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High power two-color orbital angular momentum beam generation using vertical external cavity surface emitting lasers

Michal L. Lukowski,^{1,2} Chris Hassenius,^{1,2} Jason T. Meyer,¹ Ewan M. Wright,¹ and Mahmoud Fallahi¹

¹College of Optical Sciences, The University of Arizona, 1630 E. University Blvd., Tucson, Arizona 85719, USA

²TPhotonics Inc., 489 E. Placita Boton, Sahuarita, Arizona 85629, USA

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We report the design and experimental results for a two-chip T-cavity vertical external cavity surface emitting laser utilized for two-color collinear generation of Hermite-Gaussian and Laguerre-Gaussian (LG) transverse modes. A combination of intracavity mode-control elements and an external astigmatic mode converter was used to achieve high power LG modes. By incorporating intracavity birefringent filters in each arm of the T-cavity, wide wavelength tuning in excess of 12 nm of each mode is demonstrated. Output power exceeding 1.5 W is measured for all the modes.

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Laser sources producing higher-order Hermite-Gaussian (HG) or Laguerre-Gaussian (LG) modes have attracted significant interest due to their broad range of applications. Both axially and circularly symmetric beams can be utilized in atom and microparticle trapping,^{1–4} manipulation of biological cells,⁵ light-atom interactions,⁶ and nonlinear optics.⁷ The higher-order modes have been demonstrated previously in microlasers,⁸ optically pumped solid state lasers,^{9,10} and spatially structured vertical cavity surface emitting lasers,^{11,12} by utilizing spiral phase plates¹³ or by altering HG modes with astigmatic mode converters (AMCs).¹⁴ However, low output power and/or large device size can limit the wide-usage of these structures.

Vertical External Cavity Surface Emitting Lasers (VECSELs) have been extensively studied as laser sources capable of generating multi-watt output power over a wide spectral range, while maintaining TEM₀₀ transverse mode¹⁵ operation. The most widely used VECSEL structure is the GaAs/InGaAs compound semiconductor, which provides gain for emission in the 900–1200 nm wavelength range. This structure led to achieving remarkable results in output power,¹⁶ wavelength tunability,¹⁷ and pulse generation.^{18,19} Also, the modifications to the gain region design were utilized to enable two-color emission from a single chip at ~967 nm and ~1080 nm.²⁰ To date, the research on VECSELs was mainly focused on power-scaling or short-pulse generation at various wavelengths. However, the use of VECSELs for generation of higher-order LG modes carrying orbital angular momentum (OAM) beams has not been explored.

The two-color T-cavity VECSEL developed by our group is a modification of conventional VECSEL cavities, simultaneously allowing for the generation of high-power two-color coaxial emission and a broad-range of wavelength generation through intracavity nonlinear sum or difference frequency conversion.^{21,22} In this paper, we report the demonstration of higher-order HG and LG modes in a two-color T-cavity VECSEL geometry.²³ By combining intracavity mode-control elements (MCEs) with external astigmatic mode converters (AMCs), a wide range of HG and LG mode

pairs are demonstrated. A mode control element inserted into each resonator introduces a localized loss in the transverse field, thus allowing us to obtain a variety of HG modes for both wavelengths. With the addition of an AMC, various LG modes for each color are generated, while maintaining the high output power and wavelength tuning properties of each cavity.

The separate VECSEL chips used in this experimental setup were fabricated from two different wafers with strain-compensated InGaAs/GaAs/GaAsP multi-quantum-well (MQW) heterostructures designed for emission at ~970 nm and ~1070 nm. A metal oxide chemical vapor deposition process was utilized to grow the wafer in a “bottom-emitting” manner such that the active region precedes a distributed Bragg reflector (DBR) on a GaAs substrate. To maximize the gain, in both structures, the composition and thickness of the gain region are carefully chosen such that each quantum-well (QW) is positioned at the antinode of the resonator standing wave—a design known as resonant periodic gain. While both structures have active regions consisting of 12 compressively strained 8 nm thick InGaAs QWs with pump absorbing GaAs barriers and GaAsP layers between each QW for strain compensation purposes, the semiconductor composition slightly varied between the ~970 nm and ~1070 nm wafers. Similarly, the design of the DBR stack consisting of 25 pairs of alternating AlGaAs/AIAs was adjusted to achieve high reflectivity (~99.9%) for each wavelength.

