Tunable two color emission in a compact semiconductor ring laser with filtered optical feedback

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We report on an integrated approach to obtain two color emission from a semiconductor ring laser with filtered optical feedback. This feedback is realized on-chip by employing two arrayed waveguide gratings to split/recombine light into different wavelength channels. Semiconductor optical amplifiers are used in the feedback loop to control the feedback strength of each wavelength channel independently. Results show that the effective gain of the different modes is the key parameter which has to be balanced to obtain two color emission. This can be achieved by tuning the injection current in each amplifier.

Introduction and Device description

For numerous scientific and industrial applications, it is of interest to have tunable, two color emission (TCE) lasers. Such applications include wavelength-division multiplexing in optical communications systems, optical sensing and THz generation [1]. Several approaches have been proposed to achieve TCE using different laser systems, such as fiber lasers, solid-state lasers and external cavity laser diodes. Although these systems show a good performance, they tend to be bulky and expensive. Therefore, there is a profound interest in achieving TCE in single-chip laser diodes, with devices being potentially small in size, low-cost and integrable with other photonic components.

In this paper we propose an approach to achieve TCE in a monolithic laser diode structure. Semiconductor ring lasers (SRLs) with on-chip filtered optical feedback have been proposed in [2] to obtain tunable single color emission (SCE). Here, we will show that the same scheme can also support the simultaneous emission of two longitudinal modes (LMs) by balancing the effective gain of selected LMs. This scheme has several advantages: Firstly, the SRL does not require distributed feedback or DBR mirrors, it is easily integrable with other photonic components. Secondly, The competition between

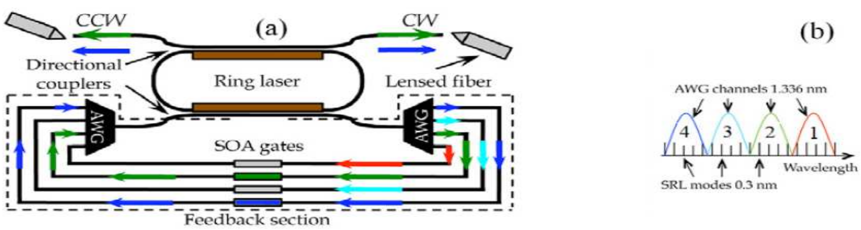

Figure 1: (a) Layout of the integrated ring laser with on-chip filtered optical feedback.
(b) The alignment of the AWG channels .

the clockwise/counterclockwise propagating modes of a SRL cavity leads to interesting dynamical regimes. Thirdly, we can select different pairs of wavelengths under TCE in a non-thermal fashion by changing the current injected in the different SOA gates. Finally, we can easily switch between TCE and single-mode operation by changing one of the gate currents.
The device consists of a SRL, two arrayed waveguide gratings (AWG) which are used to split/recombine light into 4 different wavelength channels, four semiconductor optical amplifier (SOAs) gates and passive and active waveguides to connect these components. The AWG channel spacing is 1.336 nm and the AWG free spectral range is 5.65 nm, whereas the mode spacing is 0.305 nm. Therefore, each AWG channel supports 4 modes. The scheme of the device is shown in Fig. 1(a). The channels alignment of the AWGs is shown in figure 1(b). Each SOA gate can be independently pumped electrically. When a gate is biased, the feedback strength and phase of the LMs in the corresponding AWG channel will change. When a gate is not biased, or when it is reverse biased, light is absorbed and therefore there is no feedback effect.

Experimental study

We use electrical probes to pump the SRL and the gates which are chosen to provide feedback. We measure the output in the clockwise (CW) and counter clockwise (CCW) directions using lensed optical fibers. The threshold current of this device is 64.5 mA. We pump the SRL well above the threshold at 85 mA. Without filtered feedback, the laser emits multiple longitudinal modes. By pumping one gate with sufficient current we obtain a SCE in agreement with [2]. Next when two gates are pumped simultaneously, (for example we choose to bias gates 2 and gate 3), TCE can be observed in the CCW direction for a gate 3 current of 8.63 mA and a gate 2 current of 20.6 mA as shown in figure 2(a). The two dominant peaks are located at λ_3=1582.296 nm , and λ_2=1583.210 nm (which corresponds to the wavelength channels of gate 3 and gate 2, respectively). Similar TCE is noticed in the CW direction. We can also tune the emission wavelengths under TCE operation electrically by changing the gates that are forwardly biased. Although we cannot tune the wavelengths continuously, a discrete set of simultaneously emitted wavelengths can be selected.
To investigate the influence of the gate currents on the TCE, we fix the laser current at 85 mA and the gate 3 current at 8.63 mA. We gradually increase the gate 2 current from 0

