

Wide-Range Tunable Semiconductor Lasers Using Asymmetric Dual Quantum Wells

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Abstract—Using asymmetric dual quantum wells for the laser material, the semiconductor lasers are broadly tunable. In a grating coupled ring cavity, the semiconductor laser is continuously tunable from 766 to 856 nm using a 400- μm semiconductor laser amplifier in the cavity. This letter also demonstrates that the grating coupled ring cavity could well eliminate the amplified stimulated emission noise and about 40-dB amplified spontaneous emission (ASE) suppression ratio is obtained over the entire tuning range.

Index Terms—Amplified spontaneous emission (ASE) suppression ratio, asymmetric dual quantum wells, linear cavity, ring cavity, semiconductor laser amplifiers (SLA's), tunable semiconductor lasers.

I. INTRODUCTION

TUNABLE semiconductor lasers are expected to play an important role in wavelength-division multiplexing (WDM) system and optical measurements. Wide tuning range and small frequency noise are important features for tunable semiconductor lasers. Many efforts have been devoted to the development of broadly tunable semiconductor lasers [1]–[5]. A tuning range about 50–60 nm (100 meV) at the wavelength of 0.8 μm had been demonstrated using antireflection coated laser diodes in an external cavity using the diffraction grating as the feedback mirror [1], [2]. Tuning ranges of 160 nm (113 meV) at 1.3 μm [3] and 240 nm (130 meV) at 1.55 μm [4] were also demonstrated using MQW laser in a similar cavity configuration. Using a particular single-quantum-well laser, over 105-nm (200-meV) tuning range around 0.8 μm was reported [5]. It was achieved by properly adjusting the cavity loss to excite the first and the second quantized states simultaneously, so only a certain device length is useful for this purpose. Recently, quantum wells of different widths were cascaded to form a broad-band material [6]. This broad-band nature is not mainly contributed from the second quantized state, so no particular device length is required. The similar idea had been applied to tunable semiconductor lasers using three $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ wells of different widths and a tuning range from 901 to 981 nm was reported [7]. In this letter, we report that, using asymmetric dual quantum wells for the laser material, the semiconductor lasers are also broadly tunable. In a grating coupled ring cavity, the semiconductor laser could

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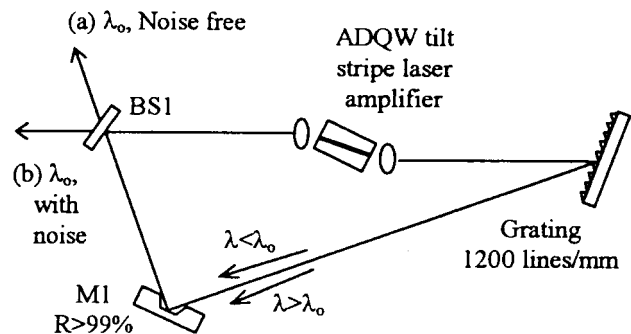


Fig. 1. The experimental setup of the triangular ring cavity. (BS1: beam splitter used as the output coupler; M1: mirror with $R > 99\%$).

have a tuning range of 90 nm (170 meV). We also demonstrate that the grating coupled ring cavity could significantly reduce the amplified stimulated emission (ASE) noise and about 40-dB ASE suppression ratio is obtained over the entire tuning range.

II. EXPERIMENT

To realize the wide-tuning range of the semiconductor laser, a gain medium with a broad bandwidth is necessary. Conventional semiconductor-laser gain medium using the quantum-well structure or heterostructure for the wavelength near 0.8 μm has only 50-meV bandwidth. However, improvement can be achieved by cascading two quantum wells of different widths. Using 40 and 75 \AA for the well widths, the quantized energy levels in the two wells separate for about 50 meV, corresponding to 300 \AA in wavelength, so the gain bandwidth can be broadened to about 100 meV [6]. Detailed discussions on the separation of energy levels and design considerations had been given in [6]. We used this material to fabricate the semiconductor laser amplifiers (SLA's) for the experiments. The devices were fabricated using the standard processing techniques. The semiconductor laser amplifiers (SLA's) have a ridge waveguide that is tilted at 7° from the normal of the cleaved facet in order to greatly eliminate the gain ripple. The ridge waveguide is 6 μm wide. Different lengths of the devices were fabricated for the tuning experiments.

The experimental setup is schematically shown in Fig. 1. Because the cross section of the active region is very small and both facets of the SLA have a very small retroreflectivity, the alignment using a linear cavity becomes extremely difficult. Therefore, a ring cavity is used for our tuning experiment. Two collimators (ThorLab C230TMB) with $f = 4.5$ mm and $NA = 0.55$ are used to collimate the light beam emitted

