode and (b) anti-symmetrical mode with $m = M$. The microring cavity interacts with only the top grating.

2. Device Fabrication

The integrated CV beam laser is fabricated with the following processing steps as depicted in Fig. S4. Firstly, proton is implanted into the p-doped lower cladding layer in the central cylindrical region right below the active region as shown in Fig. S5, which makes the laser to have better
overlap between the WGMs and the injected carriers. Secondly, n-doped ohmic contact layer above the top grating is removed to avoid extra loss. The n-InGaAs contact layer is etched off with a thin SiO$_2$ hard mask by inductively coupled plasma (ICP) etching at room temperature. Thirdly, the microring cavity with side grating is patterned with E-beam lithography (EBL). We use the lift-off process to pattern a 50-nm thick chrome (Cr) layer through EBL first, then the pattern is transferred to a SiO$_2$ hard mask layer, which is used to etch the InP-based microring cavity down to a position about 1.5 µm below the active region. The side grating has a triangular shape with a duty cycle of 0.75 as determined by the simulation for laser with outer-cavity-radius of 10 µm. For laser with larger cavity-radius of 15 or 25 µm, duty cycle should be smaller such as 0.5 to achieve single mode lasing. Fourthly, Benzocyclobutene (BCB) is spun and cured and then etched back for planarization. BCB has been adopted for its lower extra parasitic capacity, which is very useful for higher speed operation. Fifthly, the top grating is also patterned through EBL and its pattern is then transferred onto a 50-nm thin SiO$_2$ hard mask layer. The top grating is etched using ICP to a depth of 0.25 µm. Sixthly, P and N contact metal are deposited and then the electrodes are deposited with coplanar ground-signal-ground (GSG) format on BCB. The N-contact and P-contact metal are made into ring shapes to make the current injection more efficient. Finally, the wafer is thinned down for test.
Figure S4. Main fabrication processing steps of the integrated CV beam laser. (a) Ion implantation of the p-doped lower cladding layer. (b) Remove extra n-doped ohmic contact layer. (c) Dry etching of the microring with the side grating. (d) Spin BCB, cured and etched back. (e) Dry etching of the top grating. (f) Evaporation of the contact metal.

Figure S5. Schematic of the cross section of the integrated CV beam laser.

3. The Effect of the Ion Implantation

We introduce ion implantation to the integrated CV laser to improve the current injection. L-I
curves of the lasers with and without ion implantation are tested in the experiment as shown in Fig. S6. It can be seen that, the output power of the CV laser with a proper ion implantation area is much higher than the laser without ion implantation.

Figure S6. Measured L-I curves of the CV lasers with (w/) and without (w/o) ion implantation.

4. Characterization of Emitted Optical Field Intensity Distribution from Practically Fabricated Device with Electrodes

To achieve high-speed direct modulation, N and P ohmic contact layers should be connected with electrodes as shown in Fig. 1(d). Thus, the emitted beam from the microring cavity is partially obstructed by the contact electrodes in the vertical direction. Due to the partial occlusion by the electrodes, the microring cavity of the fabricated device is a non-perfect circle. As a result, the detected near field is not a perfect circle. However, the far field after emission and propagation for a short distance is still a nearly perfect radially polarized CV beam, which is confirmed by the measured far field intensity distribution in the experiment as shown in Fig. 5(a1).

The simulation results in Fig. 3 consider the ideal case of the device structure without electrodes. Here, we add more simulation and experimental results to study the impact of electrodes on the quality of emitted CV beams and clearly show the near field and far field intensity distributions.
In the simulation, we make a detailed comparison between the ideal case without electrodes and the fabricated device with electrodes. We find the practically fabricated device with electrodes (non-perfect circle) shows very similar far field intensity distribution to the ideal case, as shown in Fig. S7.

Figure S7. Simulated optical field intensity distributions of the practically fabricated device with electrodes. (a) Near-field and (b) far-field intensity distributions of the upward emission from the lasing mode and the optical field components in the x direction (horizontal polarization) and y direction (perpendicular polarization).

