Circular polarization emission from an external cavity diode laser

Fan Zhang, Jian Xu,[a)] Akhlesh Lakhtakia, Ting Zhu, Sean M. Pursel, and Mark W. Horn
Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, Pennsylvania 16802, USA

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An external cavity diode laser (ECDL) containing a chiral sculptured-thin-film (STF) mirror for very pure circularly polarized (CP) emission was fabricated and its single-mode, left-handed CP lasing performance was observed. The extinction ratio of the CP output was found to increase rapidly near the threshold of the injection current for the laser diode. The Jones-matrix representation of a chiral STF mirror was used to calculate the eigenstates in the external cavity of the ECDL with the transfer matrix method, the results suggesting that the only resonant mode in the external cavity of the laser is CP with the same handedness as the structural handedness of the chiral STF mirror. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2896306]

There is widespread interest in studying the photonic properties of two-dimensional periodic structures with helical symmetry and their interactions with circularly polarized (CP) electromagnetic fields for potential applications of CP light in optical information processing and data storage,[1,2] optical communication,[3] quantum computing and cryptography,[4] as well as bio/chemical detection.[5] Although linearly polarized emission from a laser filtered through a quarter wave plate (QWP) can be used for CP emission, the required fabrication process for integrated optics is not straightforward. Moreover, postfabrication manual alignment is needed. An alternative way would be to use either cholesteric liquid crystals (CLCs) or chiral sculptured thin films (STFs) because these structures are CP filters. CLC cells can be prepared by solution-processed self-organization of liquid crystal molecules and have been regarded as good candidates for cavity-free organic lasers[6,7] and organic light emitting diodes.[8] Chiral STFs are fabricated by physical vapor deposition of dielectric materials, such as TiO_2 and SnO_2, allowing the direct integration of structurally chiral optical components with many solid-state optical and optoelectronic devices and systems for the development of CP-based solid state photonics.[9,10]

The morphology of a chiral STF consists of upright helical nanowires that are parallel and identical to each other.[11] Thus, at visible wavelengths, the film may be said to possess a distinguished axis about which the constitutive tensors rotate. On axial excitation, i.e., when all fields vary spatially along only the distinguished axis, a chiral STF displays the circular Bragg phenomenon in a narrow wavelength range (Bragg regime).[12] CP light of one handedness is highly reflected, while of the other handedness is reflected very little, provided the film is sufficiently thick. This response characteristic has been extensively studied experimentally as well as theoretically.[11] When two STF chiral mirrors are used to create a resonant cavity, the CP-selective reflection in the Bragg regime inhibits the presence of right/left CP (RCP/LCP) light, which induces the resonance of LCP/RCP light.[13] We have recently demonstrated narrow-band CP emission from both organic molecules and inorganic quantum dots embedded in high-*Q*-factor microresonant cavities formed by two chiral STF mirrors.[14] Our results clearly suggest the possibility of developing chiral-STF reflector-based laser devices to obtain very pure and controllable circular polarization. Polarization-selective resonance in helical mirror-based Fabry–Pérot cavities was also predicted and observed by Stockley *et al.* and Abdulhalim recently.[15,16]

In this letter, we report the design and demonstration of an external cavity diode laser (ECDL) for a selected CP output. This was accomplished by employing just one chiral STF mirror as the external cavity reflector and using a properly oriented QWP inside the cavity to preserve the selected CP state. We observed single-mode, LCP lasing performance from an ECDL with a structurally left-handed STF mirror. The extinction ratio of the CP output was found to increase rapidly near the threshold of the injection current for the laser diode and saturate at higher injection levels with a maximum value up to ~112 at the lasing wavelength. Using the Jones-matrix representation of a chiral STF mirror to calculate the eigenstates in the external cavity of the ECDL with the transfer matrix method, we deduced that the only resonant mode in the external cavity is CP with the same handedness as the structural handedness of the chiral STF mirror.

The configuration of the ECDL is shown in Fig. 1. A buried heterostructure laser diode (LD) provides the gain centered at 655 nm wavelength. One facet of the LD is coated for enhanced intensity reflectivity ($R \sim 98\%$) and functions as one of the two end mirrors of the ECDL. The

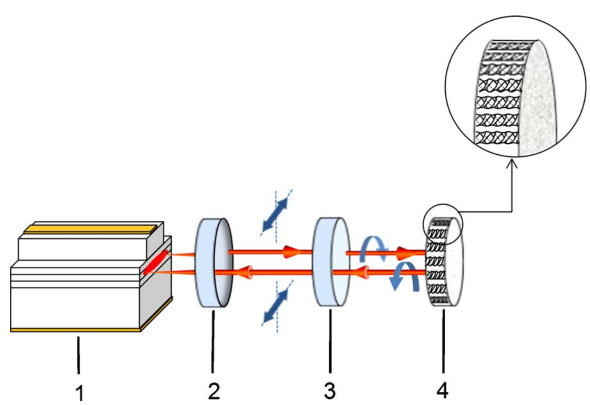

FIG. 1. (Color online) Schematic configuration of an ECDL comprising of (1) a buried heterostructure LD with an antireflective coated facet, (2) a collimating microlens, (3) a QWP, and (4) a chiral STF mirror for CP emission.

