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Tunable External Cavity Laser With a Liquid-Crystal Subwavelength Resonant Grating Filter as Wavelength-Selective Mirror

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***Abstract*—We demonstrate a tunable external cavity laser consisting of a voltage-tuned liquid-crystal cladded subwavelength resonant grating filter placed directly in front of a semiconductor laser gain chip. The filter acts as a tunable wavelength-selective mirror. As the applied voltage to the filter changes from 0 to 22 V, the laser wavelength demonstrates a tuning range of 7 nm, which may be further increased. As the laser has simple cavity design and no moving parts, it can be low cost and easy to fabricate and assemble.**

***Index Terms*—Gratings, resonant waveguide grating filter, semiconductor lasers, tunable lasers.**

I. INTRODUCTION

TUNABLE lasers are essential components in photonic applications such as data communication, sensing, and testing. Monolithic devices such as the distributed Bragg reflector laser using sampled gratings [1] and the modulated-grating Y-branch laser [2] have been demonstrated through intricate InP growth and processing and careful control of multiple tuning currents. External cavity lasers (ECLs) utilizing a first-order diffraction grating [3] and tunable vertical-cavity surface-emitting laser [4] are achieved typically via moving parts. Here, an alternative external cavity design [5]–[7] without moving parts is investigated using a compact subwavelength grating to implement a low-cost and robust tunable laser that can be easy to fabricate and assemble.

In any type of tunable single-mode laser, there must be a tunable wavelength-selective element. For this purpose, the use of a tunable subwavelength resonant grating (SRG) filter [8] is attractive because of its inherently simple and compact structure, narrow and sharp reflection peak, and normal incidence operation without any higher order diffraction loss. It was previously shown that laser output light can be controlled by an external cavity incorporating subwavelength optical elements [9], and the concept of using fixed-wavelength resonant gratings in a laser cavity to force single-wavelength lasing was previously demonstrated for large-area semiconductor lasers [10] and polymer dye lasers [11]. In those papers, the lasing wavelength is not dynamically tunable because there is no tuning mechanism incorporated into the cavity scheme. Recently, a discretely tunable laser with a thermally tuned SRG as an external mirror was demonstrated [12] with a small tuning range (1 nm).

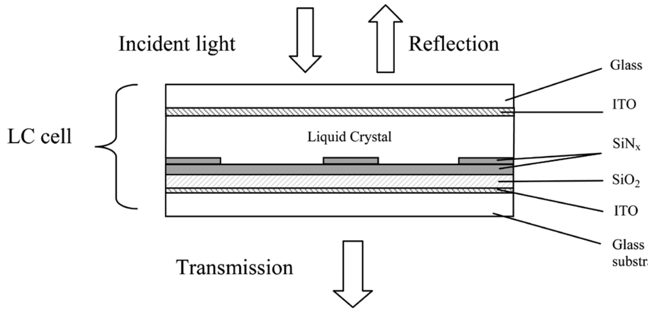

Fig. 1. Cross-sectional schematic of a tunable LC-SRG optical filter.

Here, we demonstrate a tunable ECL using a liquid-crystal subwavelength resonant grating (LC-SRG) as an electrically tuned wavelength-selective mirror in the external cavity. A tunable filter based on LC-SRG was previously demonstrated [13]. It is well-known that the peak reflection wavelength of an SRG is sensitive to the refractive index of the cladding material on top of the grating structure [14]. Our tunable SRG has a layer of nematic liquid crystal as the cladding layer on top of a subwavelength grating to tune the resonant frequency of the SRG. An electric field is used to tune the orientation of the birefringent nematic liquid-crystal molecules, leading to a change in refractive index of the liquid-crystal layer for a linearly polarized, normal incident light and, hence, a shift in the resonant peak wavelength of the SRG. Using such a tunable reflective filter as a mirror for the laser allows the tuning of the laser wavelength.

II. EXPERIMENTS

The cross-sectional schematic of the tunable LC-SRG filter used in our laser cavity is shown in Fig. 1. For a normal incident light with a wavelength at the resonance of the device, it excites a leaky waveguide mode in the homogeneous silicon nitride (SiN$_x$) layer that is underneath the subwavelength gratings due to grating coupling. This leaky mode interacts with the zeroth-order waves and in theory results in complete reflection and zero transmission for plane incident wave and infinite gratings [15]. In practice there will be a certain amount of transmission at resonance depending on the coupling strength of the gratings. The gratings can thus also serve as the laser output facet. For all other wavelengths, no waveguide mode is excited and, therefore, they pass straight through except for the Fresnel interfacial

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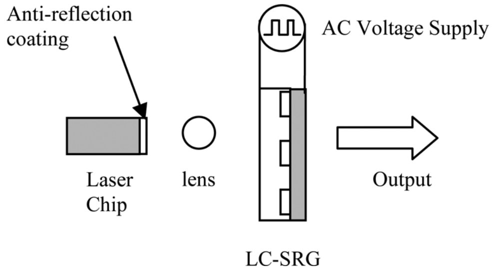

Fig. 2. Schematic of a tunable ECL using LC-SRG filter as wavelength-selective mirror.

reflections. The resonant wavelength can be tuned electrically through voltage applied to the liquid-crystal cell.