Before being fully operational, cleaved VECSEL chips need to be fabricated to facilitate optimal thermal management to achieve efficient lasing. A chemical vapor deposition diamond and a VECSEL chip are coated with Ti/Au layers and then indium solder bonded together. The removal of the GaAs substrate using selective chemical wet etching guarantees an optically flat surface of a finished bonded chip. Upon fabrication completion, the chips are mounted and clamped to water-cooled copper heat sinks and maintained at a temperature of 15 °C.

The T-cavity setup, along with the astigmatic mode converter used for this experiment, is shown in Fig. 1. For the

first part of the experiment in which HG modes were generated, the AMC was not utilized. This VECSEL configuration has been described in detail in Ref. 23. Here, a dichroic mirror which was antireflection (AR) coated at ~ 970 nm and high reflectivity (HR) coated at ~ 1070 nm for an incident angle of $\sim 45^\circ$ allows us to have completely independent laser cavities, which share the same output coupler mirror and produce collinear beams. Thus, each resonator can contain a separate intracavity birefringent filter (BF) and a mode control element. While the BFs allow for independent wavelength tuning and polarization control based on BF orientation, the MCE enables laser operation with higher order transverse modes. The MCE was made of a fused silica transparent substrate, which was selectively etched to provide a pattern, which had the least loss for a targeted HG mode, while increasing losses for non-desired HG modes. The 3 mm thick BF was inserted at Brewster's angle and oriented to favor an s-polarized field in the ~ 970 nm cavity, and the second BF of the same thickness was aligned such that a p-polarized field was circulating in the ~ 1070 nm resonator. Thus, a two-color individually tunable output with orthogonally polarized beams was obtained although if required the light could be of the same polarization. Since the MCEs were placed between the chips and the dichroic mirror, each cavity could produce a different transverse mode. Two 808 nm pump diodes were fiber-coupled and refocused to $\sim 500 \mu\text{m}$ onto each VECSEL chip to provide optical pumping. The shared output coupler mirror had a radius of curvature of 25 cm and was broadband coated to be $\sim 97\%$ reflective within the 900–1200 nm range. Considering the total distance from the chip to the output coupler, both cavities were ~ 23 cm long.

For the second part of the experiment, the external astigmatic mode converter was added and aligned with the T-cavity VECSEL. The AMC is based on a pair of identical cylindrical lenses, where distance d between them depends on their focal length f ²⁴

$$d = \frac{2f}{\sqrt{2}}. \quad (1)$$

Here, the focal length of the cylindrical lenses was 30 mm, thus resulting in a separation distance of 42 mm. Moreover, for correct mode conversion, the incoming laser beam has to be of a certain Rayleigh range Z_R

$$z_R = \left(1 + \frac{1}{\sqrt{2}}\right)f \quad (2)$$

and its beam waist has to be positioned in the center between those two lenses.²⁴ For this purpose, a spherical lens with a focal length of 150 mm was placed before the cylindrical lenses. Based on the Rayleigh range of the lasing transverse modes supported by the T-cavity resonator, the required distances were calculated to be as follows: the distance from the output coupler mirror to the spherical lens was ~ 88 mm and the distance from the spherical lens to the nearer cylindrical lens was ~ 250 mm. Finally, the incoming HG mode symmetry axis has to be oriented diagonally at 45° with respect to the curvature axis of the cylindrical lens, and thus, the MCEs were adjusted accordingly. The spherical lens and cylindrical lenses were AR coated at 900–1200 nm, and thus, the loss introduced by the AMC is minimal and $<0.5\%$.