[a)]Author to whom correspondence should be addressed. Electronic mail: jianxu@engr.psu.edu.

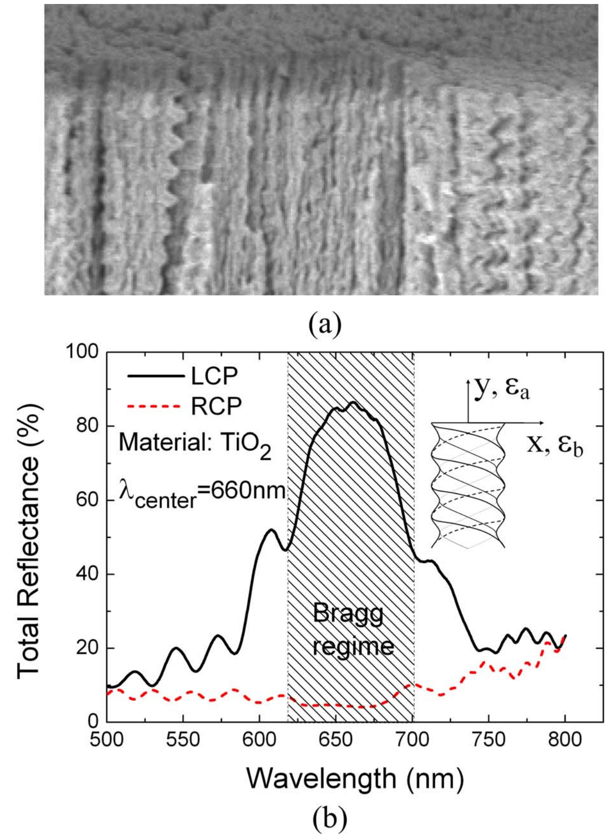

FIG. 2. (Color online) (a) Cross-sectional SEM image of the chiral STF mirror. (a) Reflectance spectra of a structurally left-handed STF mirror.

other facet of the LD is antireflection coated with $R < 3\%$. Light propagating along the waveguide of the LD is amplified and coupled to the external cavity through this facet with low reflectance loss. An antireflection-coated molded microlens collimates the output beam and passes the light through a Soleil–Babinet compensator that is used as a QWP in the cavity. A left-handed STF mirror selectively reflects LCP light at the end of the external cavity, thereby serving as the second end mirror and the sole output coupler of the ECDL. The stripe length of the LD l_{LD} is about 300 μm. The distance between the chiral STF mirror and the antireflection-coated LD facet l_{ext} is about 10 cm.

The chiral STF mirror was fabricated by the serial bideposition technique described elsewhere.[12,17] TiO_2 was chosen as the STF material for its large bulk refractive index (=2.6) and high optical transparency at the wavelengths of interest. The chiral mirror comprises nanohelixes with six structural periods each with half-period 152 nm; thus, the mirror is 1.82 μm thick, as shown in the cross-sectional scanning electron microscope image presented in Fig. 2(a). Figure 2(b) shows the measured total reflectance spectra of the chiral STF mirror for normally incident LCP and RCP light. A well-defined Bragg regime is observed in the LCP-reflectance spectrum, whereas there is insignificant reflection of RCP light over the wavelength range of measurement. The center wavelength of the Bragg regime is 650 nm and the full width at half maximum (FWHM) bandwidth is ~54 nm. The peak reflectance in the Bragg regime is 89% for incident LCP light.

