

High-Power Angled Broad-Area 1.3- μm Laser Diodes With Good Beam Quality

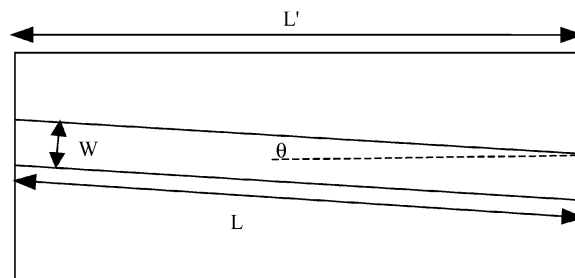
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Abstract—A new type of high-power laser diodes is fabricated with a broad-area waveguide tilted at 7° from the facet normal. For the current between 0.6 and 1.2 A, it behaves like a superluminescent diode with 40-nm spectral width and 40-mW output power. The far field emits at about 25° away from the facet normal. For the current above 1.2 A, it oscillates with a narrow spectrum. The far field emits along the facet normal with its angle only twice of the diffraction limit. The output power per facet could be 1 W at 12 A.

Index Terms—Angled-grating distributed feedback (DFB) laser, filamentation, high-power laser diode (LD), semiconductor laser.

HIGH POWER and good beam quality are desired for semiconductor lasers in many applications such as frequency doubling [1], free space communication [2], and material processing [3]. In particular, laser sources operating at the 1.3- and 1.55- μm wavelengths have important applications in cable television transmission systems, microwave photonics, interferometric sensors, and pump for Raman amplifiers. To improve the beam quality, several approaches such as tapered power amplifiers [4], antiguided arrays [5], and angled-grating distributed feedback (DFB) lasers [6] had been investigated. Although a tapered amplifier system can provide watt-scale output power, beam filamentation remains a problem and tradeoff between modal gain and beam quality must be made [7]. Angled-grating DFB lasers can provide good beam quality, but the working wavelength is fixed after fabrication. In addition, the fabrication of grating structures is difficult. Furthermore, the mismatch between the peak gain wavelength and the DFB resonance wavelength can severely affect the device performance [8].

To make a diode laser emit watt-scale optical power, the emitting facet must be large to prevent catastrophic optical damage (COD). Even with a high COD threshold (10 MW/cm^2) [9], the emitting facet also has to be large for 1-W operation. Thus, more than 30- μm broad emitting facets are necessary for watt-scale operation [10]. The broad-area waveguide leads to the small difference of the threshold gain between the high-order modes and the fundamental mode. Also, the nonlinear interaction between carriers and light will produce filamentation of optical power distribution [11]. These reasons make high-order transverse modes ex-



$$L'=1200\mu\text{m}, W=50\mu\text{m}, \theta=7^\circ$$

Fig. 1. Structure of the high-power LD. W is the width, L is the length, and θ is the tilt angle of the waveguide. L' is the length of the device.

cited in broad-area Fabry-Pérot laser diodes (LDs) and the spatial coherence of emissions on every part of the facets is poor. In this work, we propose a new type of broad-area LDs capable of emitting good beam quality with 1-W output power. The LDs have a broad-area waveguide oriented at an angle from the facet normal. This device does not require the DFB structure, so the fabrication is much simpler. The device geometry will be described, and the device performance will be discussed.

The LDs are fabricated on the wafer with multiple quantum wells (MQWs) designed for the wavelength at 1.3 μm . The LDs have a 50- μm -wide waveguide oriented at 7° from the facet normal. The device length is 1200 μm . Fig. 1 shows a sketch of the angled broad-area LDs. Unlike conventional Fabry-Pérot LDs, the waveguide direction is not perpendicular to cleaved facet, but tilted at an angle. The devices have a double-channel ridge waveguide created by reactive ion etching. The process gases are CH_4 and H_2 . The channel button is 100 ~200 nm above the undoped optical confinement layer. After the waveguide fabrication, silicon oxide grown by plasma-enhanced chemical vapor deposition is used as the insulating dielectric. The contact metal is Ti-Pt-Au on the p-side and AuGe-Ni-Au on the n-side. After processing, the devices are cleaved apart. No coatings are applied.

The light output-current (L - I) curves, spectra, near-field patterns, and far-field patterns of the angled broad-area waveguide LD are measured. The behaviors of the light emitted from both facets are almost the same. Fig. 2 shows the L - I curve of the LD emitted from one facet. The threshold current of the device is 1.2 A. This device has three regions of operation. The details of each region will be discussed in the following.