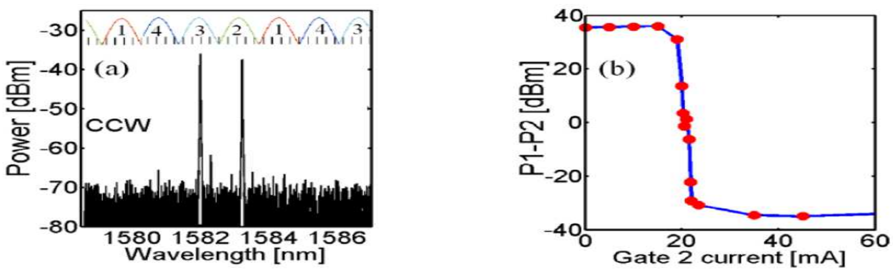

Figure 2: (a) Optical spectrum in CCW direction for a SRL current of 85 mA, a gate 3 current of 8.63 mA, and a gate 2 current of 20.6 mA. (b) Optical power difference between the two peak wavelengths in the spectrum as a function of gate 2 current. SRL current fixed to 85 mA, gate 3 current fixed to 8,63 mA. Solid line is to guide the eye

mA to 60 mA. For each value of the gate 2 current, we measure the optical spectrum and we extract the optical power at the peak wavelengths shown in figure2(a). The difference between the power P1 at the wavelength λ_3 and the power P2 at the wavelength λ_2 is plotted in figure2(b) as a function of the current applied to gate 2. When this difference is equal to 0, both wavelength modes are emitted with the same power and we achieve TCE. When the power difference is larger than 30 dBm, the laser emits only the LM at λ_3. Likewise, when the power difference is smaller than -30 dBm, the laser emits only the LM at λ_2. From figure2(b) it can be seen that there is TCE in a relatively narrow range of gate 2 currents (from 19 mA to 21 mA). If the gate 2 current is tuned away from this value, there is a continuous transition region where the power in one of the LMs decreases (accompanied by a similar increase in the other LM). A similar transition region can be observed when gate 2 is fixed at 20.6 mA and the gate 3 current is changed. Performing the measurement shown in figure 2 both for increasing and decreasing the current injected in gate 2, yields the same results. This shows that there is no hysteresis in the transition from SCE behavior to TCE. More details about this work can be found in [3]

Numerical study

We use a two-directional mode rate-equation model of the SRL extended with Lang-Kobayashi terms to take into account the effect of optical feedback. In terms of the mean-field slowly varying complex amplitudes of the electric field associated with the two propagating modes E_m^{cw} and E_m^{ccw}, and the carrier number N, these equations are

$$\dot{E}_m^{cw} = \kappa(1+i\alpha)\left[N\mathcal{G}_m^{cw}-1\right]E_m^{cw}-(k_d+ik_c^{ccw})E_m^{ccw}+\eta_m E_m^{cw}(t-\tau)e^{i\theta_m} \quad (1)$$

$$\dot{E}_m^{ccw} = \kappa(1+i\alpha)\left[N\mathcal{G}_m^{ccw}-1\right]E_m^{ccw}-(k_d+ik_c^{cw})E_m^{cw}+\eta_m E_m^{ccw}(t-\tau)e^{i\theta_m} \quad (2)$$

$$\dot{N} = \gamma\left[\mu-N-N\sum_{m=1}^{n}\left(\mathcal{G}_m^{cw}|E_m^{cw}|^2+\mathcal{G}_m^{ccw}|E_m^{ccw}|^2\right)\right] \quad (3)$$