Remarkably, in the experiment, the near-field and far-field intensity distribution measurements can be realized by employing a three-lens optical system as illustrated in Figs. S8(a) and S8(b). Lens1, Lens2 and Lens3 have 10-mm, 100-mm and 75-mm focus lengths, respectively. Lens1 with high numerical aperture (NA=0.55) and Lens3 are used to obtain the near-field image, as shown by the red rays in Fig. S8(a). Then, the far-field image is taken by inserting Lens2 to project the far field on the infrared (IR) camera, as shown by the green rays in Fig. S8(b). The camera is placed on the focal plane (Focal plane2) of Lens3. Lens1 and Lens2 have a common focal plane (Focal plane1). An additional polarizer is inserted into the setup when analyzing the CV beams. We use such a three-lens optical system to measure the far-field intensity distribution in Figs. 5(a1)-(c1). Additionally, for easy operation we also employ a single objective lens with high NA to approximately detect the near field and far field intensity distributions. By appropriately adjusting
the distance between the device and the objective lens from near to far, the approximate whole evolution process of the emitted beam from near field to far field is characterized in the experiment, as shown in Fig. S9.

Figure S8. (a) Schematic illustration and (b) experimental setup for the characterization of near-field and far-field intensity distributions.

Figure S9. Measured emission optical field intensity distributions of the practically fabricated device with electrodes. (a)-(j) Measured whole evolution process of the emitted beam from near field to far field in the experiment.

By comparing Fig. S7 and Fig. S9, one can clearly see that the simulation results are in good agreement with the experimental results for the practically fabricated device with electrodes. The obtained results indicate that the non-perfect circle induced by the contact electrodes in practically fabricated device has negligible impact on the quality of the emitted radially polarized CV beam at far field.
5. Experimental Configuration for Dynamic Characterization of the High-Speed Directly Modulated CV Laser

Figure S10. High-speed measurement setups. Experimental configuration for the dynamic characterization of the high-speed directly-modulated CV laser. The configuration consists of three parts (transmitter, free space and fiber transmission link, and receiver). LCF: large-core fiber; MMF: multi-mode fiber; Col.: collimator; VOA: variable optical attenuator; PD: photodetector; LNA: low noise amplifier; BER: bit-error rate; DSA: digital signal analyzer; DCA: digital communications analyzer.

The detailed experimental configuration for the dynamic characterization of the high-speed directly-modulated CV beam laser, including the small signal and large signal modulation cases, is shown in Fig. S10. Here we introduce the large signal case in detail, and it is similar for the small signal case.

The experiment configuration consists of three parts, i.e. transmitter, free space and fiber transmission link, and receiver. First, the fabricated laser is mounted on a micro-positioning stage. The temperature is kept at approximately 15 °C controlled by a temperature controller (TEC).
At the transmitter side, a Bias-T is used to combine the DC bias current and the RF electric signal which is amplified by a broadband amplifier OA4SMM4. The combined driving signal is then added onto the laser through a high-speed microwave probe. The RF electric signal is a non-return-to-zero data pattern with a $2^{15}-1$ bits long pseudorandom binary sequence (PRBS) generated by a bit pattern generator with a clock provided by a clock synthesizer N4960A.

The data-carrying vector beam is emitted vertically from the fabricated chip, and then collimated by a lens with a high NA (0.55) and 10-mm focus length. In such process 3dB loss is introduced. After a mirror, the vector beam is adjusted by a 2x beam shrinker in horizontal direction. The vector beam is coupled into a piece of large-core fiber (LCF) or multi-mode fiber (MMF) by an aspherical lens with 8-mm focus length, high NA and low loss. A polarization controller on the LCF is used to mitigate the mode crosstalk. The vector eigenmode excitation is very sensitive to the fiber alignment (LCF), so we employ a camera and polarizer to monitor the output pattern. The coupling losses are estimated to be 10 dB and 3 dB for LCF and MMF, respectively. The total coupling loss for LCF and MMF are 13 dB and 6 dB, respectively.

After propagating through a 2-km LCF or 120-m MMF, the output beam is collimated by a collimator first and then focused by another aspherical lens with 15 mm focus length. The output vector beam is detected by a broadband InGaAs PIN detector (ET-5000) with bandwidth more than 12.5 GHz, high responsivity ~0.8 A/W around 1345 nm, and dark current less than 1 µA. In the free-space light path, a variable optical attenuator (VOA) is used to adjust the received optical power.

At the receiver side, the output electric signal from the detector is amplified by another low noise
amplifier (SWLNA0012031). After the amplifier, the eye diagrams are recorded by using an Agilent Infinium DCA-J 86100C 70 GHz digital communications analyzer, and the BER performance is measured by using another oscilloscope (Keysight DSA-Z 204A 20 GHz digital signal analyzer) followed by offline digital signal processing. By tuning the VOA, the received optical power is changed and the BER curves can be obtained.

