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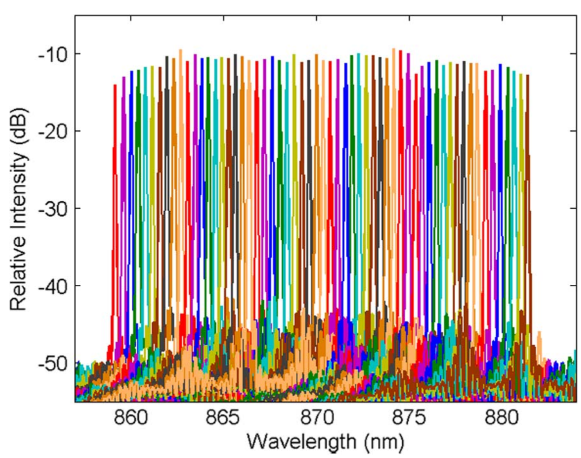

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GaAs/AlGaAs-Based 870-nm-Band Widely Tunable Edge-Emitting V-Cavity Laser

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Abstract: An 870-nm-band wavelength tunable edge-emitting semiconductor laser based on V-coupled cavities in a GaAs/AlGaAs material system is presented. It does not involve any grating or epitaxial regrowth. Using a single electrode control, 31-channel wavelength tuning with a channel spacing of about 0.38 nm is achieved, with a tuning range of 11.4 nm. By additionally varying the temperature from 8 °C to 50 °C, wavelength tuning of 60 channels over 22.4 nm is demonstrated. At lower tuning current and with a temperature variation of 18 °C, wavelength switching by carrier plasma effect is achieved with a tuning range of 8.2 nm. The simple and compact 870-nm-band edge-emitting tunable laser is suitable for multifunctional photonic integration for optical interconnect and biomedical applications.

Index Terms: Widely tunable semiconductor laser, V-cavity laser, GaAs/AlGaAs.

1. Introduction

Low-cost widely tunable lasers in the 800 nm $\sim$ 870 nm wavelength window are very desirable for next generation reconfigurable optical interconnects [1]. They are also very useful for biomedical applications such as non-invasive health monitoring [2], [3] and optical diagnostics [4] because the wavelength falls in the transparency window of biological tissues. Semiconductor lasers in this wavelength window commonly employ GaAs/AlGaAs based quantum well (QW) active regions, although high performance 850-nm diode lasers with high speed and high temperature characteristics have been achieved by using strained QWs based on AlInGaAs [5], InGaAsP [6], and InGaAs [7] due to improved differential gain in the active regions. At present, tunable semiconductor lasers in this wavelength range have been relatively immature as compared to commercially available InP-based telecom 1550 nm-band widely tunable lasers which commonly employ complex grating structures such as sampled grating distributed Bragg reflectors (SGDBR) [8], [9], although diffraction grating based external cavity lasers [4], [10], [11], micro-electro-mechanical system (MEMS) based vertical cavity surface emitting laser (VCSEL) [1], [12], [13], and distributed Bragg reflector (DBR) laser [14]–[16] have been reported. For external cavity lasers, wide tuning range has been achieved, but their large size and high packaging cost have limited their applications mainly to laboratory instruments. For the MEMS based VCSEL, wavelength tuning is enabled by thermal actuated membrane [12]. It has low output power and slow tuning speed and is not suitable for multi-functional photonic integration. For short-wavelength DBR lasers, there are difficulties related

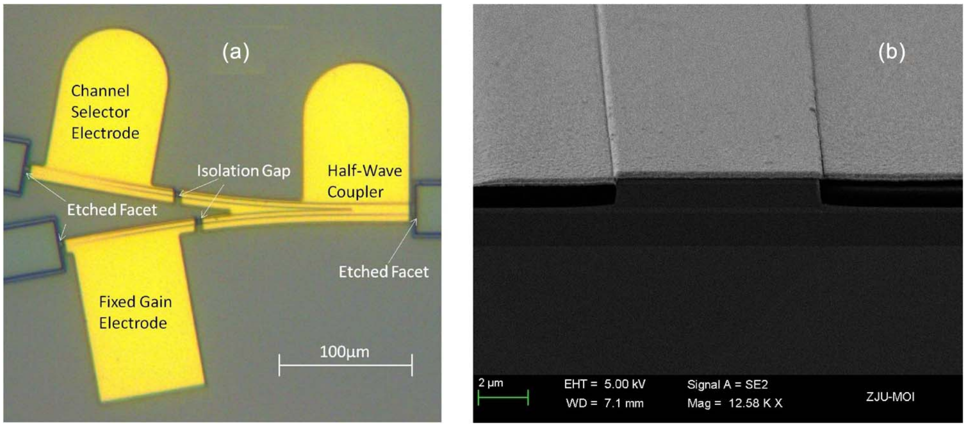

Fig. 1. (a) Top view of the GaAs/AlGaAs based V-cavity tunable laser and (b) the cross-section SEM image of the half-wave coupler.

to the grating fabrication due to the small period (~120 nm for 850 nm wavelength) and the rapid oxidation of the Al-containing layers after the grating etching.