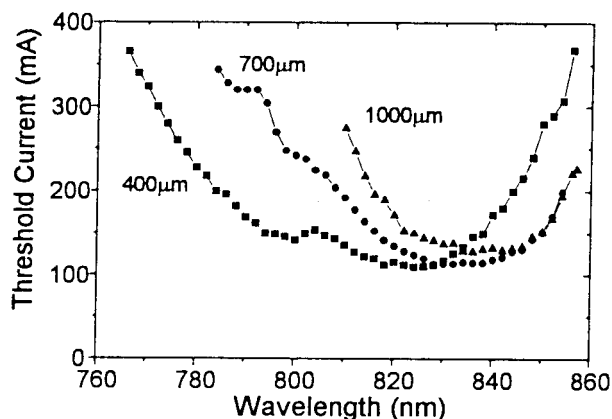


Fig. 2. Threshold current versus wavelength for the ADQW device at room temperature.

from the SLA. The coupling efficiency of the collimators is about 70%. A beam splitter with $R/T = 70/30$ is used as the output coupler. An Au-coated diffraction grating G1 with 1200 lines/mm is used to tune the lasing wavelength. The measured efficiency of the -1 order of the grating is about 80% at the wavelength around 830 nm. The mirror M1 has $R > 99\%$, but its reflectivity is reduced to about 96% at a large incidence angle of the light beam. The ring cavity has two output beams (a) and (b).

Because the SLA's have a tilted stripe, the far-field beam profile is crescent-shaped [8]. In a usual four-mirror zigzag ring cavity, an outward-bent crescent shape of the beam emitted from one facet of the SLA becomes inward-bent before the beam is returned to the other facet of the SLA. A significant coupling loss is then introduced due to the serious mismatch of the beam shape in the zigzag cavity. Therefore, a triangular ring cavity is used for our experiment. Although the triangular ring cavity slightly increases the mirror loss due to the large incidence angle of the light beam, it significantly reduces the coupling loss caused by the beam-shape mismatch.

III. RESULTS AND DISCUSSIONS

The operation current is limited to below 400 mA to protect the device from being damaged. Tuning is achieved by rotating the grating horizontally. The grating is also fine tuned vertically to maximize the output power. SLA's with different lengths have been used for the tuning experiment. The tuning characteristics of the ring-cavity laser are shown in Fig. 2. The tuning ranges are 90, 70, and 48 nm for the 400-, 700-, and 1000- μm devices, respectively. For the 400- μm device, the laser can be continuously tuned from 766 to 856 nm. At the two sides of the tuning range, the threshold currents increase significantly. The threshold currents are 366 and 368 mA for the wavelengths 766 and 856 nm, respectively. At the 400-mA injection current, the output beam (a) of the laser still emits 4-mW power and 4.8 mW, respectively, for the two wavelengths. The measured light output versus current ($L-I$) curves of the SLA's before and after the tuning experiment are the same, indicating no degradation of the devices during our experiment.

The experiments show that the tuning range is more than what a conventional AlGaAs semiconductor laser could pro-

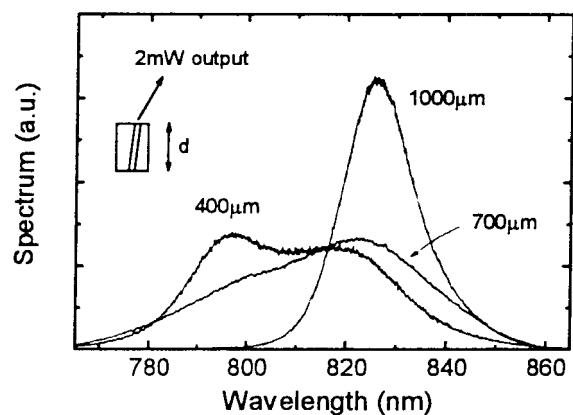


Fig. 3. The spectra for three devices of different lengths at the same output power of 2 mW.

vide [9] even for the 1000- μm device. This indicates that both wells contribute to the wide tuning ability regardless of the device length. The 75- and 40- \AA wells provide the tuning ability around 830 and 800 nm by their $n = 1$ transitions, respectively. The measurements show that the tuning range is further extended to the wavelength far below 800 nm for the 400- μm device. The extended tuning range is caused by the $n = 2$ transition in the 75- \AA well, which corresponds to the emission around 770 nm. This observation is consistent with previously reported results of broad tuning using the $n = 2$ transition in a single quantum well [6].

Fig. 2 shows that the tuning range also depends on the device length. Such dependence is caused by two reasons. First, Fig. 2 shows that the minimum threshold currents for devices of different lengths are approximately the same, so the threshold current density for the shorter device is larger. This indicates that one must pump the shorter SLA harder, which leads to the band-filling effect and so a broader emission spectrum. Second, the emission spectrum of an SLA is also approximately proportional to

$$S(\omega) \cdot \exp[\Gamma g(\omega)l] \quad (1)$$

where spontaneous emission $S(\omega)$ and the gain $g(\omega)$ are wavelength-dependent; Γ is the confinement factor and l is the device length. The exponential dependence of the emission spectrum on the device length causes the long SLA to have a narrower spectral width, which in turn leads to a shorter tuning range. Fig. 3 shows the measured spectra for three devices of different lengths at the same output power. It is obvious that the spectral width decreases with the length of the SLA. As a result, the tuning range decreases with the device length.

