# High-Power Higher Order Hermite–Gaussian and Laguerre–Gaussian Beams From Vertical External Cavity Surface Emitting Lasers

Michal L. Lukowski, Jason T. Meyer, Chris Hessenius, Ewan M. Wright, and Mahmoud Fallahi

***Abstract*—We report a vertical external cavity surface emitting laser (VECSEL) with an optical pumping scheme for the generation of higher order Hermite–Gaussian transverse modes. The VECSEL chip with emission around 1068 nm in a linear cavity configuration is capable of delivering a variety of higher order modes with Watt-level output power. A very good agreement between the modeling and experimental results validate the ideas underpinning the method. Additionally, simultaneous lasing of two independent and collinear transverse modes from a single laser cavity is demonstrated. An external astigmatic mode converter is finally utilized for the conversion of Hermite–Gaussian modes into corresponding Laguerre–Gaussian modes.**

***Index Terms*—Vertical external cavity surface emitting lasers, Hermite-Gaussian beam, Laguerre-Gaussian beam, multiple optical pumping.**

## I. Introduction

LASER sources delivering higher-order Hermite-Gaussian (HG) or Laguerre-Gaussian (LG) transverse modes have been of increasing interest for a wide range of applications. Especially, higher-order LG modes gather increased attention thanks to their capability to carry orbital angular momentum. Atom and microparticle trapping [1]–[4], light-atom interactions [5], nonlinear optics [6] and biological cells manipulation [7] can be achieved by using axially or circularly symmetric laser beams. Such higher-order modes have been previously demonstrated in optically pumped solid-state lasers [8], [9], microlasers [10], spatially structured vertical cavity surface emitting lasers [11], [12], surface-emitting lasers with an integrated intra-cavity all-dielectric meta-surface [13], by use of spiral phase plates [14] or astigmatic mode converters (AMC) [15]. Most recently, vertical external cavity surface emitting lasers have been utilized to produce higher-order HG modes by use of an intracavity mode control element [16], [17].

Manuscript received February 4, 2019; revised March 7, 2019; accepted March 14, 2019. Date of publication March 27, 2019; date of current version April 12, 2019. This work was supported by the ECCS Division of National Science Foundation Award 3024880. *(Corresponding author: Michal L. Lukowski.)*

M. L. Lukowski and C. Hessenius are with the College of Optical Sciences, University of Arizona, Tucson, AZ 87521 USA, and also with the TPhotonics Inc., Sahuarita, AZ 85629 USA (e-mail: mlukowski@optics.arizona.edu; chessenius@optics.arizona.edu).

J. T. Meyer, E. M. Wright, and M. Fallahi are with the College of Optical Sciences, University of Arizona, Tucson, AZ 87521 USA (e-mail: jtmeyer@email.arizona.edu; ewan@optics.arizona.edu; fallahi@optics.arizona.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSTQE.2019.2906256

For over the past couple of decades, optically pumped vertical external cavity surface emitting lasers have been widely studied and proven to be a reliable laser source delivering high brightness and high output powers over a wide spectral emission range [18]. The flexibility of semiconductor gain structures allowed for lasing operation in visible, near infrared and mid-infrared spectral regions [19], [20]. The open cavity design provided opportunities to achieve outstanding results in wavelength tunability [21], pulse generation [22] and nonlinear frequency conversion [23]. While in the above cases mostly the $TEM_{00}$ mode is being used, our team recently started exploring VECSELs for generation of higher-order HG and LG modes [16], [17].

Previously, we utilized an intracavity mode control element to introduce a loss for a non-desired HG mode, thus favoring a targeted higher-order transverse mode. Here, we propose a different approach using a flexible pumping control to efficiently generate various HG modes. An empty linear cavity consisting of an output coupler curved mirror and VECSEL chip with emission ~1068 nm along with multiple optical pumps focused onto a chip is used. The position of the focused pump spots, with respect to the center of curvature of the output coupler mirror, allows for the control of the lasing transverse mode. In this scheme, there is no loss inside the laser resonator, and gain provided by optical pumping is efficiently utilized to obtain a desired higher-order HG mode. Very good agreement between the modeling and experiment is reported. Moreover, this laser is capable of operating simultaneously with two independent and collinear transverse modes. The higher-order lasing output is directed into an astigmatic mode converter to obtain corresponding LG modes. All of the demonstrated transverse modes reach Watt-level output powers.

