Fabrication of Butt-Coupled SGDBR Laser Integrated with Semiconductor Optical Amplifier Having a Lateral Tapered Waveguide

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We have demonstrated a high-power widely tunable sampled grating distributed Bragg reflector (SGDBR) laser integrated monolithically with a semiconductor optical amplifier (SOA) having a lateral tapered waveguide, which is the first to emit a fiber-coupled output power of more than 10 dBm using a planar buried heterostructure (PBH). The output facet reflectivity of the integrated SOA using a lateral tapered waveguide and two-layer AR coating of TiO_2 and SiO_2 was lower than 3×10^{-4} over a wide bandwidth of 85 nm. The spectra of 40 channels spaced by 50 GHz within the tuning range of 33 nm were obtained by a precise control of SG and phase control currents. A side-mode suppression ratio of more than 35 dB was obtained in the whole tuning range. Fiber-coupled output power of more than 11 dBm and an output power variation of less than 1 dB were obtained for the whole tuning range.

Keywords: Butt coupling, integrated laser, tunable laser, integrated SOA, SGDBR laser, PBH structure.

I. Introduction

Tunable laser diodes are expected to play a major role in wavelength division multiplexing (WDM) networks. Widely and rapidly tunable laser diodes are promising components as high-speed light sources for networks and optical switching applications. Future applications may include use in wavelength routing and switching architectures. In some cases, output powers as high as 10 dBm are desired [1]. However, this has been difficult to achieve simultaneously with wide tunability. A significant advantage of the sampled-grating distributed Bragg reflector (SGDBR) over other widely tunable lasers is that it can be integrated monolithically with different devices such as semiconductor optical amplifiers (SOAs) and electroabsorption modulators [2]. The wide tunability and high-performance operation of SGDBR lasers as well as the ability of integration are of great necessity. It is well known that the performance of SOAs depends sensitively on the quality of antireflection (AR) coatings at the cleaved facet. Suppressing laser oscillation and wavelength-dependent undesirable amplification is required over the whole wavelength range of operation. The most popular approach has been single-layer AR coating with any combination of a tilted waveguide [1], window region [3], and tilted active region [4]. And recently, a wide bandwidth of about 50 nm (for $R < 1 \times 10^{-4}$) using a two-layer AR coating of TiO_2 and SiO_2 was reported for 1.3 μm InGaAsP multi quantum well (MQW) SOA devices [5].

In this work, we report on the fabrication and performance of a multi-section tunable single-mode SGDBR laser integrated

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monolithically with an SOA, which for the first time has a planar buried heterostructure (PBH) structure. We used the tapered waveguide and a two-layer AR coating of TiO_2 and SiO_2 to improve the bandwidth and fiber-coupling efficiency. In the fabrication procedure we established a butt-coupling that has a very high and reproducible coupling efficiency between the active and passive regions [6].

II. Experiment

Figure 1 shows a schematic structure of an SGDBR laser integrated with an SOA. Integrated lasers with SOAs are fabricated through a five-step metal-organic chemical vapor deposition. The integration of active gain and SOA sections with a passive waveguide tuning section was made by using an offset quantum-well structure in a PBH. This device has five sections; active, SOA, phase control, front SGDBR, and rear SGDBR sections. The lengths of each section are 400, 600, 150, 400, and 400 μm, respectively. A bulk waveguide layer (λ_g = 1.3 μm) was butt-coupled to a strained separate confinement heterostructure (SCH) MQW active layer (λ_g = 1.55 μm). There are four butt-coupling joints in the device. The SOA consists of a 300 μm long gain region and a 300 μm long laterally tapered waveguide region, which are also butt-coupled to each other. The width of the tapered waveguide varies linearly from 1.3 μm at the butt-coupled interface to 0.3 μm at the facet in order to achieve efficient coupling with a fiber. The strained SCH MQW consists of seven pairs of a 0.7% compressively strained GaInAsP (λ_g = 1.55 μm) well, a 0.35% tensile strained GaInAsP (λ_g=1.24 μm) barrier, and separate undoped GaInAsP (λ_g=1.1, 1.24 μm) confinement layers. The butt-coupling procedure is very important for high performance operation of an SGDBR laser integrated with an SOA.

For butt-coupling, we established a procedure of reactive ion etching (RIE) and selective wet etching, which has a very high and reproducible coupling efficiency between the active and passive regions [6]. A cross section of the butt-coupled interface is shown in Fig. 2(a). The scanning electron microscope (SEM) photograph shows an ideal butt-coupled shape without defects in the regrown waveguide layer. There is no roughness at the interface of the regrown waveguide and InP substrate owing to the subsequent selective wet etching after RIE. The regrown waveguide layer was free from the formation of visible defects, which is essential for the fabrication of an integrated laser with a uniform and high coupling efficiency, as shown in Fig. 2 (a). We established a procedure of RIE and selective wet etching, which has a very high and reproducible coupling efficiency between the active and passive regions. The measured coupling efficiency between the active layer and passive waveguide layer was $96\pm1.7\%$, and the threshold current was 9.6 ± 1.2 mA across a quarter of a 2-inch wafer [6].

