High-Power Superluminescent Diodes

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***Abstract*—By inclining the active stripe of a planar AlGaAs double heterojunction structure by 5° with respect to the facets, we have eliminated reflection feedback and made high-power superluminescent diodes emitting 28 mW with less than 5 percent spectral modulation.**

INTRODUCTION

SUPERLUMINESCENT diodes (SLD's) are useful light sources for fiber-optic gyroscopes because their low coherence eliminates noise found in laser-based systems [1]–[3]. High performance gyroscopes require powerful SLD's (greater than 15 mW) for high rotation rate sensitivity. SLD's can also replace LED's in communication systems where the high power contributes to increasing the number of nodes in local area networks and to reducing constraints on receiver performance. SLD's are typically made from lasers by antireflection facet coating or by the introduction of a lossy region in the optical path to reduce feedback [4], [5]. Although significant reduction of reflection has been obtained in this manner, great care must be exercised to maintain it low enough in order to amplify the spontaneous emission without Fabry–Perot spectral modulation [6], [7]. The gain of a semiconductor amplifier structure with equal facet power reflection coefficient R is [8]

$$G = \frac{(1 - R)^2 G_s}{1 + R^2 G_S^2 - 2RG_S \cos 2\beta l} \tag{1}$$

where G_S is the single pass gain, β the propagation constant in m^{-1}, and l the cavity length in m. If R is not zero, the gain undergoes maxima and minima at values of $2\beta l$ equal to even and odd multiples of π, with a modulation index given by [9]

$$m = \frac{G_{\max} - G_{\min}}{G_{\max} + G_{\min}} = \frac{2RG_S}{1 + R^2 G_S^2}. \tag{2}$$

The ideal SLD is one for which $m = 0$, which would be achievable by making $R = 0$. The net gain is simply the single pass gain G_S and the output power is $P_S G_S$ where P_S is the guided component of the spontaneous emission at the pumping current level. For a typical laser, P_S is of the order of 0.5 μw [10] and thus G_S would have to be of the order of 10^4 for a SLD to yield an output power comparable to the laser. Below saturation, G_S is of the form [11]

$$G_S = \exp\left[\Gamma\left(g_0 \eta_i \frac{J}{d} - \alpha\right) l\right] = \exp\left[\frac{\Gamma K I}{d} - \Gamma \alpha l\right] \tag{3}$$

where g_0 is the gain coefficient $= 4.5 \times 10^6$ cm^2/A for AlGaAs, J is the injection current density in A/cm^2, d is the active layer thickness in cm, Γ the confinement factor, l the active length in cm, η_i the internal quantum efficiency (~ 1), α the attenuation constant ($=150$–200 cm^{-1} for AlGaAs), $K = g_0 \eta_i / S$, S the effective stripe width in centimeters, and I the current in amperes.

For a typical laser with $R \approx 0.1$–0.3, the value of G_S is about 3.3–10 at threshold for a laser. To increase it by a factor of 1000 as needed for a SLD emitting several milliwatts, the current would approximately have to triple, but that would increase the current density excessively unless the active length is correspondingly increased. The extent to which the length is increased conveniently depends upon the attenuation constant which decreases the overall efficiency. According to (3), a good choice of structure is one with a large confinement factor and low attenuation, so the active length can be increased without penalty in efficiency. For reasons discussed later, we would like the length to be fairly long. In practice, we choose it about 3–4 times that of a laser made for the same material.

The central problem in designing a SLD is to keep the reflectivity low enough to maintain sufficiently low modulation. If a 5 percent modulation is deemed acceptable, (2) implies that R must be less than 2.5×10^{-6} for high power. Although a value as low as 2.5×10^{-4} have been reported for a scandium oxide AR coating [12], it is far too high for high power SLD's and it is doubtful that it can be achieved routinely because of the stringent material and thickness matching requirements, as well as extreme wavelength stability with temperature. High power AR-coated SLD's have been reported [13], but there are no details on spectral modulation and reproducibility.