## II. VECSEL Gain Structure, Fabrication and Linear Cavity

For this experiment a chip from a VECSEL wafer with strain-compensated InGaAs/GaAs/GaAsP multiple quantum well (MQW) heterostructure designed for emission at ~1068 nm was used. It consisted of 12 compressively strained 8 nm thick InGaAs QWs with pump absorbing GaAs barriers and GaAsP layer between each QW for strain compensation purposes. A distributed Bragg reflector (DBR) stack consisted of 25 pairs of alternating AlGaAs/AlAs layers provided high reflectivity

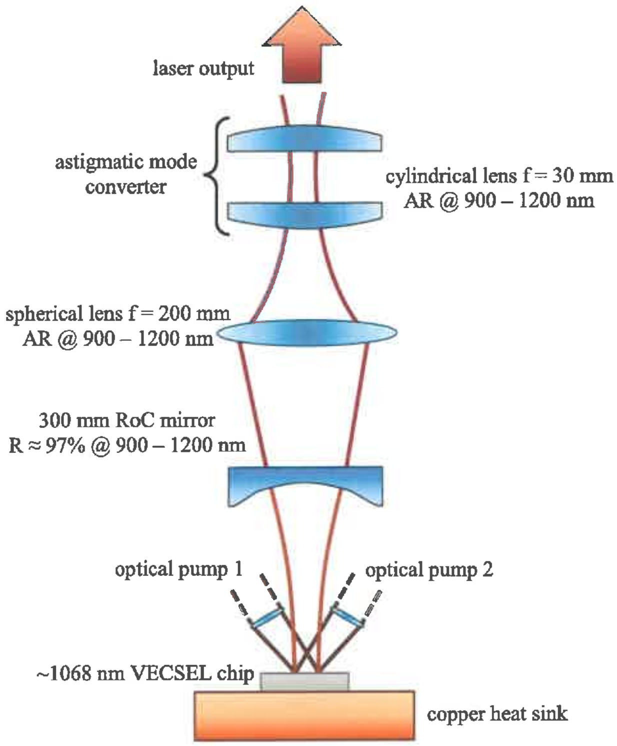


Fig. 1. Schematic of two optical pumps linear cavity VECSEL with external astigmatic mode converter.

($\sim$99.9%) at the emission wavelength. The wafer heterostructure was grown by the means of Metal Oxide Chemical Vapor Deposition process as a "bottom emitter", such that the active region is grown first on a GaAs substrate, then followed by the DBR layer. The composition and thickness of the gain region was designed such that each QW is positioned at the antinode of the cavity standing wave, thus allowing it to take advantage of resonant periodic gain.

The optimal thermal management is crucial to achieving efficient lasing, thus the VECSEL chip has to be fabricated before being fully operational. Used as a heat spreader, chemical vapor deposition diamond and a chip were coated with Ti/Au layers and indium solder bonded together. The GaAs substrate was removed by selective chemical wet etching, which resulted in optically flat surface of a bonded chip. Ref. [24] provides a detailed description of fabrication process. A finished chip was mounted and clamped to a water-cooled copper heat sink and maintained at a temperature of 10 °C.

The VECSEL linear cavity with an external astigmatic mode converter is presented in Fig. 1. A 300 mm radius of curvature and 97% reflective output coupler mirror was placed $\sim$270 mm away from the $\sim$1068 nm chip, determining a beam waist diameter of the fundamental Gaussian mode to be $\sim$340 $\mu$m. Two $\sim$808 nm pump diodes were fiber-coupled and refocused to $\sim$380 $\mu$m diameter spot sizes on the chip. When both pumps were placed in the "center" (with respect to the center of curvature of the output coupler mirror), only the $HG_{0,0}$ transverse mode was supported by the gain provided from optical pumping. When the pumps were displaced from the "center" position by a certain distance, and the output coupler mirror remained fixed, the higher order $HG_{m,n}$ modes could be induced. Thus, this VECSEL setup provided lasing outputs with Hermite-Gaussian transverse mode profiles, which then were converted to Laguerre-Gaussian beams by use of an astigmatic mode converter. Two identical cylindrical lenses with focal length of 30 mm were used as AMC. The distance $D$ between pair of these lenses is dependent on their focal lengths $f$ as follows [15]

$$D = \frac{2f}{\sqrt{2}} \tag{1}$$

thus, it resulted to be $\sim$42 mm. Additionally, for proper mode conversion, the incoming HG mode has to be refocused to a certain Rayleigh range $z_R$, where

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

and its beam waist positioned in the center between the pair of cylindrical lenses [15]. To ensure these conditions and based on the Rayleigh range of the incoming HG mode, a 200 mm focal length spherical lens was chosen, and appropriate distances were calculated. This lens was placed $\sim$180 mm behind the output coupler mirror, and $\sim$390 mm in front of the first cylindrical lens of the AMC. Finally, because the incoming HG mode axis of symmetry has to be oriented diagonally at 45° with respect to the curvature axis of the cylindrical lens, the pair of lenses in the AMC was rotated accordingly. The Laguerre-Gaussian mode orders $LG_p^l$, when obtained via AMC, are correlated to Hermite-Gaussian mode orders $HG_{m,n}$ as $l = |n - m|$ and $p = \min(m, n)$ [25]. All of the lenses were antireflection coated at $\sim$1068 nm, therefore the total loss introduced by the AMC was minimal and smaller than 0.5%.

