the oscillation threshold, it will still amplify signals as long as the gain from the medium exceeds the loss. This can be attributed to the modification of the gain and loss profile induced by the external signal, which gives the maximum gain and minimum loss at zero detuning [5]. The curves of smaller P_{sin} show larger gain at zero detuning, $\Delta\lambda = \lambda_s - \lambda_L = 0$ with the highest gain of 23.9dB for the lowest P_{sin} of –34.9dBm. As the input power is increased, the signal gain decreases. The feedback mechanism is effective, however, only over a limited bandwidth centred at zero detuning. The dashed line in Fig. 3 shows the signal gain for a single pass amplifier system. Without regenerative feedback, the gain is lower even though a P_{sin} as low as –34.9dBm was applied.

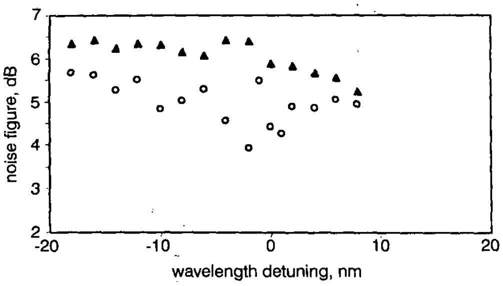

Fig. 4 *Noise characteristics of regenerative amplifier and open-ring system*

Input signal P_{sin} = –34.9dBm
○ regenerative amplifier
▲ open-ring system

Fig. 4 shows the noise against signal detuning for both systems with and without the optical feedback. Obviously, the regenerative amplifier gives a better noise performance throughout the whole spectral range. The minimum noise figure is 3.9dB as compared to the 5.2dB achieved with the open-ring system. The better noise performance for the former can be attributed to the higher gain and lower ASE power obtained around the zero detuning region. This is in good agreement with theory as presented in [4] that showed the highest signal-to-noise ratio to be around this region.

Conclusion: We have demonstrated a uni-directional regenerative erbium-doped fibre ring laser-amplifier operating below the oscillation threshold. The experimental results are in good agreement with those predicted theoretically. A comparison is made with an amplifier without optical feedback, showing the potential of the regenerative erbium-doped fibre laser-amplifier as a high gain and low noise figure active device.

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Tunable semiconductor laser with liquid crystal pixel mirror in grating-loaded external cavity

Ci-Ling Pan, Shang-Huang Tsai, Ru-Pin Pan, Chia-Reng Sheu and S.C. Wang

The wavelength of a commercial red pointer laser diode has been tuned over 4nm digitally in 0.2nm steps with a folded telescopic grating loaded external cavity incorporating a liquid crystal pixel mirror. The sidemode-suppression ratio of the laser was better than 20dB throughout this range.

Owing to their applications in areas such as optical communication, high-resolution spectroscopy and optical metrology, tunable semiconductor and fibre lasers have been extensively studied in the past decade. Typical wavelength tuning methods for these lasers include bulk and fibre-type Littrow and grazing-incidence gratings, Fabry-Perot etalon or interference filters, as well as electro-optic or acousto-optic tunable filters [1]. In particular, liquid crystal devices have been employed successfully as electronically tunable spectral filters for wavelength selection in these lasers and related WDM systems [2 – 6]. These devices are either designed as birefringent filters [2, 4] or Fabry-Perot interferometers [3, 6]. Parker and Mears [5], on the other hand, 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 fibre laser to discrete wavelengths spaced by 1.3 nm. In this Letter, we report a new type of tunable semiconductor laser by using a folded telescopic grazing-incidence grating-loaded external cavity [7, 8] incorporating a liquid crystal pixel mirror.

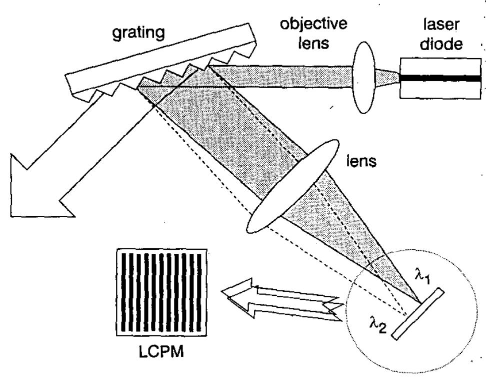

Fig. 1 *Schematic diagram of electronically tunable semiconductor laser with liquid crystal pixel mirror in folded telescopic grating-loaded external cavity*

A schematic diagram of the laser is shown in Fig. 1. A low-power red laser diode (LD, $\lambda \simeq$ 640nm, 1.5mW) from a commercial laser pointer was used without modification as the gain medium. The output of the LD was collimated and incident on the grating (2400 line/mm) at an angle of 67°. The primary laser output is the zeroth-order reflection of the grating (~ 60% of the incident light from the diode chip). Spectrally selective optical feedback was provided by the retro-reflected first-order-diffracted light from the grating, which was collected by a lens (f = 15cm) and focused on the liquid crystal pixel mirror (LCPM). It is based on the design of a normally off-state twisted nematic liquid crystal (NLC) cell. The cell was constructed with a 6μm-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 50 100μm × 2cm stripes with 5μm spacing. The polariser was aligned to transmit light parallel to that of the incident laser polarisation. The back mirror was an Au-coated silicon substrate. Narrowband laser oscillation at the desired wavelength is realised by electronically selected optical feedback of the retro-reflected light from one pixel of the LCPM to the laser diode. The width of the pixel was chosen such that only one mode of the bare diode chip was selected. The laser is electronically tunable by biasing the individual pixels, with wavelength steps $\Delta\lambda$

determined by the centre-to-centre separation of the adjacent pixels Δx:

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

where Λ is the grating period, θ_r is the first-order diffraction angle, and f is the focal length of the lens.