6. Parameters of the Large-Core Fiber (FMF) and Multi-Mode Fiber (MMF)

In the experiment, we used the fabricated high-speed directly-modulated CV beam laser to transmit optical signal through two different types of fiber. Figure S8a and S8b show the relative refractive index profile and cross-section view of the LCF, which is a circular core optical fiber with a step index profile. The radii of the LCF core and cladding are 7.4 and 62.5 μm, respectively. The relative refractive index difference ($\Delta=(n_1-n_2)/n_1$) between the fiber core $n_1$ and cladding $n_2$ is $\Delta=0.336\%$. The LCF only supports six vector modes, and the insets of Fig. S10b are two specific CV beams (radially and azimuthally polarized beams).

![Figure S11. Parameters of the LCF and MMF. (a), Cross-section view of the LCF. (b), Relative refractive index profile of the LCF. Insets are two specific vector eigenmodes (radially and azimuthally polarized modes). (c), Relative refractive index profile of the MMF.](image)

Moreover, we also demonstrate the MMF transmission seeded by the CV beam laser. As shown in
Fig. S11c, the graded-index MMF has a 50-μm core diameter and 125-μm cladding diameter. The relative refractive index between the core and the cladding is about 1% at 1345 nm.

7. Additional Results for Data-Carrying Fiber Transmission Seeded by High-Speed Directly-Modulated CV Beam Lasers

The measured BER curves for 8 and 12 Gbit/s signal transmission as a function of the received optical power are shown in Fig. S12, which are obtained with the bias of 30 mA for the CV beam laser with a radius of 15 μm. We also demonstrate 8 and 12 Gbit/s signal transmission through both LCF and MMF. The power penalty for 8 and 12 Gbit/s LCF vector eigenmode transmission is assessed to be 0.5 dB and 1.3 dB at a BER of 1.5×10⁻². The power penalty for 8 and 12 Gbit/s MMF transmission is 2.7 dB and 5.5 dB, respectively.

Figure S12. Additional data transmission results. Measured BER curves for 8 and 12 Gbit/s signal transmission through a 2-km LCF and 120-m MMF seeded by the integrated CV beam laser. Back-to-back BER performance is also shown for reference.

8. Comparison among Different Schemes of Active Integrated Vector Beam Laser

We make a detailed comparison among four different schemes of active integrated vector beam
laser, including spiral phase plate (SPP) assisted vertical-cavity surface-emitting laser (VCSEL), parity-time symmetrical microring resonator (MRR) laser, monolithically integrated vortex emitter assisted distributed feedback laser (DFB), and our work of high-speed directly-modulated vector beam laser. As listed in Tab. S1, the designed, fabricated and demonstrated laser in this work is the first high-speed directly-modulated vector beam laser. It is electrically pumped and based on the planar semiconductor technology. It shows relatively low threshold, high SMSR, high efficiency and high-speed direct modulation.

Table S1 | Detailed comparison among different schemes of active integrated vector beam laser.

<table>
<thead>
<tr>
<th>Schemes</th>
<th>Metrics</th>
<th>Pumping Method</th>
<th>Threshold Power</th>
<th>High-Speed</th>
<th>SMSR</th>
<th>Wavelength</th>
<th>Polarization</th>
<th>Planar Semiconductor Technology</th>
<th>Intrinsic Vector Beam Lasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCSEL*31</td>
<td>Electrically</td>
<td>1 mA</td>
<td>4 mW</td>
<td>No</td>
<td>N.A.</td>
<td>860 nm</td>
<td>Not stable</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>MRR30</td>
<td>Optically</td>
<td>1 GW/m²</td>
<td>N.A.</td>
<td>No</td>
<td>40 dB</td>
<td>1474 nm</td>
<td>Radially</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DFB32</td>
<td>Electrically</td>
<td>51 mA</td>
<td>0.3 mW</td>
<td>No</td>
<td>45 dB</td>
<td>1544 nm</td>
<td>Radially</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>This work</td>
<td>Electrically</td>
<td>12 mA</td>
<td>1.05mW</td>
<td>Yes</td>
<td>50 dB</td>
<td>1344 nm</td>
<td>Radially</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* The emission is vortex beam carrying orbital angular momentum but not a vector beam.