To confirm that the T-cavity provides simultaneous two-color collinear beams, the output was fiber coupled into an optical spectrum analyzer (OSA). By rotating the BFs, the spectral tuning range of each sample was examined. While each chip has been tuned individually to acquire wavelength spectra within a narrower scale on the OSA to increase the measurement resolution, the simultaneous tuning with both BFs is feasible. Figures 2(a) and 2(b) present the tunability for the ~ 970 nm and ~ 1070 nm chips, respectively. In both cases, the tuning range was ~ 12 nm, while the spectral line-width was maintained below 0.5 nm. Since the BFs do not depend on the MCEs, these tuning results remain valid for all the HG and LG modes generated throughout the experiment. Moreover, the tuning range could be enhanced, by utilizing chips with a spectrally broad gain region. Previous works have demonstrated VECSELs tunable over 30 nm.²¹ The output power remained consistent and within 10% of the maximum power.

The output powers of fundamental and higher order transverse modes generated in the T-cavity VECSEL were measured and characterized as shown in Fig. 3. Since the AMC setup did not introduce any significant loss, the measured power of HG modes (before the AMC) and LG modes (after the AMC) is considered approximately equal. The fundamental TEM_{00} maximum output powers were ~ 3.6 W and ~ 4 W for ~ 970 nm and ~ 1070 nm chips, respectively. The HG_{01} mode and the converted LG_{01} mode from the ~ 970 nm chip had a maximum power of 2.65 W. With the use of

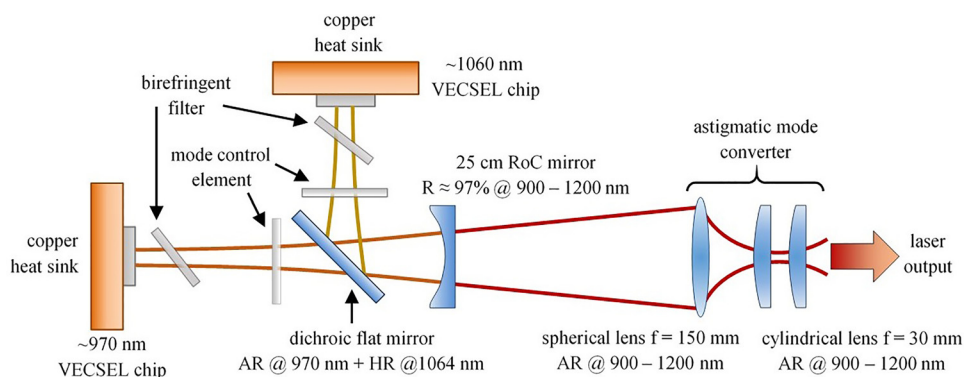


FIG. 1. Schematic of the linear T-cavity VECSEL with an external astigmatic mode converter.