We have reduced the reflected power coupled into the active region of a narrow stripe diode to very low values by inclining the stripe at an angle θ with respect to the facets, as shown in Fig. 1(a). The amplified spontaneous emission (ASE) is output at angle θ_0 determined by Snell's law. For best performance, the angle should be large enough to avoid mode trapping from total internal reflection at the lateral walls and to prevent Fabry–Perot resonances with the parallel facets. However, in order to allow output coupling, it should be much smaller than the critical angle at the facet.

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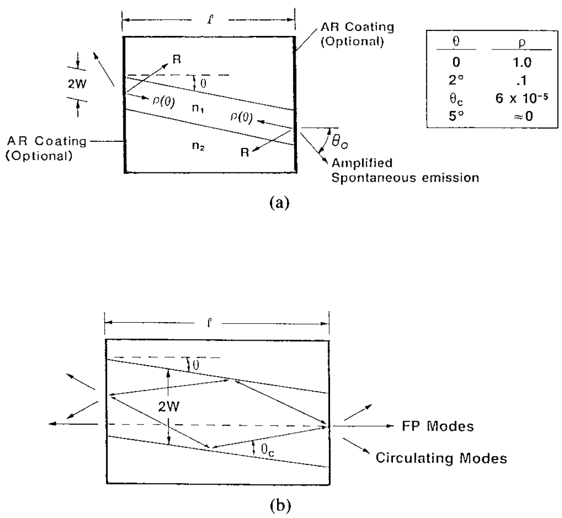

Fig. 1. (a) Incline stripe SLD in planar DH structure. Stripe inclination 5°. (b) Effect of trapped modes and of Fabry–Perot modes.

Mode trapping [14], [15] is the result of the guiding of the rays that fall within a cone of half angle equal to the critical angle θ_c, as shown in Fig. 1(b) for a structure having wide stripe. These rays are amplified and those that meet the phase condition for lasing will circulate in the guide. They will also emit as multimode lines in several directions, including the output angle, thus modulating the ASE output. For an abrupt step between the guide of index n_1, and the external lateral region of index n_2, the critical angle is

$$\theta_c = \sin^{-1}\sqrt{1 - (n_2/n_1)^2} \tag{4}$$

and its value is about 3.13° for an index step of 5×10^{-3} in AlGaAs [16].

For a propagating mode having a zero order Hermite–Gaussian distribution [17] of effective width 2 W, the fraction of reflected power trapped in the guide due to θ_c is [18]

$$\rho = \frac{1}{2}\left\{\mathrm{erf}\left[\frac{W\beta}{\sqrt{2}}(2\tan\theta + \tan\theta_c)\right] - \mathrm{erf}\left[\frac{W\beta}{\sqrt{2}}(2\tan\theta - \tan\theta_c)\right]\right\} \tag{5}$$

where erf is the error function integral. This expression is approximately equal to unity for $\theta = 0$, but it decreases rapidly to zero for $\theta > \theta_c$. It also shows why a slight misalignment will not prevent a device from lasing. For example a 2° inclination for a diode with 5 μm effective width will have $\rho \cong 0.09$, not enough to prevent lasing. On the other hand, ρ is less than 6×10^{-5} at $\theta = \theta_c$, enough to prevent circulating modes if the facets are AR coated.

Aside from preventing circulating modes, it is also necessary to prevent the excitation of Febry–Perot modes which occur if there is a direct path with enough gain between the parallel facets. Such a path would result in multimode laser emission normal to the facets as shown in Fig. 1(b). To avoid these modes, tan θ must be greater than the ratio of effective width to stripe length. This criterion is not trivial. A gain-guided structure may have a nominal stripe width of 5 μm and an effective width of 30–40 μm, as we have found experimentally for p-cap devices. In such a case, the active length for 5° inclination would have to exceed 460–570 μm to prevent Fabry–Perot oscillations. This explains why previous angled stripe devices which had wide or moderately wide effective width resulted in multimode lasers or SLD's with large spectral modulation [19]–[22]. A properly designed angled stripe SLD should have its stripe angle greater than the width to length ratio and must be such that ρ is less than 10^{-4} if the facets are AR coated or less than 10^{-6} if there is no AR coating.

