Wavelength tuning and multiple wavelength generation using a reflection-type liquid crystal spatial light modulator

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ABSTRACT

A reflection-type spatial light modulator using twisted nematic (TN) liquid crystal (the liquid crystal pixel mirror or LCPM) is employed to realize a new type of digitally tunable, narrow line-width (< 0.1 nm, instrument-limited), multi-wavelength semiconductor laser. The laser is based on a novel folded telescopic grating-loaded external cavity with LCPM at the focal plane of the folded telescope. With a 50-pixel LCPM, the single wavelength digitally tunable range of a visible laser diode was from 650.8 to 661.24 nm in 0.21 nm steps by biasing the individual pixels. Further, the wavelength can be switched and reset with a response time of 13.6 ms. By biasing two pixels at the same time, obtain dual-wavelength output with the wavelength tunable from 0.21 to 10.4 nm. Generation of tunable triple wavelengths with equal or arbitrary wavelength separation are also demonstrated. Preliminary results on such a laser operating at 1550 nm is also shown.

Keywords: Laser tuning, Semiconductor Laser, Liquid crystal devices, Narrow Linewidth

INTRODUCTION

Tunable semiconductor and fiber lasers are compact, versatile sources used extensively in dense-wavelength-division-multiplexing (DWDM) optical communication systems, precision metrology, environmental monitoring, and laser spectroscopy. These lasers were typically tuned with bulk and fiber-type gratings, Fabry-Perot Etalon or interference filters, as well as electro-optic or acousto-optic tunable filters.[1] In particular, a number of liquid crystal (LC) devices have been developed successfully as electronically tunable spectral filters for wavelength selection in lasers and related WDM system components.[2-7] These LC devices are either of the birefringent filter type[2,4,5] or have the Fabry-Perot structure[3,7]. The other approach, reported by Parker and Mears[6], employed holographic gratings electro-optically written on a ferroelectric liquid crystal spatial light modulator together with a fixed phase grating to tune the wavelength of a fiber laser to discrete wavelength spaced by 1.3 nm. Recently, we reported preliminary results on tuning the wavelength of a laser diode in a pointer over 3 nm by using a liquid crystal pixel mirror (LCPM).[8] In this work, we demonstrate narrow-band digital wavelength tuning of a red semiconductor laser over 14 nm by using a folded telescopic grazing-incidence grating-loaded external cavity[9,10] incorporating the LCPM. Electronic wavelength switching with a response time of 13.6 ms was also realized. We also present multi-wavelength generation from this laser. The same laser configuration can be modified for the 1550 nm band. Preliminary results are shown.

BASIC PRINCIPLES AND EXPERIMENTAL METHODS

A schematic of the laser is shown in Fig. 1. A low-power red laser diode (LD, Sacher-650-3, $\lambda \approx 650$ nm, 3 mW before coating) was used as the gain medium. Output from the AR-coated ($R \approx 3\times10^{-5}$, estimated) front facet of the LD was collimated and incident on a grating (2400 lines/mm) at an angle of 67°. Spectrally selective optical feedback was provided by the retro-reflected first-order-diffracted light from the grating, which was collected by a lens (f = 15 cm) and focused on the liquid crystal pixel mirror (LCPM). The LCPM is based on the design of a normally off-state twisted nematic liquid crystal (NLC) cell (See Fig. 2). The cell was constructed with a 6-μm-thick NLC (E7 manufactured by Merck) layer sandwiched between indium-tin-oxide (ITO) glass plates. One of the ITO-electrodes was patterned. The pattern consisted of fifty 100 μm × 2 cm stripes with 5 μm spacing. The back mirror was an Au-coated silicon substrate. The width of the pixel was chosen such that only one mode of the bare diode chip was selected. The polarizer was aligned to transmit light parallel to that of the incident laser polarization. The laser is electronically tuned and switched by biasing the individual pixels, with wavelength steps $\Delta\lambda$ determined by center-to-center separation of the adjacent pixels Δx,

$$\Delta\lambda = \Lambda \cos\theta_r \Delta x/f, \qquad (1)$$

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where Λ is the grating period; θ_r is the first-order diffraction angle; f is the focal length of the lens. The primary laser output is the zeroth-order reflection of the grating (~ 60% of the incident light from the diode chip).