## III. Modelling of Higher-Order Hermite-Gaussian Modes in VECSEL Linear Cavity

In our model the chip acts as a flat reflector and the cavity is formed along with a curved mirror of radius of curvature $R$, a distance $d$ from the chip. By virtue of the optical pumping, the chip imparts gain to the circulating field that varies in the transverse $(x, y)$ plane perpendicular to the cavity axis $z$. We allow for two pump beams of identical transverse profile that are symmetrically displaced with respect to the cavity axis, and write the spatially dependent gain as

$$g(x,y) = g_1 \exp\left[-\frac{(x - L_x)^2}{w_{px}^2} - \frac{(y - L_y)^2}{w_{py}^2}\right] + g_2 \exp\left[-\frac{(x + L_x)^2}{w_{px}^2} - \frac{(y + L_y)^2}{w_{py}^2}\right] \tag{3}$$

where $w_{px}$ and $w_{py}$ are the pump spot sizes along their respective directions, and $L_x$ and $L_y$ the corresponding displacements of the pump beam centers. The quantity $g(x, y)$ is the gain length product for the chip induced by the pump beams, and $g_{1,2}$ denote the peak values for each beam. The net gain experienced by the circulating field after reflection of the chip is then

$G(x, y) = e^{g(x,y)}$. Adopting a reference plane above the chip in Fig. 1 and traveling into the external cavity, the wave optical equation describing successive round trips of the field in the cavity is given by

$$E_{n+1}(x, y) = rG(x, y)\hat{K}E_n(x, y) \quad (4)$$

where $\hat{K}$ is the Huygens integral operator for propagation around the external cavity [26], $n$ counts the round trips, and $r$ is the position independent field reflectivity of the output coupler mirror, which curvature matches the one of higher-order mode wavefront. Following the numerical approach of Endo for optically pumped lasers [27], we iterate Eq. (4) for an initial field $E_0(x, y)$ that is a transversely displaced copy of the Gaussian mode of the unpumped cavity, so that it is a superposition of a large number of cavity HG modes, and the iteration is continued until the field settles down to a steady-state field profile $E(x, y)$: This yields the spatial profile of the oscillating laser mode with maximum gain. Our later wave optical simulations will show the calculated mode intensity profile $|E(x, y)|^2$ for a variety of pump beam configurations. The passive cavity modes without gain may be expressed as $U_{m_x,m_y}(x, y) = u_{m_x}(x)u_{m_y}(y)$, with $u_m(s)$ Hermite-Gaussian functions with respect to the $x$ and $y$ axes, and mode indices $m_{x;y} = 0, 1, 2, \ldots$ [28]. These HG modes are based upon the passive cavity Gaussian spot size $w_0$ as evaluated at the chip.

The VECSELs described here have low mirror losses and as a result the required gains $g_{1,2} \ll 1$ are low. As a result, it is reasonable that, depending on the pump beam configuration, the lasing mode of highest gain may be approximated by one of the HG modes $U_{m_x,m_y}(x, y)$. This leads to the simple approximation for the spatially averaged modal gain

$$g_{m_x,m_y} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x, y)\left|U_{m_x,m_y}(x, y)\right|^2 dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left|U_{m_x,m_y}(x, y)\right|^2 dxdy} \quad (5)$$

which depends on the pump beam configuration via Eq. (1). As a concrete example, we consider the case of a single pump beam varying the pump displacement $L_y$ along the $y$-axis while keeping $L_x = 0$. For this case we kept $m_x = 0$ and calculated the modal gain for a given $L_y$ versus $m_y$ according to Eq. (3). The results are shown in Fig. 2 which shows the mode index $m_y$ of maximum modal gain as a function of beam displacement $L_y$. As expected physically, the trend is that as the pump beam displacement is increased, the oscillating laser mode of highest gain becomes an $HG_{0,m_y}$ beam of increasing mode index $m_y$. These results apply in the case of displacement in the $x-$direction as well, and are quite accurately reproduced by our wave-optical simulations, including the jumps in lasing HG mode with pump beam displacement. These results show the same qualitative trends as those previously presented for single pump beams [28], [29].

Fig. 3 shows an example with two equal-power pump beams ($g_1 = g_2$) with $L_x = 360$ $\mu$m and $L_y = 390$ $\mu$m, and the modal gain is shown as a function of both HG mode indices ($m_x$, $m_y$). For this example, the highest modal gain appears for the $HG_{6,7}$ mode, which displays the capability of the two pumps configuration for generating a rich set of HG modes. We note that the generation of Hermite-Gaussian modes with variable ($m_x$, $m_y$) in our case is possible due to the two pump beams, in contrast to the arrangement in Ref. [28] where a single pump beam was used in conjunction with suitable positioning of an opaque wire.