The periods of the front SG (Z_2) and rear SG (Z_3) were designed to be 64 and 71 μm, respectively. The reflection peaks of Z_2 and Z_3 were spaced by 4.7 and 4.3 nm, respectively [7]. The lengths of both SG bursts (Z_1) were 7 μm, resulting in the wavelength tuning range of approximately 40 nm [7]. The grating burst regions were patterned by holographic lithography and formed by RIE and wet chemical etching [8].

For the formation of p-n-p current blocking, a mesa structure was formed by a two-step wet etching process [9]. After the formation of the mesa structure, the fourth growth step for current blocking was performed by growing the three layers of p-InP, n-InP, and p-InP. In the last step, a p-InP clad layer and a p-InGaAs ohmic layer were grown. Ti/Pt/Au and Cr/Au electrodes were formed on the top and bottom of the wafer as p-type and n-type ohmic contacts, respectively. Figure 2(b)

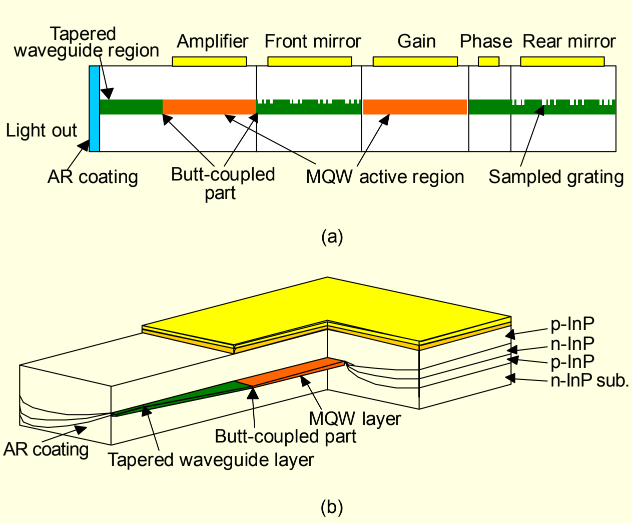
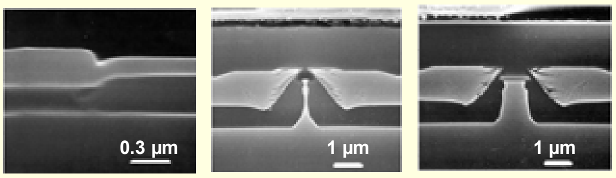


Fig. 1. (a) A schematic of an SGDBR laser integrated with an SOA and (b) a schematic of the SOA region, which has a lateral tapered waveguide and PBH structure.



(a) (b) (c)

Fig. 2. (a) SEM image of the butt-coupled portion, (b) cross-sectional SEM image of the end facet of the tapered region, and (c) cross-sectional SEM image of the active region.

shows a cross-sectional SEM image of the end facet of the laterally tapered waveguide region, and Fig. 2(c) shows an SEM image of the SOA gain region. From Figs. 2 (b) and 2(c), we can see the width of the tapered layer was changed linearly from 1.3 μm at the butt-coupled interface to 0.3 μm at the facet to achieve efficient coupling with the fiber.

The structure of the SOA has a laterally tapered waveguide, and a wideband AR coating was made at the output facet to suppress the optical feedback to the laser. SiO_2 and TiO_2 were used for AR coating. Materials were deposited on the facet of the devices using an ion-beam-assisted electron-beam evaporator. The optical constants of the deposited SiO_2 and TiO_2 layers were accurately measured using the spectro-ellipsometric technique.

III. Results and Discussions

The residual facet reflectivities of the AR coatings were determined from subthreshold amplified spontaneous emission (ASE) spectra. The net modal gain of a semiconductor laser can be measured from the depth of modulation of Fabry-Perot resonances in the ASE spectrum [10]. By comparing the modal gain spectrum before and after coating, the AR coating reflectivity can be ascertained [11]. For determining the reflectivity of the AR coated facet, the output facet of a cleaved SOA was AR coated with TiO_2 and SiO_2, and the net modal gain was then measured according to the well-known Hakki-Paoli method.