where "m" refers to different longitudinal modes. In these equations α =3.5 is the linewidth enhancement factor, κ =200 ns^{-1} is the field decay rate , γ = 0.4 ns^{-1} is the carrier inversion decay rate, μ =1.2 is the normalized injection current, η_m and θ_m represent the feedback strength and phase, respectively, τ = 76 ps is the delay time which corresponds to the propagation time in the filtered feedback section, k_d = 0.2 ns^{-1} represents the dissipative backscattering and is taken equal for the two directional modes. A small asymmetry between the two directional modes is introduced via the conservative backscattering coefficients: k_c^{cw} =0.88 ns^{-1} whereas k_c^{ccw} =1.144 ns^{-1}. This asymmetry is needed in order to reproduce the experimentally observed asymmetry in the power output when the gates in the filtered-feedback section are unpumped [8]. The differential gain functions are given by $\mathcal{G}_m^{cw}=\left(1-s|E_m^{cw}|^2-c|E_m^{ccw}|^2\right)$, $\mathcal{G}_m^{ccw}=\left(1-s|E_m^{ccw}|^2-c|E_m^{cw}|^2\right)$, where s=0.005 is the self saturation and c = 0.01 is the cross-saturation between the two directions of the same LM. We have limited the number of LMs to two (n=2) as it corresponds to the minimum number of equations needed to describe TCE.

We consider the case for which LM_1 is initially selected by introducing a finite amount of feedback η_1=15 ns^{-1} in the corresponding filter channel. We then change the feedback strength η_2 experienced by LM_2 while the feedback phases are fixed to $\theta_1 = \theta_1 = 0.5\pi$. As long as η_2 is much smaller than η_1, LM_1 will be lasing while LM_2 remains switched off. When the feedback strength η_2 becomes comparable to η_1, the intensity in LM_2

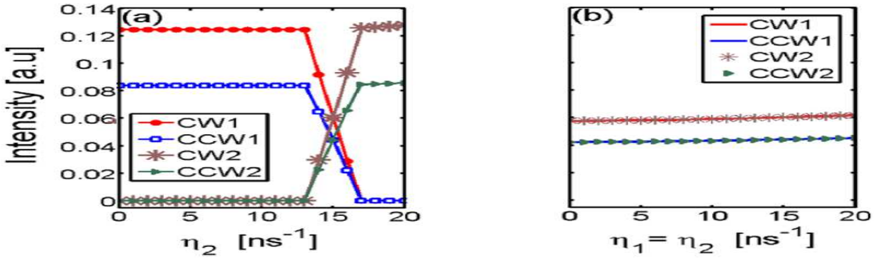

Figure 3: (a) Intensities of both modes when the feedback strength η_2 was increased while η_1 was fixed to 15 ns^{-1} and $\theta_1 = \theta_1 = 0.5\pi$. (b) Intensities of both modes when feedback strengths η_1, η_2 are equal and increased equally at the same time.

gradually grows and it becomes equal to the intensity in LM_1 when η_2 is equal to η_1. For still higher values of η_2, LM_1 will gradually be switched off, as can be seen in figure 3(a). This indicates that the TCE is actually due to a precise balancing of the total gain (i.e. including gain, losses and feedback) in the SRL. We also checked in the simulations that there is no hysteresis in the transition between LM_1 and LM_2 plotted in figure 3(a). We obtain the same results by increasing or decreasing η_2, similarly as in the experiments. The simulations shown in figure 3(a) indicate that TCE is obtained when the feedback strengths in the two selected wavelength channels are equal. This is further elaborated on in figure 3(b) where we plot the simulated intensities when keeping η_1 equal to η_2 and changing both feedback strengths simultaneously. In that case we obtain TCE for all values of the feedback strength. This clarifies why TCE can be observed experimentally for several different values of the gate currents.

Conclusions

In this contribution, we have experimentally and numerically demonstrated that TCE can be achieved in a SRL with filtered optical feedback. The wavelengths can be tuned discretely by selecting different wavelength channels. This can be done by changing the currents injected in the SOA gates to balance the effective gains of the two modes. We have supported these experimental results by numerical simulations which have shown qualitative agreement with the experimental observations.

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