Fabrication of the tunable LC-SRG starts with plasma-enhanced chemical vapor deposition of a 1-μm-thick silicon dioxide (SiO_2) layer and then 500-nm-thick SiN_x on a commercial indium tin oxide (ITO)-coated glass substrate. The ITO serves as a transparent electrode for applying voltage across the liquid crystal that is later incorporated. The SRG is fabricated on top of the SiN_x layer by thermal nanoimprint lithography [16]. The period of the gratings is 950 nm. The depth of the gratings is about 100 nm. Next, a liquid-crystal cell is assembled on top of the SRG using a commercially available polyimide ring of 12 μm in thickness (not shown in Fig. 1) and an ITO-coated glass cover to confine the liquid crystal on top of the SRG. The inside wall of the cover glass and surface of resonant grating are coated with organic surfactant to align the initial orientation of the liquid-crystal molecules. The commercially available liquid-crystal E7 (Merck) is used.

The Frederiks transition threshold for this particular liquid-crystal cell is around 5 V at which an increase of the resonant wavelength by 0.5 nm occurs. From then on, the filter can be tuned continuously, as the applied voltage is increased up to a maximum tuning range of 7 nm. The full-width at half-maximum of the LC-SRG is measured to be 1 nm. The measured filter reflectivity varies between 50% to 60% within the tuning range.

Fig. 2 shows the schematic of the ECL configuration. A commercially available 1.55-μm InGaAsP multiple quantum-well Fabry–Pérot (FP) ridge laser chip is used as the gain medium. As purchased, the FP laser chip had multiple lasing modes in its output spectrum with a mode spacing of around 0.9 nm. We coated the front facet of the laser diode with an aluminum oxide antireflection (AR) layer by E-beam evaporation. The residual reflectivity is estimated to be around 3%. The tunable LC-SRG filter was placed directly in front of the low-reflectivity facet, with a ball lens in between to collimate the light onto the gratings and focus the reflection back into the gain section. The entire cavity is 3 mm long, with an estimated FP longitudinal mode spacing of around 0.23 nm.

At the resonant wavelength of the LC-SRG filter, light is reflected 180° by the resonant grating filter and feedback into the gain medium of the FP laser. Thus, a resonator, formed between the SRG filter and the back facet of the diode, induces the laser to lase at a particular wavelength determined by the tunable LC-SRG. For all other nonresonant wavelengths, the reflection will be greatly reduced. The lasing wavelength can be tuned by adjusting the amplitude of the ac voltage connected to the LC-SRG.

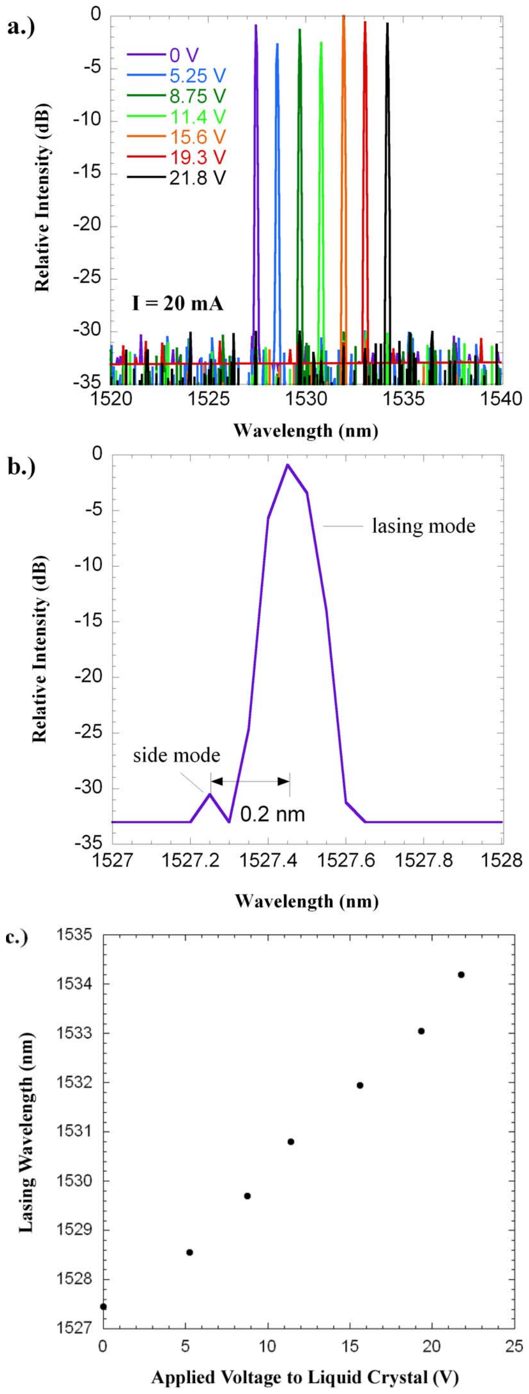

Fig. 3. (a) Optical spectrum of LC-SRG ECL at different applied voltages to the LC-SRG, showing a tuning range of 7 nm. (b) Lasing mode at 1527.5 nm in closer detail, showing single-mode lasing. (c) Tuning curve of LC-SRG ECL, with lasing wavelength as a function of voltage applied to the liquid-crystal cell.