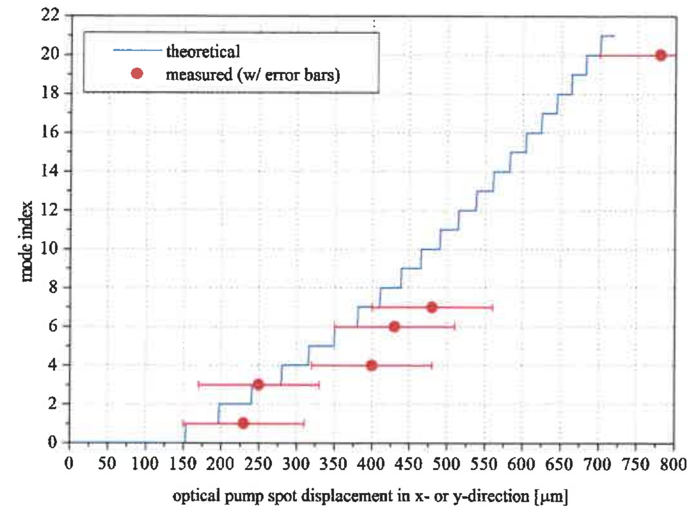


Fig. 2. The mode index $m_y$ of maximum modal gain as a function of beam displacement $L_y$.

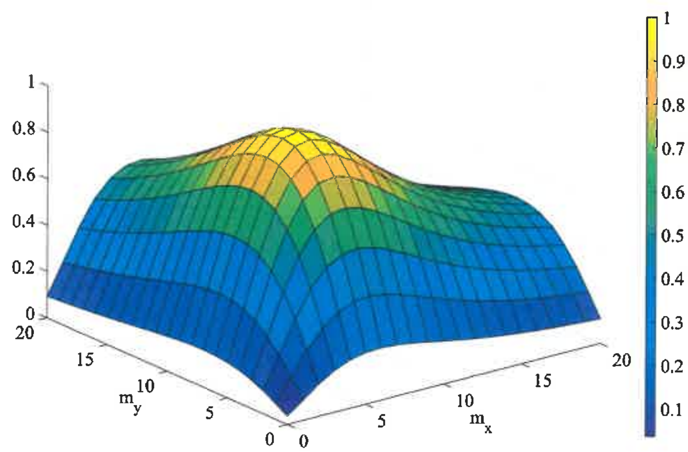


Fig. 3. An example with two equal-power pump beams ($g_1 = g_2$) with $L_x = 360$ $\mu$m and $L_y = 390$ $\mu$m, and the modal gain shown as a function of both HG mode indices ($m_x$, $m_y$), with its maximum for $HG_{6,7}$ mode.

In the following sections we shall refer to the above results of the simplified analysis in comparison to both the experimental results and also the wave optical simulations.

## IV. Experimental Results

A variety of optical pumps displacements were tested to demonstrate a broad range of obtainable higher-order Hermite-Gaussian modes. The output powers, optical spectra and images of transverse mode profiles were captured to demonstrate high quality of produced beams.

The displacement of the optical pumps with respect to the supported higher-order mode was measured using images of the VECSEL chip surface. Due to the low resolution of the used CCD camera, the error margin of these measurements was

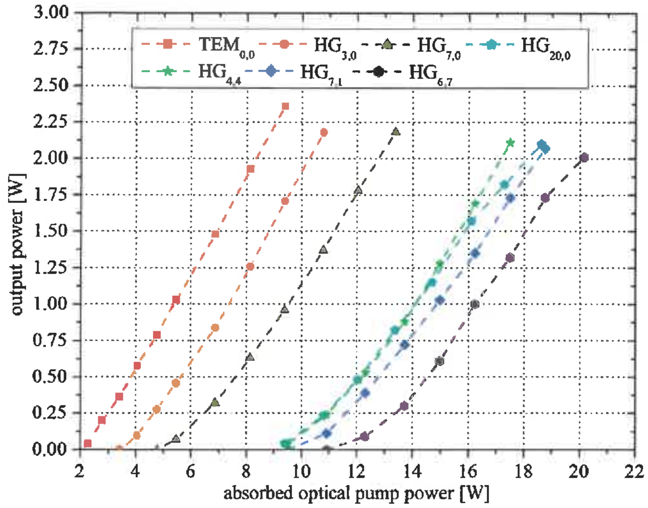


Fig. 4. The output power of high order Hermite-Gaussian (Laguerre-Gaussian) modes vs. absorbed optical pump power.