Results

For the reasons discussed above, an angle of 5° was chosen for our devices, with $\rho \approx 0$, and a planar DH AlGaAs structure was used for simplicity, with the layer composition shown in Fig. 2 grown by LPE. An n-type current blocking layer was used as a cap. This was followed by a SiO_2 layer from which a stripe window was etched out at the 5° angle. The whole surface was metallized after zinc diffusion into the cap for ohmic contact. The facets were AR coated with scandium oxide to help reduce reflection and increase output power. This coating material was chosen because its refractive index of 1.84 closely matches the required near quarter-wave value for AlGaAs materials [12]. The lengths of the devices varied from 100 μm to over 1000 μm. As expected, the shorter devices exhibited strong spectral modulation (20 to 60 percent) of a broad spectrum output at about 15° from the facet, together with a multimode laser output normal to the facet. Direct observation of the near field revealed an emitting surface about 30–40 μm wide, indicating insufficient lateral confinement in this gain-guided structure. The longer devices showed almost ideal superluminescent characteristics, exhibiting a broad uniform spectrum at all power levels. This is shown in Fig. 3 for a 1000 μm long device at power levels of 8, 14, and 28 mW. With a spectrometer resolution of 0.5 Å, no modulation is observed at the 8–14 mW level, and only a 5 percent modulation is observed at the 28 mW. The spectral half-power bandwidth is about 8 nm, and it is broader for the shorter devices (15 nm for 250 μm active length.)

The light–current characteristics are shown in Fig. 4 for a number of devices. The longer devices exhibit a knee similar to the laser, but at a current larger than lasing threshold due to the factor $\Gamma\alpha$ in (3). This knee is the point where the net gain exceeds unity. Beyond that point the slope efficiency is 10–20 percent. The electrical efficiency is 5–10 percent. Our gain-guided devices appear expectedly less efficient than the twin-channel angled

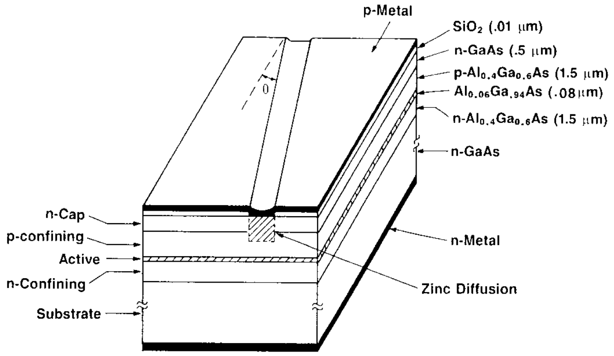

Fig. 2. Layer structure and composition of inclined stripe SLD.

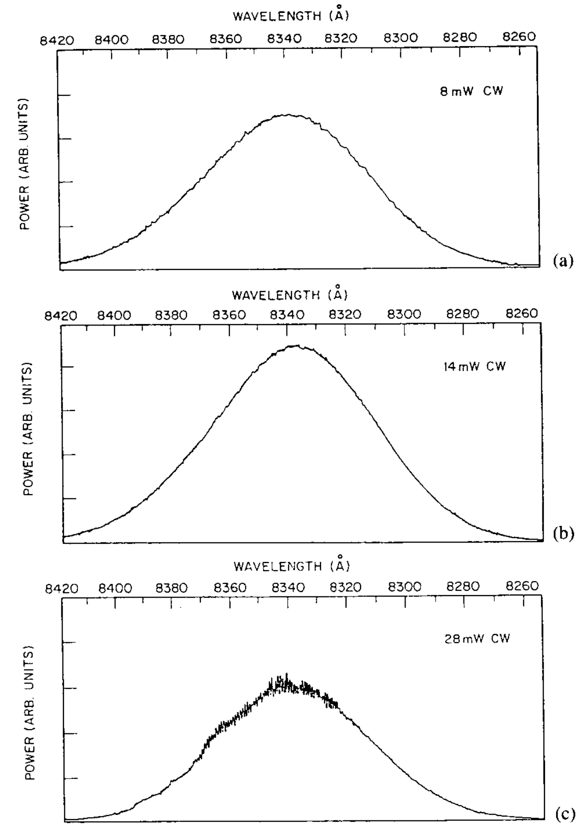

Fig. 3. Output spectrum of 1000 μm long SLD at 8, 14, and 28 mW CS, respectively.

stripe SLD [23], [24], but with somewhat less spectral modulation.