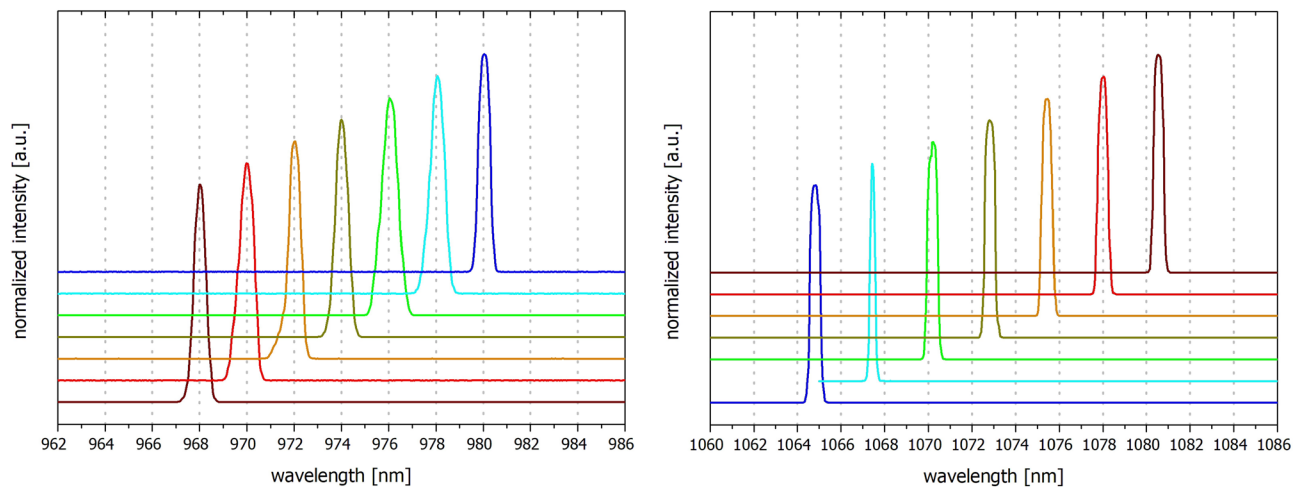


FIG. 2. The tuning spectra obtained with BFs for both (a) ~ 970 nm and (b) ~ 1070 nm chips.

MCE, the ~ 1070 nm cavity generated HG_{01} and HG_{11} modes delivering maximum powers of ~ 3.4 W and ~ 1.8 W, respectively. The output powers of the corresponding LG_{01} and LG_{10} modes were the same. The output power for the higher order modes is smaller compared to the fundamental Gaussian beam output due to the small amount of loss introduced by the MCEs. Additionally, in the current experimental configuration, the pump spot size remained fixed for all the modes, and thus, there was less gain provided to higher order modes. A combined pair of HG modes (without AMC) or LG modes (with AMC) from the ~ 970 nm and ~ 1070 nm chips was collinear. Thus, the total output power from the T-cavity is the sum of the individually measured powers.

The images of various transverse modes were captured using a CCD camera. To get clear profiles of the separate HG and LG modes, we first captured the images when only one chip was lasing. Figure 4 presents the images of these beams. The diagonal HG_{01} beams (left) from ~ 970 nm and ~ 1070 nm chips were converted to LG_{01} modes (right), respectively. Also, the ~ 1070 nm HG_{11} mode was obtained and converted to the LG_{10} mode. In order to confirm the purity of the generated LG_{01} mode, we observed the interference of the beam with a spherical reference wave. Figure 4(c)

shows the spiral intensity interference pattern, as suggested in Ref. 13. Based on these images, it is noticeable, that the HG modes were of good quality and the AMC worked properly in generating true LG modes. To demonstrate that the laser beams from both VECSEL samples are collinear, the images of overlapping modes were taken as well. Figure 4(e) shows the ~ 970 nm and ~ 1070 nm LG_{01} mode lasing simultaneously when they are collinear (left) as well as the case when they are displaced with respect to each other (right). Thus, a good overlap between these two modes can be achieved, while the possibility to adjust the relative position between them still exists if required for certain applications. The wavelength separation and intensity of those two transverse modes can be individually adjusted as well.

In conclusion, we reported on the design and experimental results of a two-color collinear T-cavity VECSEL which was utilized to generate a variety of Hermite-Gaussian modes at ~ 970 nm and ~ 1070 nm, with the capability to spectrally tune both these wavelengths individually. An astigmatic mode converter was designed and aligned externally to the T-cavity, and so, the HG modes could be converted to Laguerre-Gaussian modes. All the higher order transverse modes delivered Watt-level output power and were of high quality. This laser can be further optimized and power scaled to achieve higher output power or broader tuning, if desired. The mode control element for different HG modes can be fabricated by different methods, including conventional microfabrication techniques on transparent substrates. This can include patterning of the structured features by photolithography and dry etching. Using this method, the generation of higher order LG modes can also be obtained via the same AMC by using the MCE to generate higher-order HG modes.²⁵ Finally, due to the VECSEL open cavity design, the AMC can be incorporated into the laser resonator itself. Obtaining high-power circulating LG modes could be of great interest because it could open the path to producing circularly symmetric transverse modes at other wavelengths by means of nonlinear frequency conversion. The currently limited availability of higher order transverse modes in spectral regions such as UV, visible, or mid-IR could be expanded. Thus, this laser, thanks to its flexibility and customization, can be implemented when beams with particular orbital