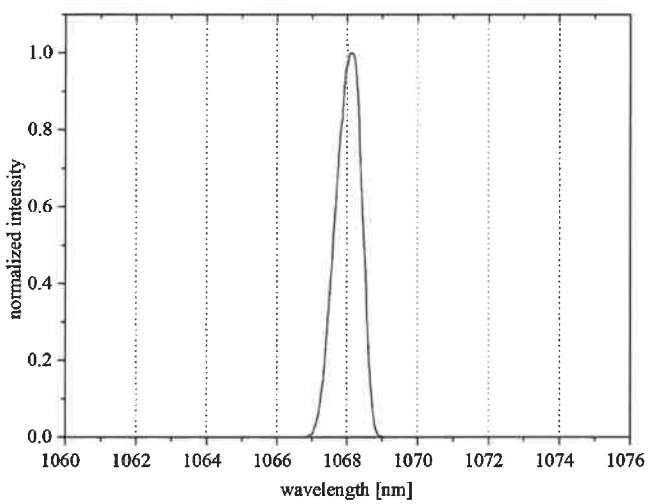


Fig. 5. The optical spectrum of a lasing mode.

estimated to be ∼80 $\mu$m. This data was plotted against the theorical curve previously shown in Fig. 2. Based on these results, it is noticeable that experiment is with good agreement with the calculated theoretical trend.

The output power characteristics for fundamental and higher order modes are compiled in Fig. 4. The measured powers of HG modes (before the AMC) and LG modes (after AMC) are considered equal, because the lenses used did not introduce any significant loss. The output power is plotted against the total absorbed optical pump power. The maximum output powers measured for $TEM_{00}$, $HG_{3,0}$, $HG_{7,0}$, $HG_{20,0}$, $HG_{4,4}$, $HG_{7,1}$, $HG_{6,7}$ and their LG mode counterparts were 2.36 W, 2.18 W, 2.18 W, 2.1 W, 2.11 W, 2.07 W and 2.01 W, respectively. Similarly, the optical spectrum for all the beams was captured using an optical spectrum analyzer and for all of the cases no significant spectral shift was observed due to the resolution limitations. The emission wavelength stayed around ∼1068 nm and a single spectrum is demonstrated in Fig. 5.

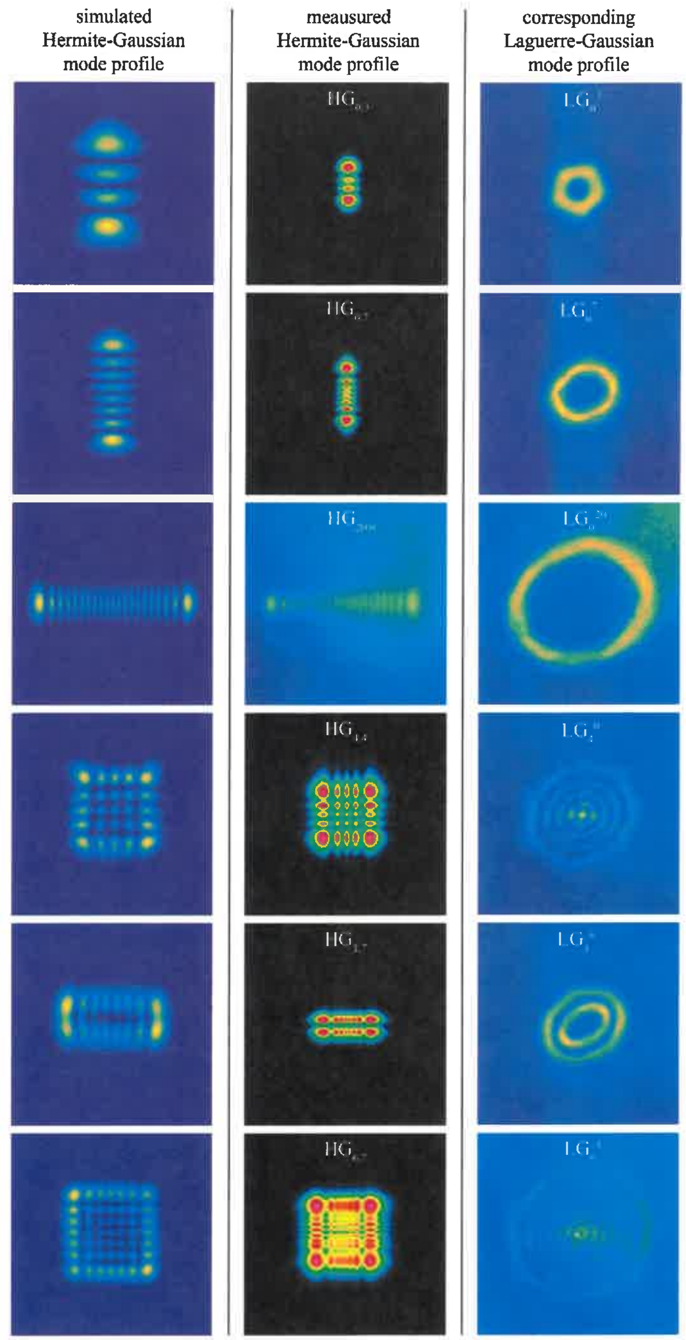


Fig. 6. Simulated and measured 2D profiles of various Hermite-Gaussian modes: $HG_{0,3}$, $HG_{0,7}$, $HG_{20,0}$, $HG_{4,4}$, $HG_{1,7}$ and $HG_{6,7}$, as well as their corresponding Laguerre-Gaussian modes after astigmatic mode converter.