The contrast ratio and on state reflectivity of the homemade LCPM were about 7:1 and 35% respectively. Because of high gain of the semiconductor media, the LCPM can achieve the desired spectral filtering function. The threshold switching voltage of the LCPM is 4 V_{pp} (peak - to – peak) at 10 kHz. Complete switching from off- to on-state is achieved at $10V_{pp}$.

RESULTS AND DISCUSSIONS

Figure 3 illustrate the narrow-band (< 0.1 nm, instrument limited) output of the laser as measured by an optical spectrum analyzer (Anritsu, model MS9030). The laser wavelength can be tuned discretely in 0.21 nm steps by biasing sequentially the 50 pixels. At I = 72.3 mA (or 1.54 I_{th}), the tuning range was 10.4 nm with λ = 650.8 nm for pixel #1 and λ = 661.24 nm for pixel # 50. Since we are limited by the number of pixels available for the present LCPM, the maximum tuning range was determined by switching on one pixel and translating the LCPM assembly with respect to the optical axis. The shortest and longest wavelength that can be tuned at this bias current was 650.04 nm and 664.04 nm. The side-mode-suppression-ratio (SMSR) of the laser was better than 25 dB throughout this range. In Fig. 4, we plot the lasing wavelength as a function of the pixel number. It is in good agreement with the theoretical prediction according to Eq. (1). The wavelength repeatability of the present laser is excellent. After switching to a different pixel, the laser wavelength is reset. Realignment of the laser cavity is not necessary.

In the wavelength-switching experiment, the 10kHz biasing signal was alternately applied to pixel # 13 (λ_1= 653.2 nm) and # 25 (λ_2= 658.48 nm). These switching waveforms are shown as trace 1 and 3 of Fig. 5. A second grating was used to angularly disperse the co-axial laser output at λ_1 and $\lambda_{2,}$, which were monitored by two photodiodes (PD1 and PD2 in Fig. 1). These are shown as traces 3 and 4 in Fig. 5. Wavelength switching is clearly demonstrated. The switch-on time, the time it takes for a pixel to change from an off state to an on state, is ~ 13.6 ms. This is primarily determined by the dynamic characteristics of the twisted NLC cell.

Figure 6 illustrates tunable dual-wavelength generation with wavelength separation tunable from 0.21 nm to 10. 4 nm. The two wavelengths are symmetric with the line center of the gain profile. Triple-wavelength generation with symmetric wavelength separation is shown in Figs. 7. An example of generation of three arbitrary wavelengths is given in Fig. 8. Preliminary result for using the present laser configuration for the 1550 nm band is shown in Fig. 9.

CONCLUSIONS

We demonstrate a novel electronically tunable laser diode. This is realized by using a folded telescopic grating-loaded external cavity with a liquid-crystal pixel mirror (LCPM) at the focal plane of the folded telescope. Broadband tunable (> 14 nm), narrow-band (< 0.1 nm, instrument-limited) output in 0.2 nm steps in the visible have been achieved. The SMSR of the laser output was better than 25 dB throughout this range. The tuning range and SMSR is limited by the available LD and LCPM. Electronic wavelength switching was also demonstrated. The wavelength switching time was ~ 13.6 ms. This can be speeded up by using different liquid crystal materials and surface alignment techniques. This laser configuration is particularly suitable for tunable multi-wavelength generation. Dual-wavelength generation with wavelength separation tunable from 0.21 nm to 10.4 nm is demonstrated. Triple-wavelength generation with equal and arbitrary wavelength separation is also realized. Preliminary result is also given for a laser operating in the 1550 nm band.

