Orbital angular momentum vertical-cavity surface-emitting lasers: supplementary information

HUANLU LI,^{1,2} DAVID B. PHILLIPS,^{3,4,*} XUYANG WANG,¹ YING-LUNG DANIEL HO,¹ LIFENG CHEN,¹ XIAOQI ZHOU,³ JIANGBO ZHU,⁵ SIYUAN YU,^{1,5} XINLUN CAI,^{5,*}

¹ Department of Electrical and Electronic Engineering, University of Bristol, University Walk, Bristol, BS8 1TR, UK

² School of Engineering, Rankine Building, Oakfield Avenue, University of Glasgow, Glasgow G12 8LP, UK

³ H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

⁴ Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

⁵ State Key Laboratory of Optoelectronic Materials and Technologies and School of Physics and Engineering, Sun Yat-sen University, Guangzhou 510275, China

*Corresponding author: caixlun5@mail.sysu.edu.cn, david.phillips@glasgow.ac.uk

Published 4 June 2015

This document provides supplementary information to “Orbital angular momentum vertical-cavity surface-emitting lasers,” <http://dx.doi.org/10.1364/optica.2.000547>. In section 1, we provide information on the performance of the unmodified VCSEL device. In section 2 we describe in detail the steps required to fabricate the SPPs on top of the VCSEL devices. In section 3 we provide more information on how the numerical model of the modified VCSEL emission was implemented, and in section 4 we describe how the simulated spectra of the fields produced by the modified VCSELs were measured. © 2015 Optical Society of America

<http://dx.doi.org/10.1364/optica.2.000547.s001>

1. Characterization of the Single Mode Linearly Polarized VCSEL Device

Figure S1 shows the SEM image of the VCSEL device. The size of the VCSEL is $200 \times 200 \mu\text{m}$ with the contact pad in a size of $100 \times 100 \mu\text{m}$. The inset figure enlarges the emitting area where the nano-grating leads to the linear polarized output beam.

Fig. S1. SEM images of the VCSEL device.

Figure S2 plots the L-I characteristics of the emission beam from the VCSEL device under room-temperature continuous-wave (CW) operation. The typical threshold current of the device is 1 mA and the maximum output power can achieve 4 mW with laser current of 6 mA. The emission beam diameter was measured to be about $8 \mu\text{m}$ (see the inset), which was characterized by the width of the 99% drop in power intensity. The typical operating wavelength is between 860-861 nm. The polarization state of the emission beam is characterized ($I=2 \text{ mA}$) in Fig. S3 with an extinction ratio of 13 dB.

Fig. S2. L-I characteristics of the VCSEL device. The inset is the intensity profile of the emission beam.

Fig. S3. The output power measured through a polarization filter as a function of its angle.

2. Fabrication of SPPs

The fabrication of SPPs has been achieved in various materials, such as quartz[1], [2], photoresists[3], [4]. In order to produce a nano-scale structure on the VCSEL device, we introduce a new approach to fabricating the SPP, by the etching of a silicon nitride film with a Focused Ion Beam (FIB). The VCSEL device on the gold substrate was mounted on an alignment stage in a chamber kept under high vacuum condition ($<7 \times 10^{-6}$ mbar). Loading the designed etching pattern into the system by a string file, the Si_3N_4 film was etched with a beam current of 70 pA and a gallium ion beam energy of 30keV. During the FIB etching process, the magnification was set as 10 kX to improve the etching resolution, yielding an ion beam size of approx. 20-30 nm in diameter.

The optical axis of the fabricated SPP and the VCSEL device have to be aligned as closely as possible. Any misalignments between these axes will lead to a spread of the OAM mode into neighbouring modes[5]. This is a factor which has been taken good care of during our fabrication process. In our FIB system, the magnification was set as 10 kX, yielding a transverse overlay accuracy of less than 20 nm. This accuracy can be further improved to be less than 10nm, by using marker registration technique. The resolution with which we can fabricate the phase steps places a limit on the OAM mode. Therefore we estimate that the maximum OAM order achievable with this technique will be in the range $l = 8 - 10$, before the resolution by which the steps can be defined in the middle of the SPP prohibits their creation.