The far field is shown in Fig. 5 for a 400 μm device at 8 and 15 mW output power and at CW and 1 percent duty cycle. The FWHM is 11 × 58°, and the spectrum is centered at about 12° from facet normal. The deviation from the expected 15° is due mainly to misalignment of the SLD from the edge of the device mount taken as a reference. The same misalignment is shown in the small spurious Fabry–Perot output (peak at 3° instead of 0°).

In conclusion, we have reduced the feedback to nearly zero in a new superluminescent diode design by inclining the narrow active region to 5° from facet orthogonality in a planar DH structure at 0.83 μm wavelength. CW power output of 15 mW is routinely obtained with negligible modulation, and 28 mW has been obtained with 5 percent spectral modulation.

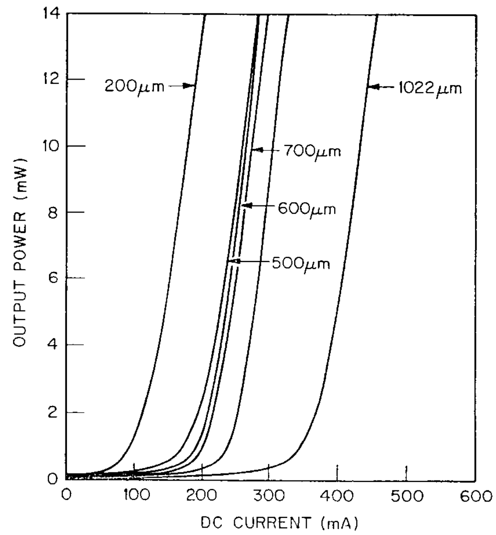

Fig. 4. Light output versus current characteristics of SLD's with various active lengths.

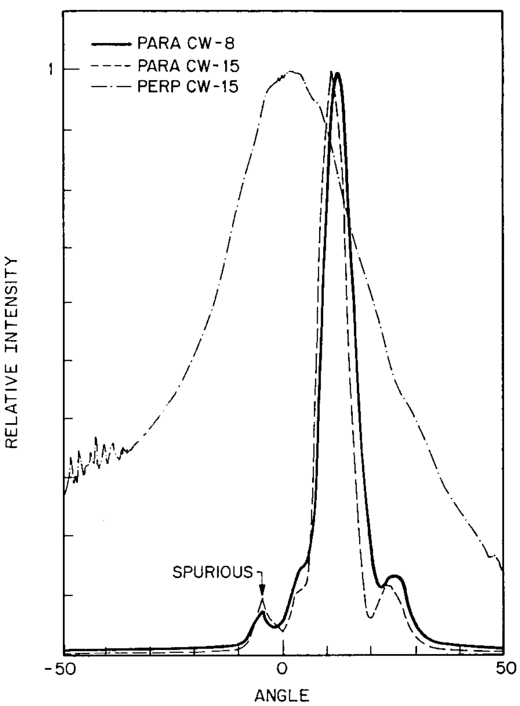

Fig. 5. Far-field spectrum and output angle of typical SLD (PARA = plane parallel to layers; PERP = plane perpendicular to layers). Insert: near-field for a 400 μm long device.

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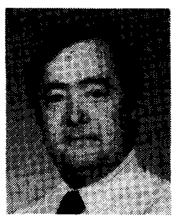

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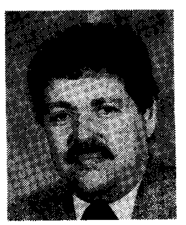
M. G. Harvey, photograph and biography not available at the time of publication.



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