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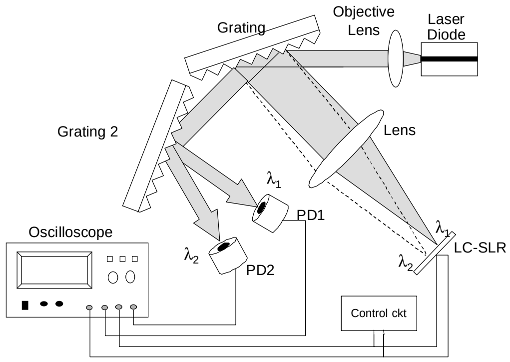

Fig. 1A schematic of the electronically tunable laser. Grating 2 and the photodiodes (PD1 and PD2), as well as the control circuit are for wavelength-switching expriments.

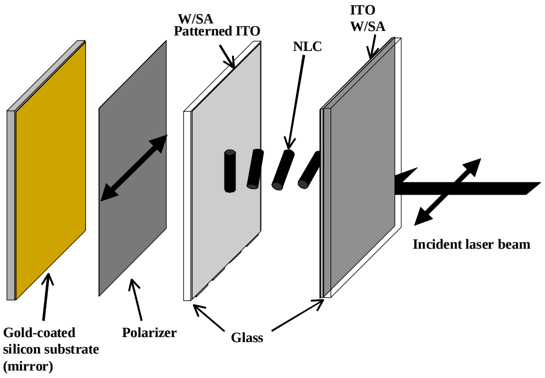

Fig. 2Configuration of the LCPM: ITO: indium-tin-oxide coating; NLC: nematic liquid crystal; SA: surface alignment layer.

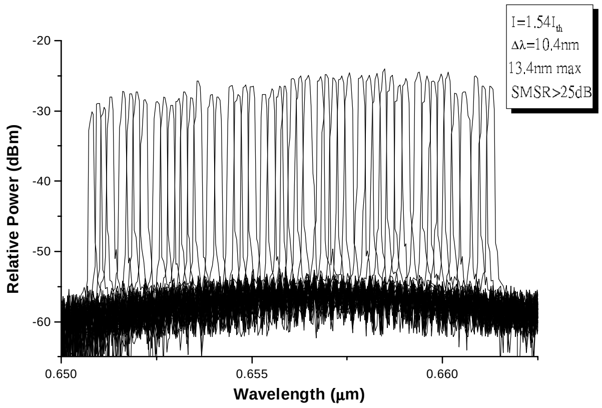

Fig. 3 Narrow-linewidth output spectra of the tunable laser diode by biasing successive pixels (50 in total) of the LCPM.

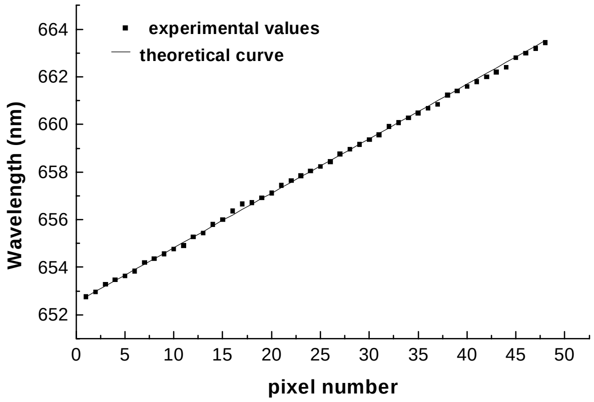

Fig. 4 Lasing wavelength as a function of the pixel number. The solid line is the theoretical curve according to Eq. (1). The solid squares are experimental data.

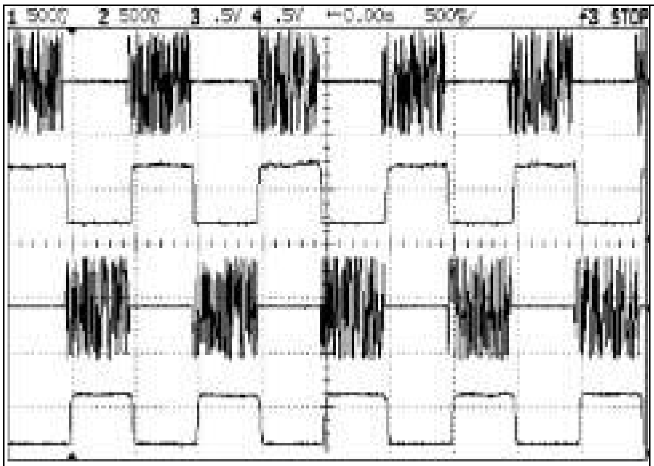

Fig. 5Wavelength-switching performance of the laser. Trace 1 and trace 2 are switching voltage waveforms applied to two pixels of the LCPM. Trace 3 and 4 are laser output