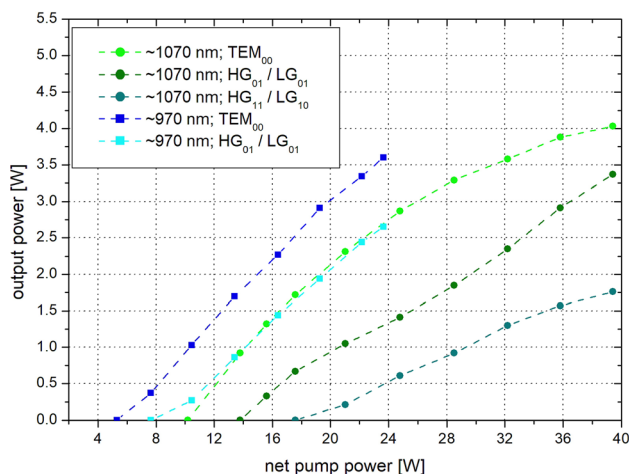


FIG. 3. The output power for various transverse modes generated in the T-cavity VECSEL.

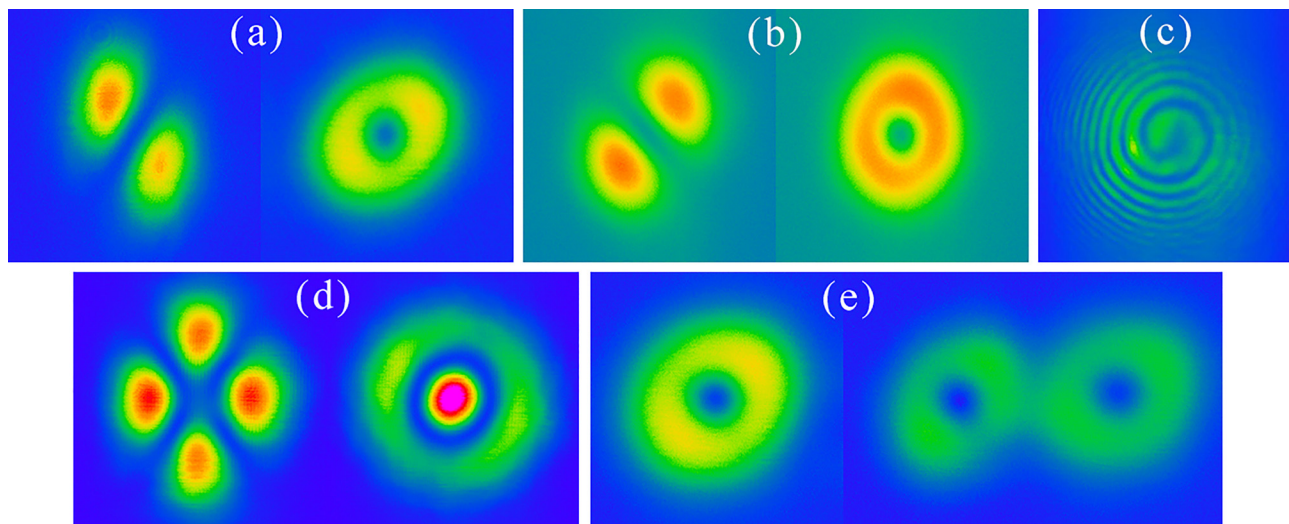


FIG. 4. Beam profiles of various higher order modes: (a) ~ 970 nm chip HG_{01} and LG_{01} , (b) ~ 1070 nm chip HG_{01} and LG_{01} , (c) spiral interference pattern of the LG_{01} mode with a spherical reference wave, (d) ~ 1070 nm chip HG_{11} and LG_{10} , and (e) overlapped (left) and displaced (right) LG_{01} modes from ~ 970 nm and ~ 1070 nm chips.

angular momentum are required for applications such as atom and particle manipulation.

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