Recently, a simple and compact V-coupled cavity semiconductor laser has been proposed [17], and single-electrode controlled wide wavelength tuning was demonstrated in the 1.55 μm window in InP based material system [18], [19]. In this paper, we report V-coupled cavity lasers based on GaAs/AlGaAs multiple QW (MQW) material system operating in the short-wavelength 870 nm-band. The fabrication process of the laser is similar to Fabry-Perot lasers, and its size is only 300 μm $\times$ 300 μm. The V-cavity laser does not require any grating structure or epitaxial regrowth, which makes it particularly advantageous for realizing widely tunable edge-emitting lasers suitable for photonic integration based on GaAs/AlGaAs or other Al-containing material system.

2. Device Structure and Fabrication

The layer structure of the laser consists of three 80 Å GaAs QWs separated by 100 Å $Al_{0.2}Ga_{0.8}As$ barriers, with 900 Å top and bottom barrier layers which also constitute the separate confinement layers for the optical waveguide. The upper and lower claddings consist of 0.9 μm p-doped $Al_{0.8}Ga_{0.2}As$ and 1.5 μm n-doped $Al_{0.8}Ga_{0.2}As$, respectively. A 0.2 μm p^+-doped GaAs cap layer is used for ohmic contact. The wafer is grown by metal-organic chemical vapor deposition on n-doped GaAs substrate. The center wavelength of the photoluminescence peak is measured to be about 870 nm.

The operation principle of the V-coupled cavity laser has been described in detail in [17] and [18]. Fig. 1(a) shows the top view of the V-cavity laser fabricated in GaAs/AlGaAs. It consists of two Fabry-Perot cavities with V-shaped ridge waveguides coupled by a reflective 2 $\times$ 2 half-wave coupler. The coupling coefficient of the coupler is optimized to achieve single longitudinal mode output with high side mode suppression ratio (SMSR). The half-wave coupler has a length of 50 μm and a gap of 1.8 μm between two 3 μm-wide waveguides, which produces a self-coupling coefficient of 78%. In order to accurately control the lengths of the half-wave coupler and of the two cavities, deep etched facets are used to form the cavity mirrors. The two cavities are designed to have slightly different lengths so that the Vernier effect can be employed to increase the wavelength tuning range. In the current device, the lengths of the two cavities are 277 μm and 305 μm, respectively. The corresponding free spectral range (FSR) of the tunable laser as determined by the Vernier effect is about 3.4 nm. The laser has three electrodes separated by isolation gaps. One is deposited on the half-wave coupler and can be used for direct modulation of the laser. The fixed gain electrode on the shorter cavity is used to inject a constant current to provide a fixed optical gain, and the channel selector electrode is used for applying a variable current to change the effective index in order to switch the laser wavelength. The total chip size is about 300 μm $\times$ 300 μm.

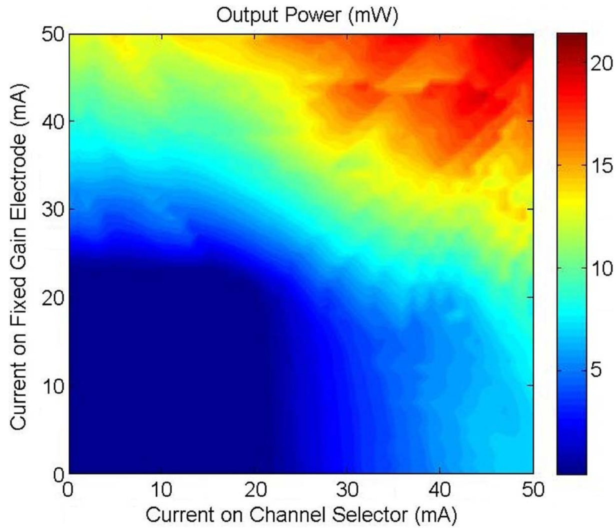

Fig. 2. Output power versus current on fixed gain electrode and channel selector.

