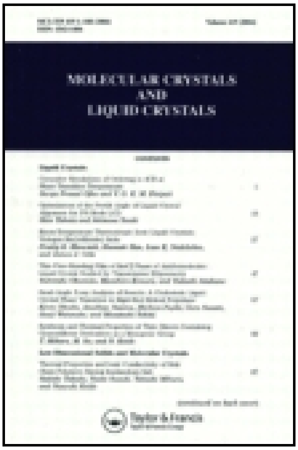
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A NOVEL TUNABLE DIODE LASER WITH LIQUID CRYSTAL INTRACAVITY TUNING ELEMENT

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We propose a novel and simple approach for tuning of the laser wavelength. A homogeneously aligned nematic liquid crystal (NLC) cell with 4′-n-pentyl-4-cyanobiphenyl (5CB) is inserted in an external-cavity semiconductor laser as the fine-tuning element of wavelength. Varying the voltage biasing the NLC cell, its extraordinary index of refraction would change due to field-induced reorientation of the LC director. This is equivalent to tune the laser cavity length. As a result, the laser wavelength can be continuously tuned. With a NLC cell 35.5 μm in thickness, the output frequency of the present laser can be tuned over 4 GHz for a 30-cm-long laser cavity without hopping. The driving rms voltage was less than 2 volts.

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1. INTRODUCTION

Tunable semiconductor lasers are compact, versatile sources and have a wide range of applications for coherent optical communication, optical spectroscopy, and precision metrology. These lasers were typically tuned either mechanically or electronically. Mechanical tuning, however, is slow and requires bulky components. Electronic means based on electro-optic or acousto-optic effects allows fast and accurate wavelength tuning. The driving voltage required is usually quite high, in the kV range. Several types of liquid crystal elements, on the other hand, have also been used successfully as intracavity tuning element in external-cavity semiconductor or fiber lasers. These elements can be categorized as birefringent filters [1–3], Fabry-Perot etalons [4,5], or spatial light modulators [6,7]. The use of liquid crystal device as tuning elements enables electronical tuning at low voltages and has wide tunability. In this paper, a novel and simple approach for tuning of the laser wavelength is proposed and demonstrated. It is designed for fine-tuning of laser wavelength, in combination with other means that allow rapid and broad wavelength tuning. Briefly, a homogeneously aligned nematic liquid crystal (NLC) cell is inserted between the grating and mirror of an external-cavity semiconductor laser (ECL). The laser polarization direction is along the rubbing direction of the NLC cell. Varying the voltage biasing the NLC cell, its extraordinary index of refraction would change due to field-induced reorientation of the LC director. The laser cavity length would change accordingly and the output frequency of the present laser can be continuously tuned in single longitudinal mode operation without hopping.

2. EXPERIMENTAL METHODS

The schematic of the laser configuration is shown in Figure 1. It is basically an external-cavity semiconductor laser based on the Littman-Metcalf design [8]. One facet of the laser diode (Sacher, model 780–40) is anti-reflection (AR) coated ($R < 1 \times 10^{-4}$) to suppress self-lasing, so that the diode serves as a gain medium for the external cavity. The output light is collimated by an AR coated aspheric lens of numerical aperture (N.A. = 0.5) for optical coupling to the diffraction grating. A grazing-incidence diffraction grating (1200 lines/mm, blazing wavelength 750 nm) is used for wavelength selection and output coupling. The zeroth-order reflected beam from the grating is the output of the laser.

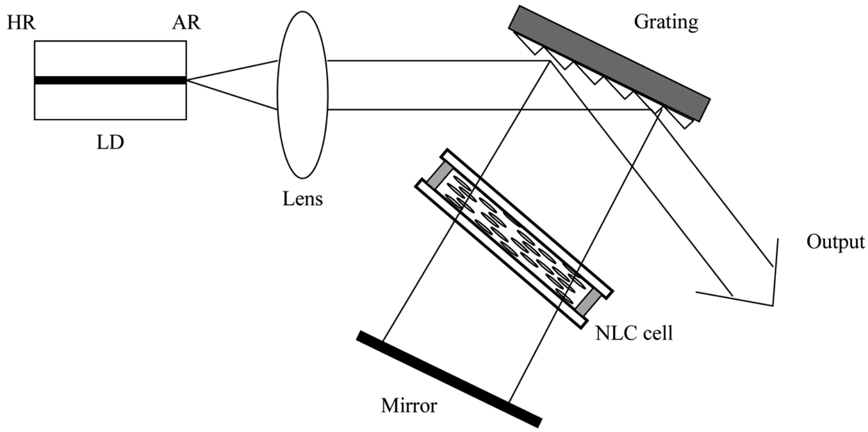

FIGURE 1 A schematic of the laser configuration. LD: Laser Diode; HR: High Reflector; AR: Anti-reflection Coating; NLC: Nematic Liquid Crystal.