Past works on broadly tunable semiconductor lasers using the linear external grating cavity had suffered from the severe ASE noise [3], [7], [10]. Generally, the spectral noise contributed from ASE is about -25 to -35 dB for the lasing wavelength near the gain center. This noise could increase to -10 dB or more when the wavelength is tuned far away from the gain center [7], [10]. In our experiment, the ring cavity shows a particular advantage in the elimination of the ASE noise over the traditional external linear cavity using a grating. Because of the large gain of the SLA, the ASE noise is inevitable. In the linear cavity configuration, the single-

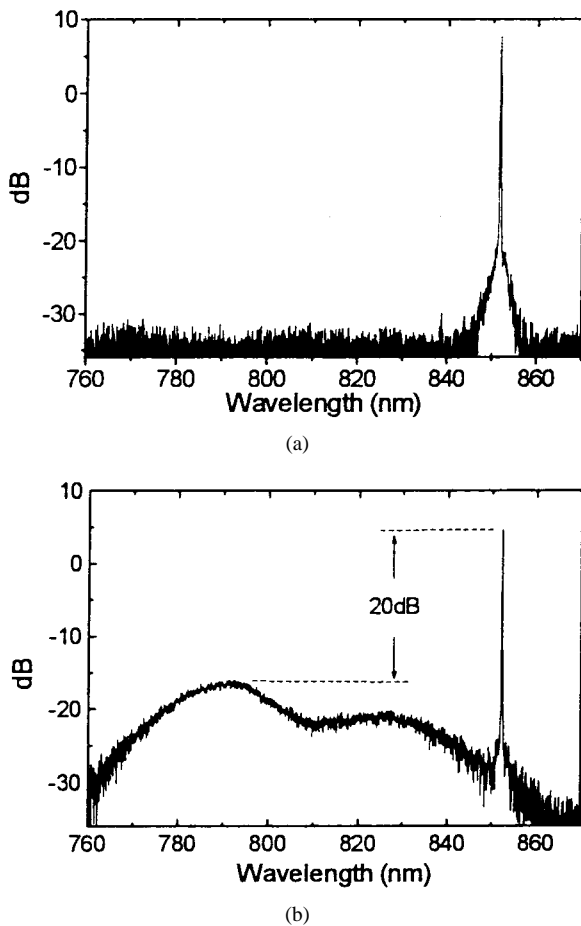


Fig. 4. The spectra measured from the output beams (a) and (b), respectively.

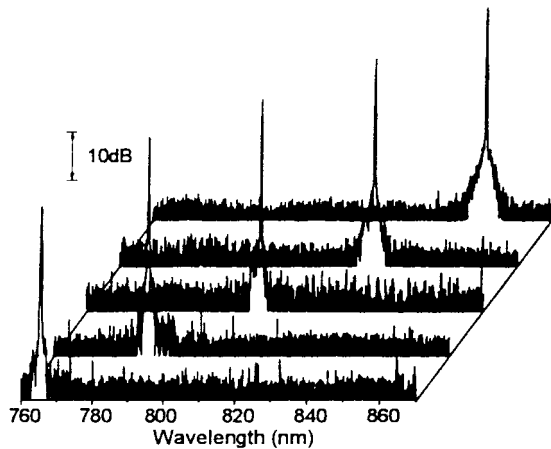


Fig. 5. The spectra measured from the output beam (a) at different wavelengths.

wavelength output beam is accompanied with the ASE noise because they spatially overlap. In our ring cavity for the clockwise propagating beam, the ASE noise is first dispersed by the grating. Then this noise could be filtered out by the proper design of the cavity before it reaches the output coupler BS1, so the output beam (a) contains mainly the lasing mode. The spectrum of this beam tuned to the wavelength 852 nm is shown in Fig. 4(a). The ASE noise is very small. The measured ASE suppression ratio is about 40 dB, limited by our experimental instruments. The spectrum is measured

using a monochromator with the intensity signal from the photomultiplier digitized by the A/D card. This system is calibrated to have a 40 dB signal-to-noise (S/N) ratio for the spectral measurement from 500–900 nm. The same ASE suppression ratio is obtained over the entire tuning range, as shown in Fig. 5. On the other hand, for the counterclockwise propagation direction, the output beam (b) is emitted from the output coupler before it arrives at the grating. Therefore, the ASE noise still overlaps with the lasing mode. Fig. 4(b) shows the spectrum of this beam tuned to the wavelength 852 nm. The ASE noise is clearly shown in this figure. Similar to the conventional linear cavity case, the ASE suppression ratio is only 20 dB. This ratio could increase as the wavelength is tuned near the gain center. The spatially overlapped ASE noise in the output beam (b) could be removed if this beam passes through another grating outside the cavity.

IV. CONCLUSION

Using the tilted-stripe SLA's fabricated on the substrate with well-designed asymmetric dual quantum wells, the external-cavity semiconductor lasers are broadly tunable. In a grating coupled ring cavity, the semiconductor laser is continuously tunable from 766 to 856 nm using a 400- μm SLA. The tuning range decreases with the device length. The length-dependence is due to the amplified spontaneous emission, which exponentially grows with the propagation distance. It is also demonstrated that the grating coupled ring cavity could greatly eliminate the ASE noise and about 40-dB suppression ratio is obtained over the entire tuning range.

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