The fabrication process starts with the deep etching for the reflection facets with photoresist used as the mask. Ar and BCl_3 are used for the dry etching of GaAs/AlGaAs. The etching depth is about 2.6 μm. The ridge waveguide is then fabricated by dry etching of about 1.1 μm using the same recipe. The ridge waveguide is planarized using benzocyclobutene (BCB), after which Ti/Pt/Au is sputtered on the top side to form the contact electrode pads using a lift-off process. The shallow isolation gaps are formed by dry etching to remove the p^+-doped GaAs cap using the electrode pad as the self-aligned mask. Finally, the backside of the wafer is lapped and polished before Ge/Au/Ni/Au is sputtered to form the back side electrode. Fig. 1(b) shows a scanning electron microscope (SEM) picture of the waveguide cross-section of the half-wave coupler.

3. Measurement Results and Discussions

The laser is tested after being mounted on an aluminum nitride chip carrier with a thermo-electric cooler (TEC) control. The three electrodes are biased with three independent current sources under the CW condition. Fig. 2 shows the output power versus currents on the channel selector electrode and the fix gain electrode, while the current on the coupler is held at 5 mA and the TEC temperature is set at 20 °C. The threshold current for the V-coupled cavity laser is about 23 mA when the current is injected on a single cavity. The output power from the coupler side can reach about 22 mW when both of the fixed gain and channel selector electrodes are injected with 50 mA. The slope efficiency ranges from 0.33 W/A at low currents to about 0.2 W/A at high currents.

Fig. 3 shows an emission spectrum of the laser. The currents on the half-wave coupler, the fixed gain electrode, and the channel selector are 3 mA, 42 mA, and 81 mA, respectively. The TEC temperature is controlled at 22 °C. The SMSR is about 36 dB, and the lasing wavelength is 874.2 nm.

Fig. 4(a) shows the wavelength of the main mode as a function of the tuning current on the channel selector when the current on the half-wave coupler and the fixed gain cavity are 3.5 mA and 28 mA, respectively, and the temperature is controlled at 20 °C. When the tuning current on the channel selector changes from 30 mA to 70 mA, 31 channels discrete wavelength tuning with channel spacing of about 0.38 nm is obtained. The wavelength varies from 872.2 nm to 883.6 nm, for a tuning range of 11.4 nm. As the current on the channel selector increases, the wavelength increases, which indicates that the refractive index of the channel selector increases with the current and therefore the tuning is dominated by thermal-optic effect. Fig. 4(b) shows the superimposed spectra of the 31-channel consecutive wavelength switching.

The tuning curve of Fig. 4(a) can be shifted up and down by varying the current on the fixed gain electrode. Because the fixed gain cavity has a shorter length than the channel selector cavity, the

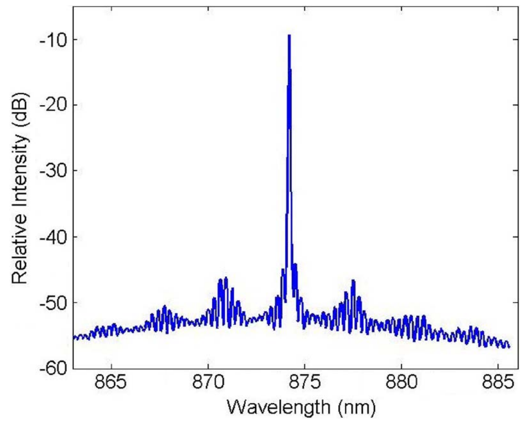

Fig. 3. Single channel spectrum with SMSR of 36 dB.

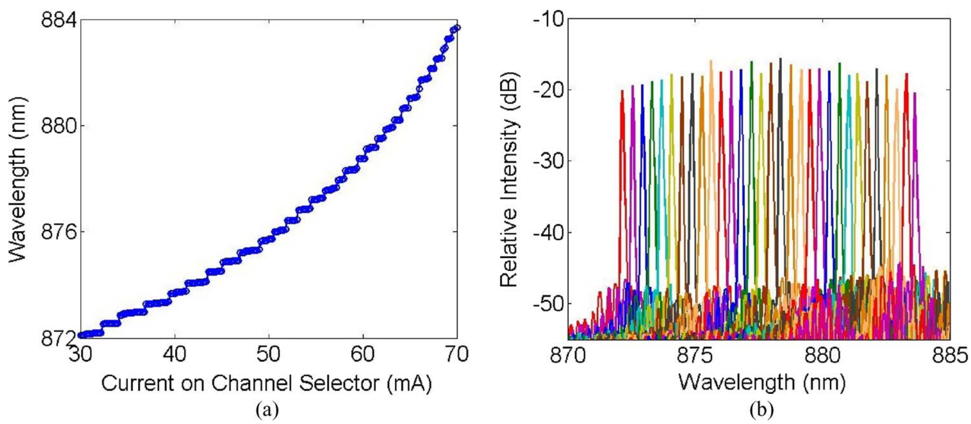

Fig. 4. (a) Measured wavelength tuning curve and (b) superimposed 31-channel spectra.