III. RESULTS AND DISCUSSION

The optical spectrum of the output light is measured using an optical spectrum analyzer. The measured spectra at an input current I to the semiconductor laser chip of 20 mA are given in Fig. 3(a). The resolution of the optical spectrum analyzer is 0.1 nm. When the applied voltage across the liquid-crystal cell is zero, the laser has an output wavelength at around 1527.45 nm. As the applied voltage is increased, the lasing wavelength red-shifts. At an applied voltage of 21.8 V, the lasing wavelength

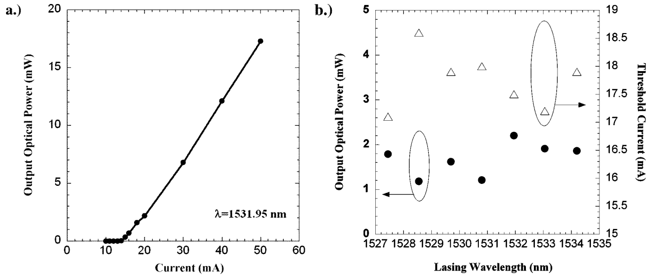

Fig. 4. (a) Light–current characteristics of tunable LC-SRG ECL at a lasing wavelength of $\lambda = 1532$ nm. The threshold current is 17.5 mA. (b) Output optical power for different lasing wavelengths at an input current of 20 mA and threshold current at different lasing wavelengths.

reaches 1534.5 nm. Increasing the applied voltage further beyond 22 V does not have any effect on the lasing wavelength, indicating that the limit of the tuning range of this particular LC-SRG is reached. In this case, the tuning range is 7 nm.

Fig. 3(b) shows in closer detail the optical spectrum of the lasing mode at 1527.45 nm. The adjacent sidemode at 1527.25 nm is shown to be 30 dB down from the lasing mode at this resolution, confirming single-mode lasing of the laser. The linewidth of the lasing mode in Fig. 3(b) is limited by the resolution of the instrument. The resonant grating provides only part of the mode selectivity mechanism. The residual reflectivity at the gain chip facet facing the gratings results in a coupled cavity laser: there is an internal cavity that is the original FP laser gain chip, and there is the external cavity. These two cavities are coupled, which leads to interference between waves propagating in the two cavities, and allows the use of a resonant grating with moderately narrow bandwidth to select out a single mode.

The tuning curve of lasing wavelength versus applied voltage across the liquid crystal is given in Fig. 3(c). Because there is no phase control element in the cavity and of the residual reflectivity from theAR-coated laser chip facet, the tuning is discrete with a tuning step of around 1.15 nm.

The light–current characteristics of the laser at a lasing wavelength of 1532 nm is measured using a calibrated broad-area photodetector and is shown in Fig. 4(a). The threshold is shown to be 17.5 mA and the slope efficiency is 0.5 mW/mA. The optical output power and threshold current at different lasing wavelengths are given in Fig. 4(b). The variations in output power and threshold current are due to the variation in resonant grating filter reflection strength arising from imperfect alignment of liquid-crystal molecules which is likely to be improved by stronger anchoring of the liquid-crystal molecules.

The wavelength tunable range of such a laser is in general determined by the medium gain spectrum and filter tuning range. For the laser here, the tuning range is limited by the filter tuning range. The filter tuning range is in turn limited by the anchoring of the liquid-crystal molecules. To significantly increase the maximum tuning range of the LC-SRG, we need to improve 1) the quality of initial orientational alignment (anchoring) of the liquid-crystal molecules with a better liquid-crystal alignment scheme such as a double-grating structure that has demonstrated a tuning range of 20 nm [17], and 2) inherent birefringence by incorporating liquid crystal with higher birefringence. To achieve continuous tuning, a better AR-coating needs to be applied at the original laser chip facet and a phase-control element will be needed in the cavity.

IV. CONCLUSION

In summary, we have demonstrated a discretely tunable external-cavity laser using a tunable subwavelength resonant grating filter as a wavelength-selective reflector in the cavity. The tuning range is shown to be 7 nm, which can be further improved by using a filter with wider tuning range. The laser can be low-cost and easy to fabricate and assemble, with no moving parts.

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