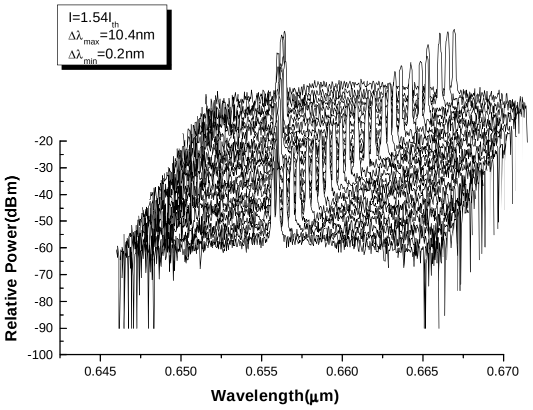

Fig. 6 Tunable dual-wavelength performance of the laser with symmetric wavelength separation

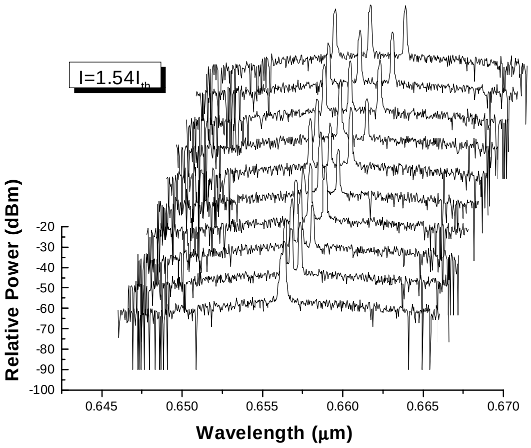

Fig. 7 Triple wavelength generation with symmetric wavelength separations.

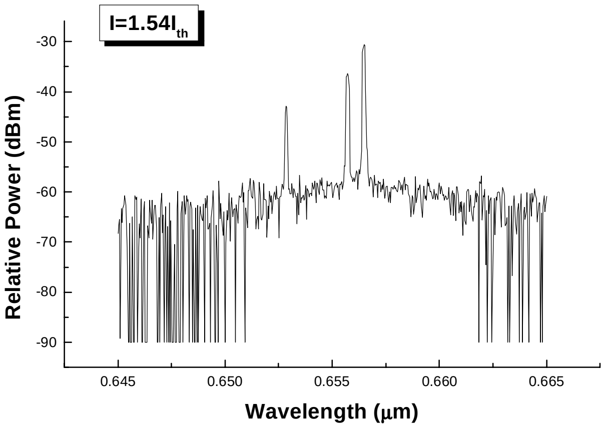

Fig. 8 Generation of three wavelength with arbitrary wavelength separation.

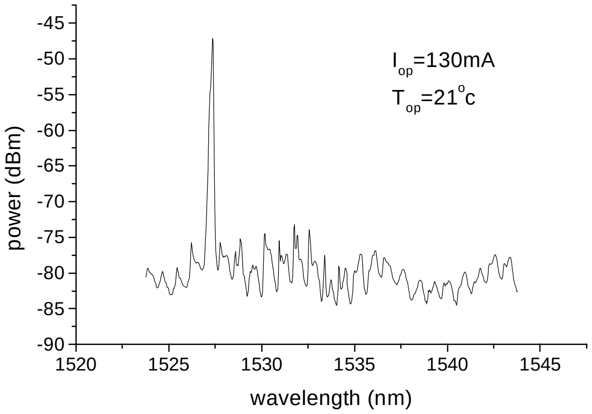

Fig. 9 Narrow-band single-wavelength generation for the 1550 nm band using the present laser configuration.