wavelength shifts to shorter wavelength direction when the current on the fixed gain electrode increases, opposite to the case where the current on the channel selector is varied. Further, the tuning curve can be shifted by varying the TEC temperature. Since the material gain spectrum shifts to longer wavelength when the temperature increases, the tuning range can be increased beyond the FSR determined by the cavity length difference when the channel selector current is tuned under the thermal-optic regime [19]. For GaAs based material system, the gain spectrum shifts at a rate of about 0.35 nm/°C, the tuning range can therefore be extended by about 14 nm for a temperature range of 40 °C. Fig. 5(a) shows the tuning curve of the laser at four different temperatures of 8 °C, 22 °C, 40 °C, and 50 °C, when the current on the fixed gain cavity is set at 42 mA. A total of 60 channels are obtained, covering the wavelength range from 859 nm to 881.4 nm, for a total of 22.4 nm. Fig. 5(b) shows the overlapped spectra of the wavelength tuning. The SMSR ranges from 33 dB to 36 dB.

Since the tunable V-cavity laser is fabricated in an all-active MQW material system with a single bandgap throughout the device, the increase of current in the tuning electrode tends to increase the output power at the same time. This is the case when the injected currents are low. However, at high current levels, the local temperature increase in the ridge waveguide results in lower quantum efficiency, thus reducing the output power. Therefore, the output power remains quite flat over a wide tuning range due to counter-balance of the two effects, as can be seen in Fig. 5(b).

In the above experiments, the tuning current on the channel selector is above 30 mA, and the refractive index change under the tuning electrode is mainly caused by thermo-optic effect. Fig. 6

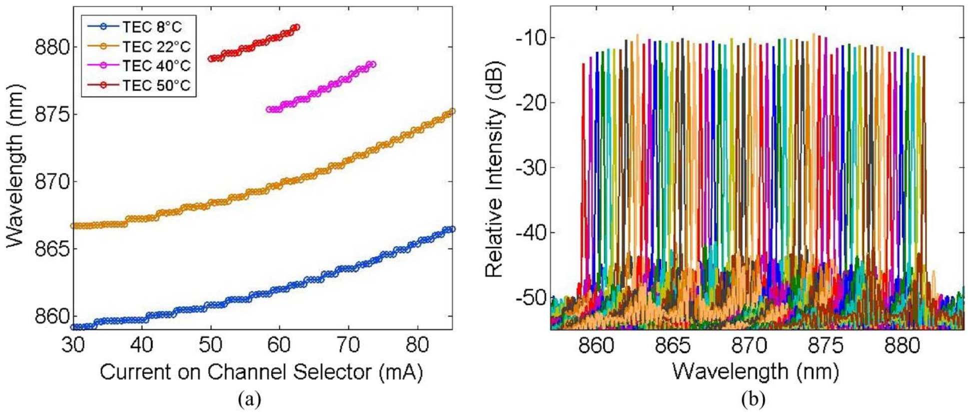

Fig. 5. (a) Measured tuning curves at four different TEC temperatures of 8 °C, 22 °C, 40 °C, and 50 °C. (b) Overlapped 60-channel wavelength tuning spectra.

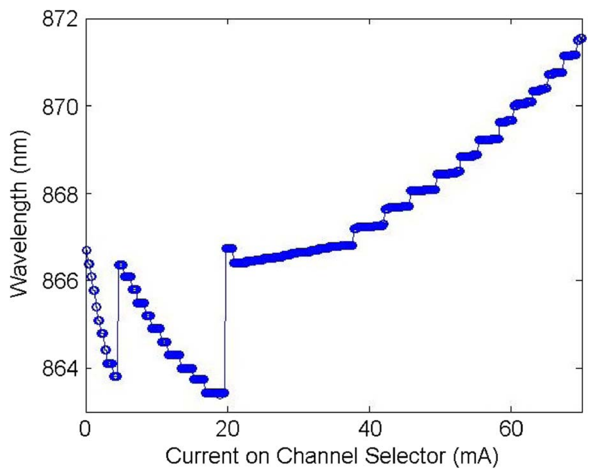

Fig. 6. Wavelength versus tuning current under both carrier plasma dispersion and thermal-optic regimes.

shows the wavelength tuning curve when the current on the channel selector varies from 0 to 70 mA at 22 °C. We can see that when the tuning current is below 20 mA, the thermal effect becomes negligible and the carrier injection induced plasma dispersion becomes the dominant effect for the refractive index change. The wavelength decreases as the tuning current increases, opposite to the case of thermo-optic regime. At 5 mA and 20 mA, the wavelength jumps by one FSR. For current between 20 and 40 mA, the tuning effect is weak because of the counter-balance between the plasma dispersion and the thermal-optic effects.