In the case of the HG modes, a scanning-slit DataRay BeamMap2 beam profiler was used, whereas for LG modes a ThorLabs CCD camera was utilized to capture beam images. Fig. 6 showcases the diverse range of simulated HG modes along with their measured counterparts as well as their corresponding LG modes obtained by use of the AMC. The experimental profiles of HG modes clearly match the ones computed in simulation. Also, the images of HG and LG modes demonstrate their high quality and efficient conversion of axially symmetric

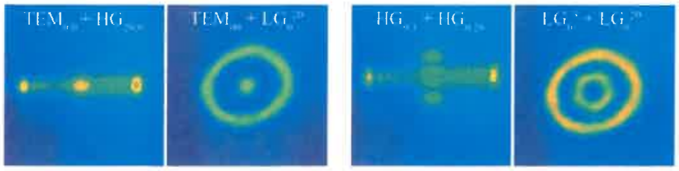

Fig. 7. Two optical pumps allow for independent, simultaneous and collinear HG modes lasing operation. Here, two cases are shown before (HG) and after AMC (LG).

modes into ones of circular symmetry. To further showcase the uniqueness of our VECSEL setup, a simultaneous operation of two different order transverse modes is presented in Fig. 7. By usage of two optical pumps, lasing of two independent modes is viable, which is not possible when using intracavity mode control elements. The order of the modes can be controlled independently by the displacement of each pump. Here, pairs of $TEM_{00}$ and $HG_{0,20}$ as well as $HG_{3,0}$ and $HG_{0,20}$ modes with their converted analogues are demonstrated. These beams were also collinear, clearly noticeable when looking at corresponding LG modes pairs. Such beams would not be obtainable by other means and do not have their single LG mode counterparts.

## V. Conclusion

In conclusion, we reported on the design, theoretical simulations and experimental results of a single-chip linear cavity VECSEL, which incorporates two optical pumps and no intracavity elements to generate a wide range of Hermite-Gaussian transverse modes at ∼1068 nm. An astigmatic mode converter was mode-matched to the linear laser resonator for efficient generation of Laguerre-Gaussian transverse modes. While the lasing threshold increased for higher-order modes, all of the beams delivered Watt-level output powers and their transverse profiles were of very high quality and matched the theoretical calculations. Only several higher-order modes were showcased, even though this configuration allows for smooth transition between many mode orders. The most unique feature of this VECSEL is the capability of lasing operation with two collinear, simultaneous and independent HG beams of different orders, which intensities can be controlled separately, which is not feasible by other means such as intracavity opaque wires. This allows for great flexibility of beam shaping, whether axially or circularly symmetric transverse modes are demanded. In case of beams carrying angular momentum, the $l$-number values can be precisely adjusted, which is of great importance for applications such as atom and particle trapping. Moreover, there are no restrictions which would limit the number of optical pumps to two, and more could be used to generate multiple higher-order HG modes, and if the orientation between transverse modes and AMC requirement is fulfilled, efficient conversion to LG modes can occur. With this method, complex beam profiles, which are very difficult or impossible to generate, could be easily produced. Alternatively, additional pumps can be used to provide more gain to the same transverse mode, thus increasing maximum output power. Based on our experiment, the maximum available mode order is only limited by the size (aperture) of a VECSEL chip and end mirror. This advantage, combined with flexible design of VECSEL heterostructure and free-space cavity, can lead to obtaining a very broad range of higher-order transverse modes or combination of them at a wide spectrum of wavelengths. Additionally, this setup can be incorporated with a cavity designed for mode-locking, wavelength tuning, or nonlinear frequency conversion, thus expanding the variety of applications even further.

## Acknowledgment

We thank R. Perry for early simulations and laboratory assistance during the early stages of this work.

## References

[1] T. P. Meyrath, F. Schreck, J. L. Hanssen, C. S. Chuu, and M. G. Raizen, "A high frequency optical trap for atoms using Hermite–Gaussian beams," *Opt. Express*, vol. 8, no. 13, pp. 2843–2851, 2005.