We obtained the reflectivity spectrum of the AR-coated facet by measuring the modal gain difference before and after AR coating at the same current. It is written [12] as

$$R_{\text{after}}(\lambda) = R_{\text{before}}\exp(-2\Delta g_{net}(\lambda)\,L), \tag{1}$$

where $\Delta g_{net}(\lambda)$ is the modal gain difference, R_{before} and R_{after} are the reflectivities before and after AR coating, and L is the cavity length. The net gain spectra before and after AR coating at a current of 15 mA for a 600 μm long device are shown in Fig. 3. The modal gain difference at the wavelength of the 1550 nm gain peak was 55 cm^{-1}, and thus a reflectivity of 0.03% was obtained according to (1).

The obtained facet reflectivity of the AR coating is shown in Fig. 4. The reflectivity was calculated by measuring the difference of the net modal gain before and after AR coating from Fig. 3. The reflectivity is found to be in the range of 3×10^{-4} to 8×10^{-5} for a wide bandwidth. The bandwidth of lower than 3×10^{-4} is 85 nm, from 1485 nm to 1580 nm, approximately.

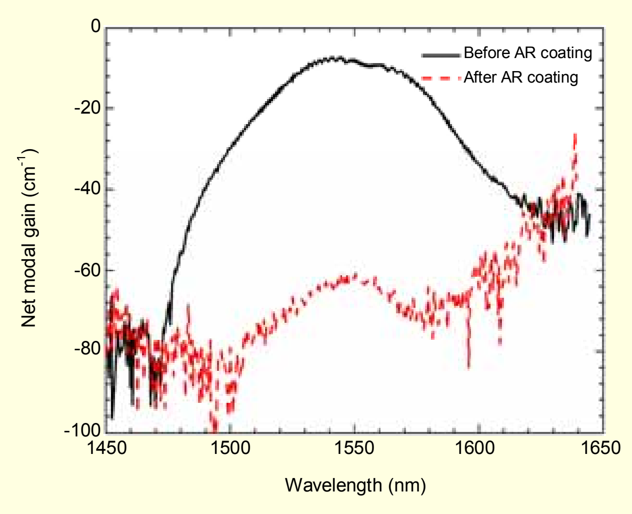


Fig. 3. The net gain spectra before and after AR coating at a current of 15 mA for 600 μm long devices.

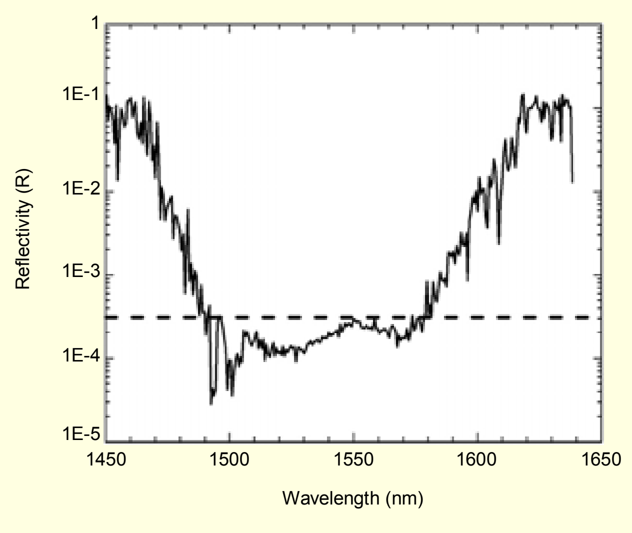


Fig. 4. Reflectivity spectrum for the output facet of an AR-coated SOA.

The fiber-coupled output power using only one SGDBR current at a 25°C continuous wave (CW) condition is shown in Fig. 5(a). In the measurement, the active and SOA regions were kept constant at 100 mA and 200 mA, respectively. And either the front or rear SGDBR current was changed from 0 to 30 mA in 1 mA steps. The fiber-coupled output power is more than 10.6 dBm of CW operation, and the output power variation is less than 0.6 dB for the whole tuning range. The fiber coupling efficiency was about 50% compared to I-L characteristics of an SGDBR laser integrated with an SOA [13]. The fiber-coupled power is not less than those in [2]. The side mode suppression ratio (SMSR) and the tuning characteristics are also plotted in Fig. 5(b). The tuning operations in seven front SG modes and six rear SG modes are obtained with an SMSR of more than 35 dB except near the mode changing