Figure S4 shows the fabrication process followed to etch the integrated SPP onto the VCSEL. The device is mounted on a gold substrate that serves as the n-contact of the VCSEL as well as for mechanical support and heat dissipation, as shown in Fig. S4a. The device is then coated with a $1\mu\text{m}$ thick Si_3N_4 (Silicon Nitride) layer (shown in Fig. S4b) using plasma enhanced chemical vapour deposition (PECVD). The silicon nitride is a transparent dielectric material that is etched to varying thicknesses in order to create the SPP. The p-contact must be exposed for wire bonding in a later step, and so ideally only the VCSEL aperture needs to be coated in Silicon Nitride. In order to achieve this, once the entire top surface of the device has been coated in a Silicon Nitride layer, the VCSEL aperture alone is then manually coated with LOR 1813 photoresist (Fig. S4c). This then serves as a mask in the following reactive ion etching (RIE) process, which leaves the VCSEL aperture coated in Silicon Nitride as shown in Fig. S4d. FIB etching is then performed on the Silicon Nitride to structure the multi-level SPP over the VCSEL aperture (Fig. S4e). The etching depth and the size can be well controlled by the FIB etching. In our case, the pattern size is $8.5\mu\text{m}$ in diameter in accordance with the size of the aperture and the total etched depth is 836 nm as described in the text. After the etching, a wire bond is made to the bond pad, as pictured in Fig. S4f.

Figure S5 shows SEM images and schematics of the etched SPPs, with topological charges from $l=-3$ to $l=3$. As can be observed from these images the fabricated SPPs are nearly identical with the designed structures.

3. Numerical Simulations

Numerical simulations were carried out in order to validate the SPP design. The field at the plane of the SPP was approximated as a Gaussian amplitude with a phase distribution represented by the 8 stepped SPP. This field was then numerically propagated to a distance equivalent to 10 times the Rayleigh range (an approximation to the farfield) of the Gaussian beam, using the Fresnel diffraction integral. The amplitude and phase of the resulting beam at the new plane are then shown.

4. Overlap Integral Method to Determine Theoretical Beam Purity

The overlap integral was numerically calculated between the simulated farfield intensity distributions, and Laguerre-Gaussian modes of azimuthal index (topological charge) $l = -20$ to $l = 20$, and radial index $p = 0$ to $p = 12$. Assuming there is negligible power found in modes outside this range, we normalised all of the powers relative to the total power measured within this range. We then summed the power found in all modes p for a specific l to calculate each bar of the OAM spectrum.

Fig. S4. Fabrication processing of SPP on a VCSEL: (a) device mounting, (b) Si_3N_4 layer deposition, (c) covering the aperture with a photoresist, (d) Si_3N_4 etching (RIE), (e) SPP etching (FIB) and (f) wire bonding.

Fig. S5. The SEM images and Schematic pictures of the integrated SPPs.

References

- [1] V. V. Atuchin, S. L. Permyakov, I. S. Soldatenkov, and F. A. Starikov, "Kinoform generator of vortex laser beams," in *International Conference on Lasers, Applications, and Technologies 2005: Advanced Lasers and Systems* (2005), p. 60540P-4.
- [2] G. A. Swartzlander, Jr., "Achromatic optical vortex lens," *Opt. Lett.* **31**, 2042 (2006).
- [3] M. W. Beijersbergen, R. P. C. Coerwinkel, M. Kristensen, and J. P. Woerdman, "Helical-wavefront laser beams produced with a spiral phaseplate," *Opt. Commun.* **112**, 321-327 (1994).
- [4] V. V. Kotlyar, A. A. Almazov, S. N. Khonina, V. A. Soifer, H. Elfstrom, and J. Turunen, "Generation of phase singularity through diffracting a plane or Gaussian beam by a spiral phase plate," *J. Opt. Soc. Am. A* **22**, 849-61 (2005).
- [5] M. V. Vasnetsov, V. A. Pas'ko, and M. S. Soskin, "Analysis of orbital angular momentum of a misaligned optical beam," *New J. Phys.* **7**, 46-46 (2005).