The first-order reflection from the grating is reflected back into the diode by an external mirror. The temperature of the laser diode is stabilized at $20.5 \pm 0.01^{\circ}$C. The longitudinal mode spacing for this external cavity of 30-cm length is 0.5 GHz. A 35.5-μm-thick NLC cell is introduced in the cavity for fine-tuning.

To align the cavity, the laser injection current is first set to a value a little below the threshold. Second, the NLC cell is put into the cavity. Then the mirror is adjusted to direct the return first-order diffraction beam back into the laser until lasing occurs. The lasing spectrum of the ECL is shown in Figure 2. Because the surfaces of the NLC cell are not AR-coated, the NLC cell is placed between the grating and the mirror at a tilted angle to avoid the unwanted feedback light from both surfaces of the cell windows.

The NLC cell used in the experiment is formed by sandwiching a 35.5-μm-thick layer of 4′-*n*-pentyl-4-cyanobiphenyl (5CB) between two glass plates coated with Indium-Tin-Oxide on the inner sides of substrates. The driving voltage to the NLC cell was a 1 kHz ac square wave. The NLC cell is characterized before it is introduced in the ECL system. The transmission characteristic of the NLC cell was first investigated. In the transmission measurement, the NLC cell is inserted between two crossed polarizers. The polarization of the incident light is parallel to the orientation of the first polarizer. The transmission intensity I through the second polarizer can be expressed as

$$I = I_0 \sin^2 \frac{\Delta\Phi}{2}, \quad (1)$$

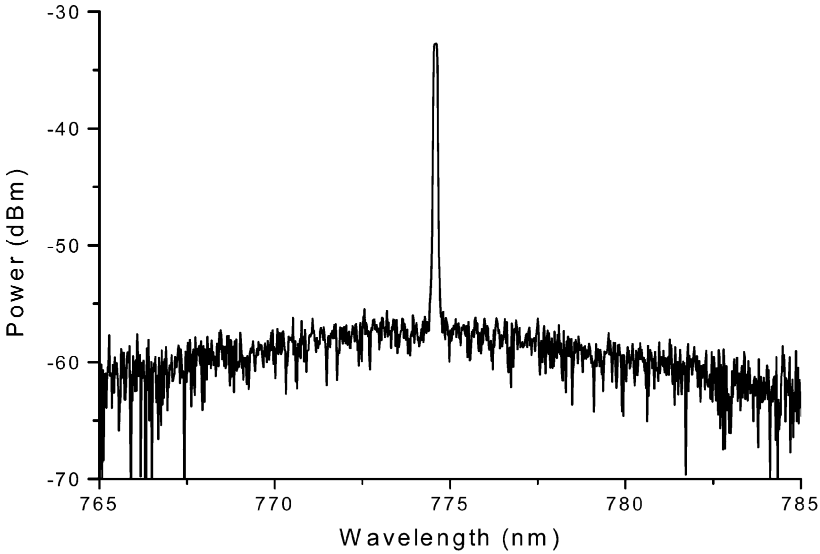

FIGURE 2 Lasing spectrum of the external-cavity diode laser.