As the current is below 0.6 A, the output power is very low. Only 2-mW output power is measured even when the pumping current is 0.5 A. Fig. 3(a) shows the spectra of the device at 0.5 A. The spectrum is broad with a full-width at half-maximum (FWHM) of 60 nm. The spectrum indicates that there is no

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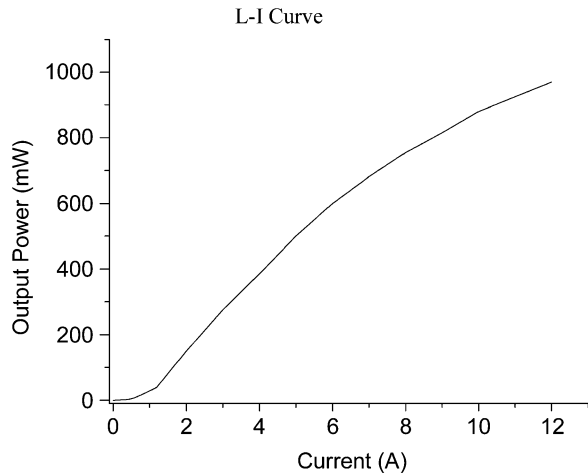
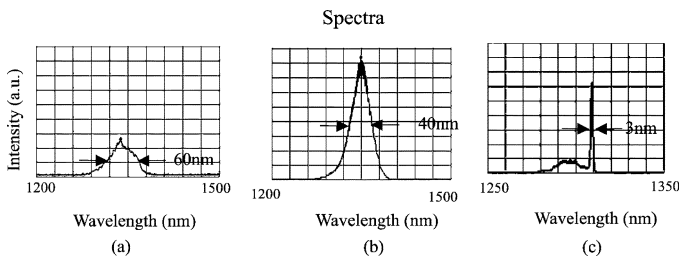

 Fig. 2. L - I curve of 1200- μm length device.


Fig. 3. Spectra of the device at (a) 0.5, (b) 1, and (c) 6 A.

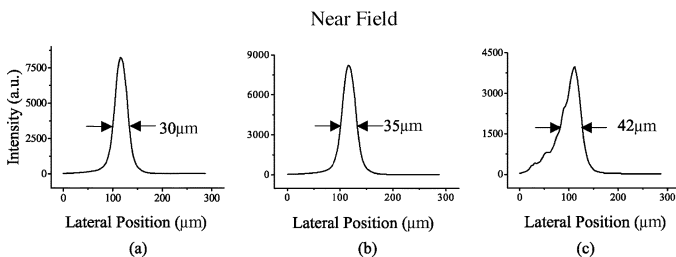
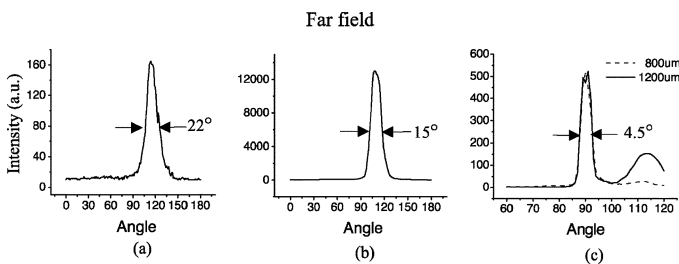


Fig. 4. Near field of the device at (a) 0.5, (b) 1, and (c) 6 A.


 Fig. 5. Far field of the device at (a) 0.5, (b) 1, and (c) 6 A (solid line: device length = 1200 μm ; dashed line: device length = 800 μm).

oscillation in this region of operation. Figs. 4(a) and 5(a) show the near-field and far-field patterns of this device at 0.5 A, respectively. The FWHM of the near-field distribution is about 30 μm . The near field is mainly emitted from the waveguide region at the cleaved facet. The corresponding far field is emitted toward the same side of the waveguide relative to the facet normal. The peak of the far field is at 27° from the facet normal. This far field has a broad angle with the horizontal FWHM of 22° at 0.5-A pumping current. The behaviors are similar for the current below 0.6 A. It indicates that below 0.6 A, the light path is approximately along

the waveguide direction. Thus, the output light is emitted at 27° from the facet normal according to Snell's law.

As the pumping current is between 0.6 and 1.2 A, the emission power significantly increases with the injection current. The output power is up to 40 mW as the current is 1.2 A. In this region of operation, the emission spectrum shrinks slightly. Fig. 3(b) shows the spectra of the device at 1 A. The FWHM of the spectrum is 40 nm. Figs. 4(b) and 5(b) are the near-field and far-field patterns of this device at 1 A, respectively. The near field slightly broadens and mainly distributes within the waveguide with an FWHM of 35 μm at the facet. The horizontal far field has FWHM angle of 15° , which shrinks slightly in comparison with the measurement for current below 0.6 A. The reduced spectral width, the increased output power, and the reduced far-field angle indicate that the light is amplified as it propagates along the waveguide because of the significant amplified spontaneous emission. The L - I curve in this region also shows that the light power has significantly superlinear increases with the injection current. However, the device is not oscillating because the light path along the tilted waveguide provides no feedback in this region of operation. The high power and the broad spectral width make this device in this operation region a good candidate of high-power superluminescent diodes (SLDs).