[2] C. Alpmann, C. Schöler, and C. Denz, "Elegant Gaussian beams for enhanced optical manipulation," *Appl. Phys. Lett.*, vol. 106, no. 24, 2015, Art. no. 241102.

[3] A. P. Porfirev and R. V. Skidanov, "Optical trapping and manipulation of light-absorbing particles by means of a Hermite–Gaussian laser beam," *J. Opt. Technol.*, vol. 82, no. 9, pp. 587–591, 2015.

[4] K. T. Gahagan and G. A. Swartzlander, "Optical vortex trapping of particles," *Opt. Lett.*, vol. 21, no. 11, pp. 827–829, 1996.

[5] L. Allen, M. Babiker, W. K. Lai, and V. E. Lembessis, "Atom dynamics in multiple Laguerre–Gaussian beams," *Phys. Rev. A*, vol. 54, no. 5, 1996, Art. no. 4259.

[6] J. Courtial, K. Dholakia, L. Allen, and M. J. Padgett, "Second-harmonic generation and the conservation of orbital angular momentum with high-order Laguerre–Gaussian modes," *Phys. Rev. A*, vol. 56, no. 5, 1997, Art. no. 4193.

[7] M. Ozkan, M. Wang, C. Ozkan, R. Flynn, and S. Esener, "Optical manipulation of objects and biological cells in microfluidic devices," *Biomed. Microdev.*, vol. 5, no. 1, pp. 61–67, 2003.

[8] M. Okida, T. Omatsu, M. Itoh, and T. Yatagai, "Direct generation of high power Laguerre–Gaussian output from a diode-pumped Nd: YVO 4 1.3-$\mu$m bounce laser," *Opt. Express*, vol. 15, no. 12, pp. 7616–7622, 2007.

[9] S.-C. Chu, T. Ohtomo, and K. Otsuka, "Generation of doughnutlike vortex beam with tunable orbital angular momentum from lasers with controlled Hermite-Gaussian modes," *Appl. Opt.*, vol. 47, no. 14, pp. 2583–2591, 2008.

[10] P. Miao *et al.*, "Orbital angular momentum microlaser," *Science*, vol. 353, no. 6298, pp. 464–467, 2016.

[11] K. Li, Y. Rao, C. Chase, W. Yang, and C. J. Chang-Hasnain, "Beam-shaping single-mode VCSEL with a high-contrast grating mirror," in *Proc. Conf. IEEE Lasers Electro-Opt.*, 2016, pp. 1–2.

[12] K. Tanabe, X. Gu, A. Matsutani, and F. Koyama, "Vortex beam emitter laterally integrated with vertical cavity surface emitting laser," in *Proc. 11th Conf. IEEE Lasers Electro-Optics Pacific Rim*, 2015, vol. 3, pp. 1–2.

[13] M. S. Seghilani *et al.*, "Vortex Laser based on III-V semiconductor metasurface: Direct generation of coherent Laguerre-Gauss modes carrying controlled orbital angular momentum," *Sci. Rep.*, vol. 6, 2016, Art. no. 38156.

[14] K. Sueda, G. Miyaji, N. Miyanaga, and M. Nakatsuka, "Laguerre–Gaussian beam generated with a multilevel spiral phase plate for high intensity laser pulses," *Opt. Express*, vol. 12, no. 15, pp. 3548–3553, 2004.

[15] M. Padgett, J. Arlt, N. Simpson, and L. Allen, "An experiment to observe the intensity and phase structure of Laguerre–Gaussian laser modes," *Amer. J. Phys.*, vol. 64, no. 1, pp. 77–82, 1996.

[16] M. L. Lukowski, J. T. Meyer, C. Hessenius, E. M. Wright, and M. Fallahi, "Generation of high-power spatially structured beams using vertical external cavity surface emitting lasers," *Opt. Express*, vol. 25, no. 21, pp. 25504–25514, 2017.

[17] M. L. Lukowski, C. Hessenius, J. T. Meyer, E. M. Wright, and M. Fallahi, "High power two-color orbital angular momentum beam generation using vertical external cavity surface emitting lasers," *Appl. Phys. Lett.*, vol. 112, no. 4, 2018, Art. no. 041108.