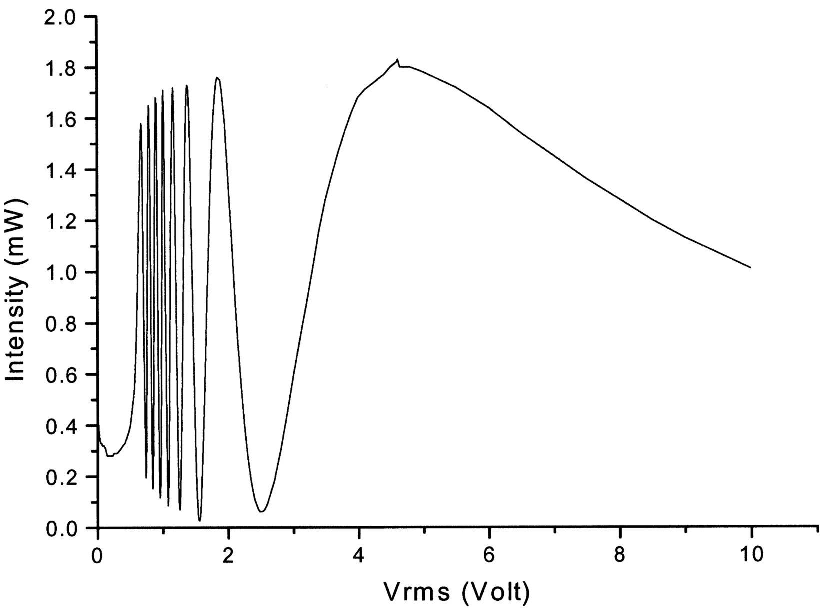

FIGURE 3 Transmission characteristic of the NLC cell at 772 nm is plotted as a function of the driving voltage.

where $\Delta\Phi = \Delta nkd$ is the phase retardation, Δn is the difference in refractive indexes for the two principal dielectric axes, d is the layer thickness of NLC cell, and $k = 2\pi/\lambda$ where λ is the wavelength of the light. The transmission maxima and minima are periodic and occur when Δnd is half-integer and integer, respectively. Figure 3 is a plot of the transmission of the NLC cell as a function of the driving voltage obtained at a probing wavelength of 772 nm.

In the laser cavity, the NLC cell is oriented such that the laser polarization direction is along its rubbing direction. Varying the voltage biasing NLC cell, its extraordinary index of refraction would change due to field-induced reorientation of the LC director. This is equivalent to tuning the laser cavity length. According to the above results, the relative frequency shift is given by

$$\frac{\Delta l}{l} = -\frac{\Delta f}{f}, \tag{2}$$

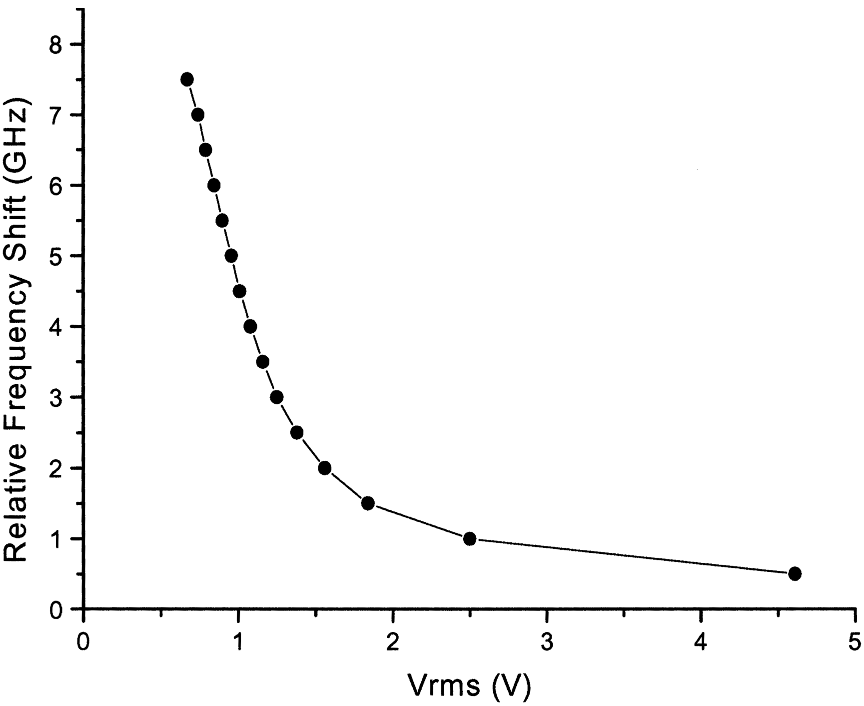

FIGURE 4 Relative frequency shift of the laser as the voltage biasing the NLC cell is changed. This curve is the theoretical prediction calculated from field-induced birefringence information.