The peak of the far field is now emitted at 25° from the facet normal. It still satisfies Snell's law. The reason for the reduced angle of peak emission is due to the carrier-induced reduction of refractive index at an increased injection current level [12]. When the current is beyond 1.2 A, the laser oscillation begins. Output power of this device can increase up to 1 W as the pumping current is 12 A. The differential efficiency of this device is 0.12 mW/mA per facet. Above the threshold current of 1.2 A, the spectrum becomes very narrow. Fig. 3(c) shows the spectra of the device at 6 A. The lasing wavelength is centered at 1325 nm with an FWHM spectral width of 3 nm. The spectrum above the threshold actually consists of many Fabry-Pérot modes with the spectral spacing of 0.18 nm. Fig. 4(c) shows the near field for the pumping current of 6 A. The near field further broadens and distributes in a region wider than the waveguide. However, the major power is still within the waveguide. The FWHM of the near-field pattern is 42 μm .

It is very interesting that the far field emits along the normal direction of the cleaved facet when the operation current is above 1.2 A. Fig. 5(c) shows the far-field pattern of the device for the pumping current of 6 A. The horizontal FWHM of the far-field pattern is 4.5° . This angle is only twice of the diffraction-limited value corresponding to the near field shown in Fig. 4(c). Fig. 5(c) also shows that a sidelobe is at 24° from the facet normal and the FWHM angle of this lobe is 15° . In the L - I curve experiment, the brightness of both the normal lobe and sidelobe are taken into account. The sidelobe will decrease if the device length is properly chosen. The reason will be discussed later.

One of the major reasons for the filamentation to occur in the conventional broad-area waveguide is the index variation across the waveguide caused by the nonuniform carrier concentration or nonuniform temperature distribution, in particular near the waveguide boundary, leading to the distortion of the beam profile [11]. For the conventional broad-area waveguide

normal to the cleaved facets, the light path is along the waveguide direction, so light trace does not vary its distance from the waveguide boundary. Then the beam distortion accumulates along the propagation distance. In our devices operated above the threshold, the light path is not along the waveguide direction. Instead, the light path is zigzag, so each light trace varies its distance from the waveguide boundary. As a result, the index fluctuation across the waveguide experienced by each light trace is averaged out, so filamentation is significantly reduced. Devices with broad-area waveguide normal to the cleaved facets have also been fabricated on the same wafer. Their near field has severe filamentation. The far field has several spikes and the corresponding FWHM divergence angle is as large as 16° .

For the mode along the zigzag path to oscillate, the optical-path length is not the same as the waveguide length. As shown by device sketch in Fig. 1, L' is the length of the device, W is the width, and θ is the tilt angle of the waveguide. For the light to oscillate between the two facets, the optical-path length is $2mW/\sin\theta$. The waveguide length is $L = 2mW\cos\theta/\sin\theta$ and the device length is $L' = 2mW\cos\theta/\tan\theta$, where m is a positive integer. When the light is reflected twice at the waveguide boundary and then goes straight toward the cleaved facets, $m = 1$. Too long or too short waveguide for the devices will cause some portion of the output beam to emit toward other directions. For $W = 50\ \mu\text{m}$ and $\theta = 7^\circ$, L' should be $808\ \mu\text{m}$. Therefore, Fig. 5(c) shows that the far field of a $1200\text{-}\mu\text{m}$ length device has the sidelobe emitted at about 24° from the facet normal because some portion of the light still propagates along the waveguide instead of the zigzag path. $800\ \mu\text{m}$ length devices have also been fabricated and the sidelobe is significantly reduced. Its far field is also shown in Fig. 5(c) for comparison.

For the double-channel ridge waveguide, the difference of refractive index between the waveguide and the channel regions is only about 0.5% [13]. Thus, the light is not completely reflected at the waveguide boundary, leading to some extra loss of the lasing modes. In addition, the decreasing slope in the L - I curve at the large current indicates bad heat dissipation. Thus, the differential efficiency is not very good after oscillation. Improved efficiency is expected with some optimization, e.g., better control of the QW structure, waveguide fabrication, facet coating, and heat dissipation.

In conclusion, a new type of angled broad-area waveguide LD is fabricated on a substrate with MQWs designed for $1300\ \text{nm}$.

The devices have three regions of operation. For the injected current between 0.6 and 1.2 A, it behaves like an SLD with a spectral width of about 40 nm and the output power of 40 mW. When the current is above 1.2 A, this device oscillates and could emit 1-W output power per facet at 12 A. The far-field pattern has interesting changes between below and above the threshold current. When the device is oscillating, the far field emits along the facet normal. The horizontal far-field angle is only twice of the diffraction-limited value.

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