[18] M. Guina, A. Rantamäki, and A. Härkönen, "Optically pumped VECSELs: review of technology and progress," *J. Phys. D, Appl. Phys.*, vol. 50, no. 38, 2017, Art. no. 383001.
[19] J. E. Hastie *et al.*, "High power CW red VECSEL with linearly polarized TEM 00 output beam," *Opt. Express*, vol. 13, no. 1, pp. 77–81, 2005.
[20] A. Khiar *et al.*, "Continuously tunable monomode mid-infrared vertical external cavity surface emitting laser on Si," *Appl. Phys. Lett.*, vol. 97, no. 15, 2010, Art. no. 151104.
[21] L. Fan *et al.*, "Extended tunability in a two-chip VECSEL," *IEEE Photon. Technol. Lett.*, vol. 19, no. 8, pp. 544–546, Apr. 2007.
[22] A. H. Quarterman *et al.*, "A passively mode-locked external-cavity semiconductor laser emitting 60-fs pulses," *Nature Photon.*, vol. 3, no. 12, pp. 729–731, 2009.
[23] M. Lukowski, C. Hessenius, and M. Fallahi, "Widely tunable high-power two-color VECSELs for new wavelength generation," *IEEE J. Sel. Topics Quantum Electron.*, vol. 21, no. 1, Jan./Feb. 2015, Art. no. 1700208.
[24] C. Hessenius, P. Y. Guinet, M. Lukowski, J. Moloney, and M. Fallahi, "589-nm single-frequency VECSEL for sodium guidestar applications," *Proc. SPIE*, vol. 8242, 2012, Art. no. 82420E.
[25] M. W. Beijersbergen, L. Allen, H. E. L. O. Van der Veen, and J. P. Woerdman, "Astigmatic laser mode converters and transfer of orbital angular momentum," *Optics Commun.*, vol. 96, no. 1-3, pp. 123–132, 1993.
[26] A. E. Siegman, *Lasers*. Mill Valley, CA, USA: University Science, 1986.
[27] M. Endo, "Numerical simulation of an optical resonator for generation of a doughnut-like laser beam," *Opt. Express*, vol. 12, no. 9, pp. 1959–1965, 2004.
[28] S.-C. Chu, T. Ohtomo, and K. Otsuka, "Generation of doughnutlike vortex beam with tunable orbital angular momentum from lasers with controlled Hermite–Gaussian modes," *Appl. Opt.*, vol. 47, no. 14, pp. 2583–2591, 2008.
[29] S.-C. Chu, Y.-T. Chen, K.-F. Tsai, and K. Otsuka, "Generation of high-order Hermite–Gaussian modes in end-pumped solid-state lasers for square vortex array laser beam generation," *Opt. Express*, vol. 20, no. 7, pp. 7128–7141, 2012.

**Michal L. Lukowski** received the M.S. degree in applied physics from the Warsaw University of Technology, Warsaw, Poland, in 2009, and the Ph.D. degree in optical sciences from the University of Arizona, Tucson, AZ, USA, in 2016.

Since 2016, he has been Postdoctoral Researcher with the University of Arizona and Research Scientist, TPhotonics, Inc., USA. His research interests include high power semiconductor lasers, nonlinear frequency conversion, and laser beam shaping.

**Jason T. Meyer** received the B.S. degree in optical engineering and the M.S. degree in optical sciences from the University of Arizona, Tucson, AZ, USA, in 2013 and 2016, respectively. He is currently working toward the Ph.D. degree in optical sciences at the University of Arizona.

He is working on mode locked semiconductor lasers for nonlinear frequency conversion to the UV spectrum.

**Chris Hessenius** received the BSEE and MSEE degrees from the University of Southern California, Los Angeles, CA, USA, in 2003 and 2006, respectively, and the Ph.D. degree from the University of Arizona, Tucson, AZ, USA, in 2013.

He is Co-Founder of TPhotonics Inc. and is currently working on developing short and long wavelength semiconductor lasers. He has been author or coauthor of numerous journal and conference papers covering a range of topics including high-power lasers, semiconductor lasers, nonlinear optics, laser cavity design, and nonlinear frequency conversion.

**Ewan M. Wright** received the Ph.D. degree in physics from Heriot-Watt University, Edinburgh, U.K., in 1983, after which he spent two years as a Postdoctoral Fellow at the Max-Planck Institute for Quantum Optics in Munich, Germany.

His doctoral work included the theory of optical bistability and also the mode properties of optical resonators. He has been at the College of Optical Sciences in Tucson, AZ, since 1985, becoming a Full Professor, in 1999. His research interests include the theory and simulation of laser resonators, optical pulse propagation in the atmosphere, as well as ultracold atomic gases.

**Mahmoud Fallahi** received the Ph.D. degree from the University of Paul Sabatier and LAAS-CNRS, Toulouse, France, in 1988.

He joined the National Research Council of Canada as a Postdoctoral, Fellow, in 1989, and became a member of technical staff as a Research Scientist during 1992–1995. He joined the University of Arizona, AZ, USA, as an Assistant Professor in 1995. He is currently a Professor at the College of Optical Sciences, University of Arizona. He has authored or coauthored more than 170 journal and conference papers in the fields of high power semiconductor lasers, micro/nano fabrication, photonic integrated circuits, and hybrid organic-inorganic heterogeneous integration. He has served as Conference Chair and Program Committee member in numerous international conferences in the field of semiconductor lasers and integrated optics.