To characterize the polarization performance of the ECDL, the LD was operated at 17 °C by thermoelectric cooling. The fast axis of the intracavity QWP was aligned at

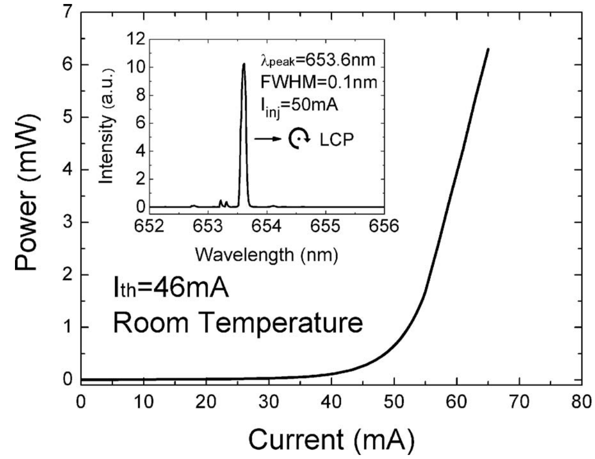

FIG. 3. Light-current characteristic of the ECDL. Inset: spectrum of the ECDL output.

+45° with respect to the polarization of the transverse electric (TE) mode in the LD, thereby converting the linearly polarized field in the gain medium (LD) of the ECDL to the LCP field in the external cavity. A resonant LCP mode developed in the external cavity due to the LCP-selective reflection from the left-handed STF mirror.

Light-current characterization of the ECDL was carried out with a precision current source (LDX-3200, ILX Lightwave Inc.) and a low power detector (818-SL, Newport Inc.). The resulting plot is presented in Fig. 3. The threshold current was measured as 46 mA.

A HP 71450B optical spectrum analyzer was used to study the spectral characteristics of the ECDL, see the inset of Fig. 3. The pump current was 50 mA. We deduced therefrom a LCP laser oscillation of a single longitudinal mode at the peak wavelength of 653.6 nm and a FWHM linewidth of 0.1 nm. The side-mode suppression of the adjacent cavity modes of the lasing peak was measured to be 26 dB. It is speculated that the observed high side-mode suppression of the ECDL output originates from the combined effects of narrow gain bandwidth, LD-cavity resonance condition, wavelength dependence of the QWP, as well as the limited bandwidth of the chiral STF's Bragg regime. At a substantially higher injection current, multimode lasing was observed arising from the enhanced gain behavior.

The polarization purity of the ECDL output was analyzed with an optical bench comprising a quarter-wave Fresnel-rhomb retarder, a Glan–Thompson prism analyzer, and a low power detector, see Fig. 4(a). The Fresnel-rhomb retarder converts CP light to linearly polarized light over the wavelength range of interest. The degree of CP of the emission was characterized by measuring the analyzer transmission as a function of the optical-axis orientation of the analyzer. Figure 4(b) contains a polar plot of the normalized analyzer transmission versus the angle between the linear polarization direction of the analyzer and the optical axis of the Fresnel-rhomb retarder. The polarization characteristics of the TE emission from an isolated LD and the plain transmission from an isolated chiral STF mirror are also presented for comparison. The analyzer transmission for ECDL output displays a minimum at −45° and a maximum at +45° with a high extinction ratio, $I(45°)/I(-45°) = I_{\mathrm{LCP}}/I_{\mathrm{RCP}} \approx 112$, thereby confirming that the ECDL output is substantially LCP. In contrast, the calculated CP ratio of the transmittance from an isolated chiral STF mirror, $T_{\mathrm{LCP}}/T_{\mathrm{RCP}}$

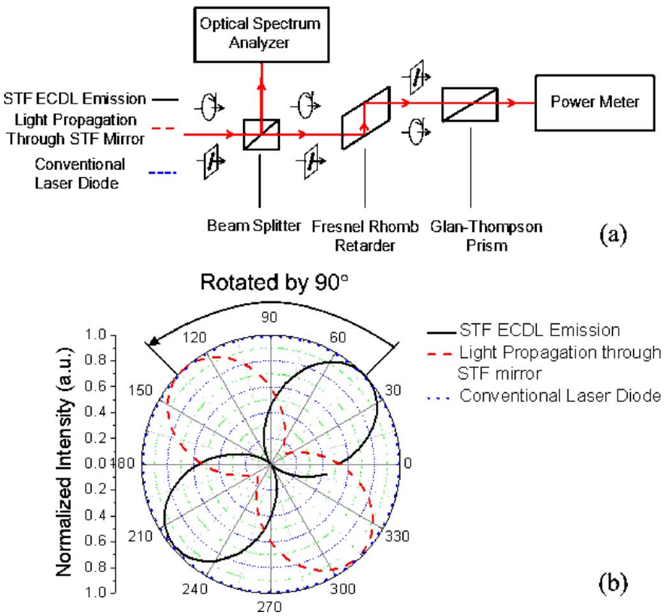

FIG. 4. (Color online) (a) The optical bench for the analysis of CP states in ECDL output. (b) A polar plot of the normalized analyzer transmission vs the angle between the optical axes of the analyzer and the Fresnel-rhomb retarder. The polarization signature of the STF-mirror transmission was deliberately rotated by 90° in the plot to distinguish it from that of the STF cavity output.