Mainly limited by the extinction ratio of the polariod, the on/off state contrast ratio of the pixels of the homemade LCPM is only ~ 5:1. Nevertheless, this is sufficient for achieving the desired spectral filtering function. The threshold switching voltage of the LCPM is $4V_{pp}$ (peak-to-peak) at 10kHz. Complete switching from the off- to on-state is achieved at $10V_{pp}$. The switch-on time, i.e. the time it takes for a pixel to change from an off state to an on state, is ~ 175ms. This is determined by the characteristics of the twisted NLC cell.

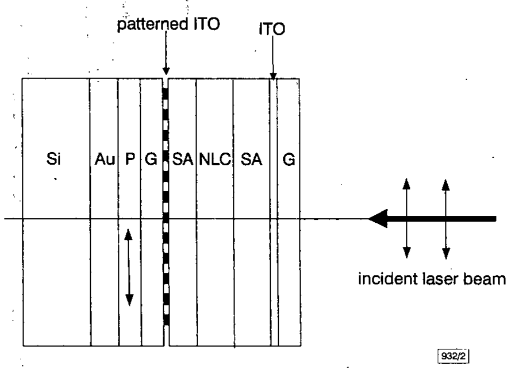

Fig. 2 *Configuration of LCPM*

G: glass plate; ITO: indium-tin-oxide coating; NLC: nematic liquid crystal; SA: surface alignment layer; P: polariser; Au: evaporated gold coating; Si: silicon substrate

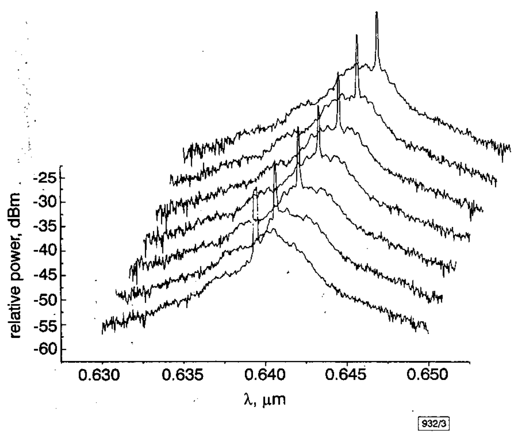

Fig. 3 *Narrow-linewidth output spectra of tunable laser as successive pixels were biased*

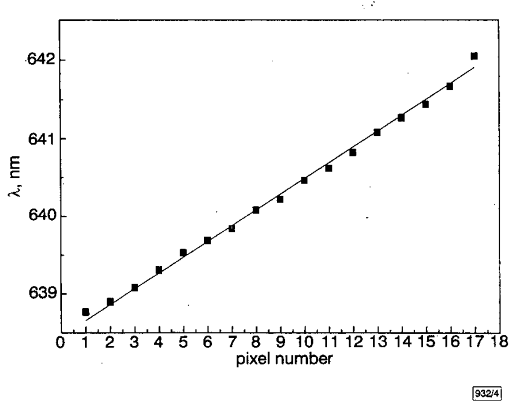

Fig. 4 *Lasing wavelength against pixel number*

——— theoretical curve according to eqn. 1
■ experimental data

The laser wavelength can be tuned from 636 to 643nm discretely in 0.20nm steps by biasing sequentially the pixels (see Fig. 3). The sidemode suppression ratio (SMSR) of the laser was better than 20dB throughout this range. In Fig. 4, we plot the lasing wavelength against the pixel number. It is in good agreement with the theoretical prediction according to eqn. 1. The wavelength re-setability 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. The tuning range of the laser is limited by the reflectivity of the front facet of the LD. With antireflection coating such that $R < 1\%$ for this facet, the tuning range of the laser can easily exceed several tens of nanometres [7, 8]. The SMSR of the laser output can be improved if we employ LCPMs with higher contrast ratios.

In summary, we have realised a novel tunable semiconductor laser by using a folded telescopic grating-loaded external cavity with a liquid crystal pixel mirror (LCPM) at the focal plane of the folded telescope. We achieved narrow-band (< 0.1nm, instrument-limited) electrically-tunable output from 636 to 643nm in 0.27nm steps with a low-power red LD in a commercial laser pointer. The SMSR of the laser output was better than 20 dB throughout this range. The tuning range and SMSR are limited by the reflectivity of the front facet of the LD and contrast ratio of the LCPM. The wavelength switching time was ~175ms. The use of different liquid crystal materials and surface alignment techniques can speed this up.

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