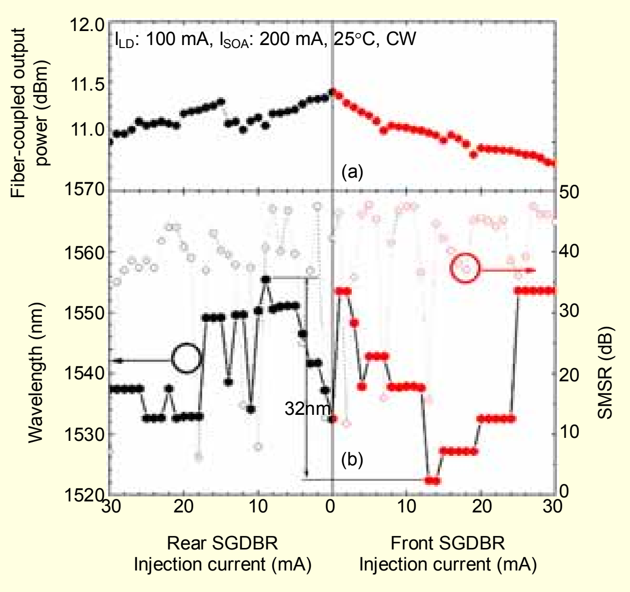


Fig. 5. (a) Fiber coupled output power and (b) experimental wavelength characteristics and mode suppression ratio when only one SGDBR current was changed.

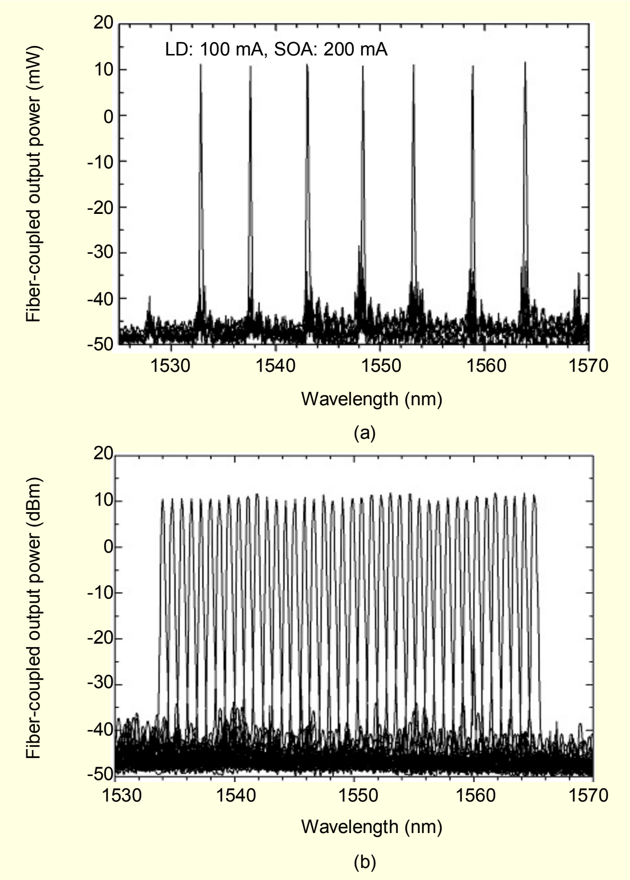


Fig. 6. (a) Superimposed spectra of seven SGDBR supermodes demonstrating a 32 nm tuning range with a greater than 35 dB SMSR and (b) superimposed spectra of 40 channels with 50 GHz spacing and SMSR characteristics.

points. The reflection peaks of the front SG and rear SG were spaced about 5.2 nm and 4.8 nm, respectively, which are well matched with the designing scheme. A full coverage of the SG modes can be seen from 1532 to 1564 nm. The wavelength tuning range is about 32 nm.

Figure 6(a) shows superimposed CW spectra spaced at 5.2 nm within the 32 nm tuning range. These spectra are the reflection peaks of the seven front SG modes of Fig. 5(b) with more than a 35 dB SMSR. Figure 6(b) shows superimposed CW spectra of 40 WDM channels spaced at 50 GHz within the 16 nm tuning range. These spectra were obtained with a simultaneous control of both SG currents and the phase current, but the active current and SOA current fixed at 100 and 200 mA, respectively. The current into the phase section allowed all 40 channels to be aligned precisely at 50 GHz intervals with more than 35 dB of side mode suppression. The fiber-coupled output power was more than 11 dBm at CW operation, and the output power variation was less than 1dB.

IV. Conclusion

We have demonstrated a high-power and widely tunable SGDBR laser monolithically integrated with an SOA using a PBH structure, where the active and passive regions are butt-coupled using a well established procedure. The calculated reflectivity of the integrated SOA is from 3×10^{-4} to 8×10^{-5}. The bandwidth of lower than 3×10^{-4} of reflectivity is 85 nm. We obtained a total tuning range of 33 nm and spectra of 40 WDM channels with 50 GHz spacing, which have more than 35 dB of side mode suppression. Fiber-coupled output power was more than 11 dBm at CW operation, and the output power variation was less than 1dB.

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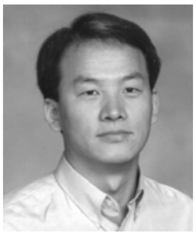

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