$=I(135°)/I(45°)$, is only 32. The higher CP ratio of the ECDL output with respect to that of the isolated chiral STF mirror transmittance clearly indicates that the LCP mode dominates in the external cavity of the ECDL.

The CP ratio of the EDCL output was also measured as a function of the injected current of the LD, as shown in Fig. 5. The rapid increasing of CP ratio near the threshold current adds further evidence to the fact the buildup of a resonance field of circular polarization in the ECDL produces the desired CP laser emission.

The Jones-matrix representation of an ideal chiral STF mirror can be derived from its CP-selective transmission and reflection properties. With unity reflectance for LCP/RCP and unity transmittance for RCP/LCP for a structurally left/right-handed STF, we get the Jones matrixes

$$T_{\mathrm{STF}}^{\mathrm{left}} = \frac{1}{2}\begin{bmatrix} 1 & -i \\ -i & -1 \end{bmatrix}, \quad T_{\mathrm{STF}}^{\mathrm{right}} = \frac{1}{2}\begin{bmatrix} 1 & i \\ i & -1 \end{bmatrix}. \tag{1}$$

The eigenstates of polarization in the external cavity of ECDL can be deduced by calculating the overall Jones matrix M for one round trip inside the cavity starting from a structurally left-handed STF chiral mirror[18]

$$\begin{aligned} M &= \sqrt{R_{\mathrm{LD}}R_{\mathrm{STF}}}G_{\mathrm{TE}}e^{2ikL}T_{\mathrm{QWP}}T_{\mathrm{coordinate}}T_{\mathrm{QWP}}T_{\mathrm{coordinate}}T_{\mathrm{STF}}^{\mathrm{left}} \\ &= \sqrt{R_{\mathrm{LD}}R_{\mathrm{STF}}}G_{\mathrm{TE}}e^{2ikL}\begin{bmatrix} 1 & -i \\ i & 1 \end{bmatrix}, \end{aligned} \tag{2}$$

where k is the wave number of the intracavity field, R_{LD} and R_{STF} are the intensity reflection coefficients of the HR-coated LD facet and the chiral STF mirror, respectively, G_{TE} is the double-pass complex gain associated with the TE axis of the LD, T_{QWP} is the Jones matrix of the QWP, and $T_{\mathrm{coordinate}}$ is a coordinate-transformation matrix.

The matrix M of Eq. (2) has two eigenvectors, one LCP and the other RCP. Only the LCP eigenvector has a nonzero eigenvalue, suggesting that the LCP mode is the only contained mode in the external cavity of our ECDL. It is worth mentioning that the Fresnel reflection of CP light from conventional mirrors, such as distributed Bragg reflectors and cleaved LD facets, invariably inverts the polarization handedness,[13] which will not preserve the LCP mode in the external cavity if the chiral STF mirror in ECDL were replaced by a standard dielectric or metal mirror.

In summary, single-mode, CP coherent emission was observed from an ECDL containing a chiral STF end mirror and a QWP in the external cavity. The rapid increase of output CP ratio near the threshold current indicates the buildup of a resonance CP mode in the external cavity, thereby producing the desired CP lasing behavior. Our technique to realize CP emission is different from coupling a laser to a QWP, because our technique is potentially extendable to integrated optics.

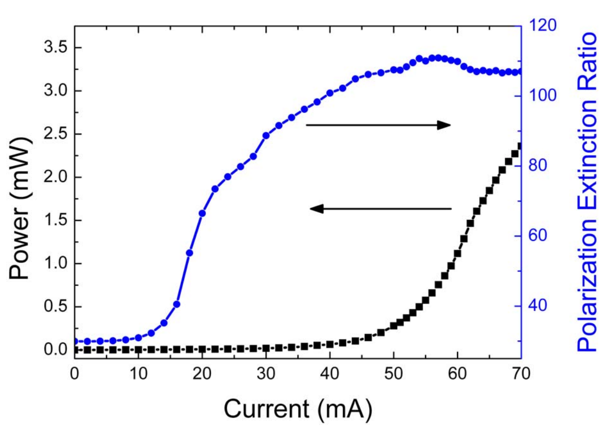

FIG. 5. (Color online) Measured polarization extinction ratio of the ECDL output as a function of the injection current. The light-current characteristic of the ECDL is also plotted for reference.

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