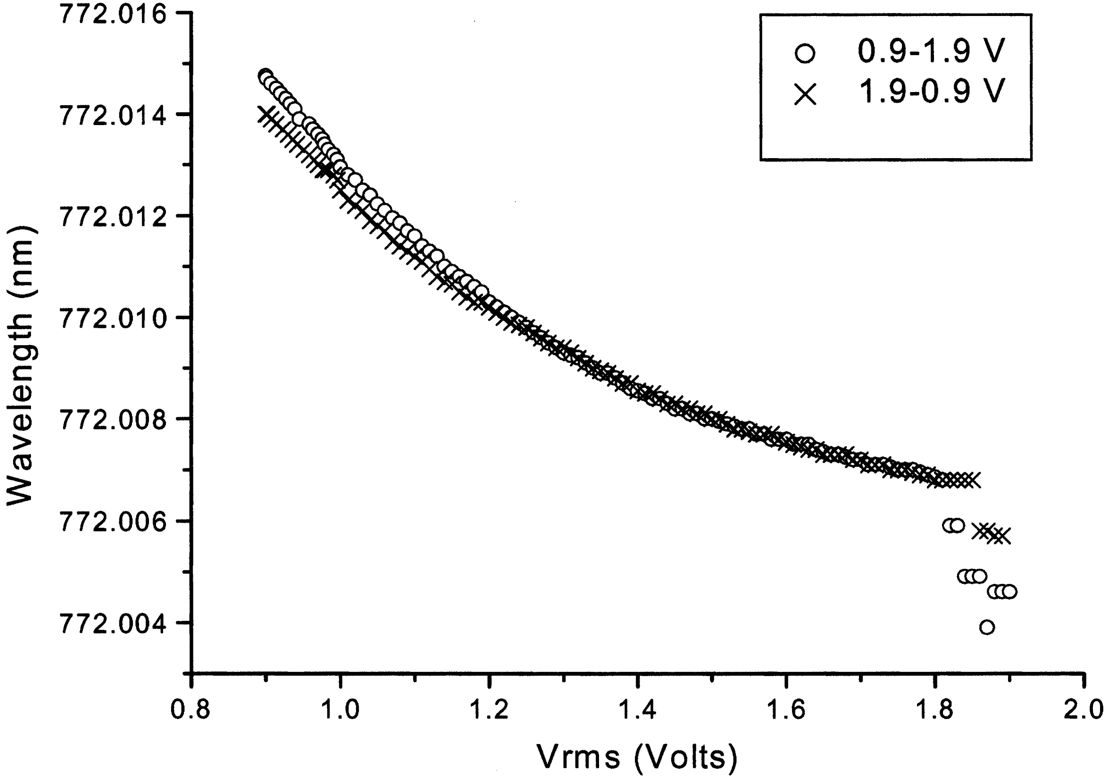

FIGURE 5 Laser frequency shift as the driving voltage of the NLC cell is ramped up and down in the range of 0.9 volts to 1.9 volts. The mode-hop-free range is about 0.008 nm.

where $\Delta l = \Delta nd$ is the optical length variation, l is the cavity length, Δf is the induced relative frequency shift, f is laser frequency. We demonstrate the relative frequency shift as the driving voltage of the NLC cell is changed in Figure 4. This curve is the theoretical prediction calculated from field-induced birefringence information derived from the results of Figure 3 and Eq. (2). It is obvious that a linearly continuous frequency shift can be obtained for the linear operation range of the NLC cell.

3. RESULTS AND DISCUSSIONS

The output wavelength and the wavelength tuning range of the ECL are measured by using a wavelength meter with a resolution of 0.0001 nm (Burleigh WA-1500). In some experiments, it is also monitored by a scanning Fabry-Perot (FSR = 2 GHz). At room temperature (~25°C), measurements are carried out for a 30-cm long cavity. The results of laser frequency shift as the driving voltage on NLC cell is ramped up and down in the range of 0.9 volts to 1.9 volts are demonstrated in Figure 5. Continuous wavelength tuning ranges are 0.008 nm (ramp up from 0.9 V to 1.9 V) and 0.0072 nm (ramp down from 1.9 V to 0.9 V) which corresponding to 4.02 GHz and 3.62 GHz respectively. The mode-hop-free tuning range within the linear operation region from 0.9 V to 1.3 V is 2.77 GHz. This is in good agreement with the theoretical prediction of 2.46 GHz. The slight discrepancy is within the accuracy of the wavelength meter, calibrated to be 3×10^{-7} by the National Measurement Laboratory of Taiwan. With a thicker LC cell, broader continuous tuning range should be possible.

4. CONCLUSIONS

We have demonstrated that a liquid crystal cell formed by nematic liquid crystal sandwiched between two glass plates can be used as the fine-tuning device in an extended-cavity semiconductor laser. A continuous tuning range of 4.02 GHz for a 30-cm ECL in single longitudinal mode operation is obtained. This is in good agreement with the theoretical predictions. The system does not require any moving part comparing with other mechanically controlled fine-tuning device, low driving voltage (<2 V) and no critical alignment requirements. The introduction of this intracavity LC cell thus makes it more convenient to realize fine-tuning.

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