Fig. 7(a) shows the wavelength tuning curve at three different temperatures of 12 °C, 20 °C, and 30 °C with the current on the channel selector electrode varying from 2 mA to 7.5 mA. The currents on the coupler and the fix gain electrode were set at 5 mA and 34 mA, respectively. Fig. 7(b) shows the superimposed wavelength switching spectra. As we can see, only a small current variation is needed to realize channel switching and the output power is very flat. Under the regime of the carrier plasma effect, the switching time is very fast (on the order of nanoseconds) [20]. Because the tuning section in the current device has the same bandgap as the gain section, the refractive index variation is limited. However, it is sufficient to tune the wavelength over one FSR of the V-cavity laser at each temperature. By varying the temperature from 12 °C to 30 °C, the laser was able to tune over 27 channels with a total tuning range of 8.2 nm. The SMSR was about 31 dB, somewhat

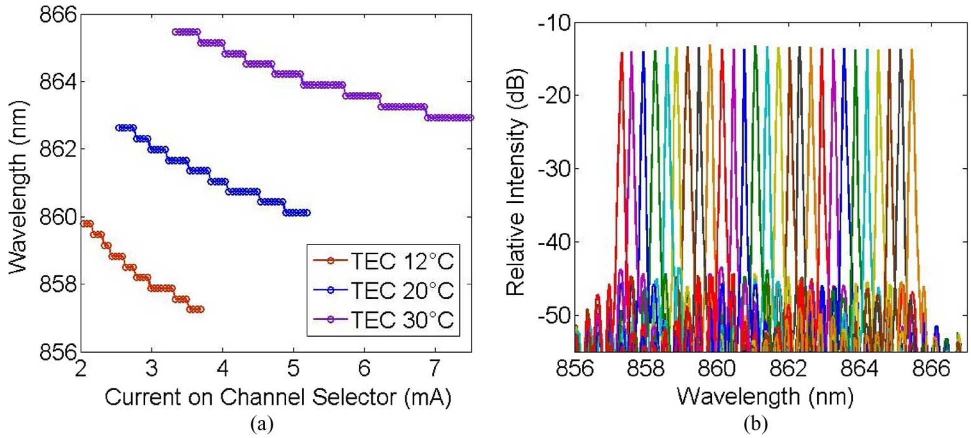

Fig. 7. (a) Wavelength versus tuning current by carrier plasma effect and (b) superimposed tuning spectra

lower than the case under thermal-optic regime because of the lower current injection and more imbalanced gains in the two cavities.

Note that unlike in a laser with a single gain electrode, the carrier density in the V-cavity laser with multiple gain electrodes is not completely clamped under each of the electrode. The increase of the tuning current in the channel selector can result in a decrease in the carrier density under the fixed gain electrode due to increased optical power, and an increase in the carrier density under the tuning electrode, with an overall clamping effect. This allows the wavelength tuning of the V-cavity laser by carrier plasma effect even though the channel selector is an active gain section inside the laser operating above the threshold.

4. Conclusion

In conclusion, we have demonstrated an 870 nm-band wavelength tunable edge-emitting semiconductor laser based on V-coupled cavity in GaAs/AlGaAs material system. It does not involve complex grating or multiple epitaxial growths and has the advantages of compactness and fabrication simplicity. This structure is particularly interesting for the short-wavelength band laser based on GaAs/AlGaAs because the conventional DBR and SGDBR structures face difficulties related to the grating fabrication due to the small period and oxidation of the Al-containing layers. Under the thermo-optic regime, a 31-channel single-electrode controlled wavelength tuning over 11.4 nm is achieved, and a 60-channel wide wavelength tuning over 22.4 nm is demonstrated by using a single-electrode current control in combination with TEC temperature variation from 8 °C to 50 °C. The SMSR ranges from 33 dB to 36 dB. At lower tuning current, wavelength tuning by carrier plasma effect is also demonstrated for 27-channel switching over 8.2 nm with temperature variation of 18 °C. The laser performance can be further improved by design optimization and fabrication improvement. The simple and compact 870 nm-band tunable laser has great potential for applications in reconfigurable optical interconnect and noninvasive biomedical applications.

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