Surface-emitting, distributed-feedback diode lasers with uniform near-field intensity profile

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Theoretical analysis of second-order surface-emitting, complex-coupled distributed feedback diode lasers with first-order distributed Bragg reflectors (DBR) is presented. The DBR reflectors are shown to insure simultaneous operation in a virtually uniform near-field profile with high efficiency and adequate intermodal discrimination. Such devices display symmetric-mode (single-lobed) surface emission with relatively high external differential quantum efficiency (30%), low gain threshold (18 cm⁻¹), and <8% near-field intensity profile variations (in the longitudinal direction). The devices have the potential to provide >100 mW of stable, single-mode cw power, significantly higher than it is possible with vertical-cavity surface-emitting lasers. It is also shown that the device studied here can be combined with a resonant optical waveguide array device to produce a 2D uniform near-field surface-emitting source capable of providing greater than 1 W cw power in a stable, single-lobed beam. © 1998 American Institute of Physics. [S0003-6951(98)01542-3]
Transmission electron microscopy photographs show that 100–150 Å thick InGaAs quantum wells are curved but well defined in the troughs of the InGaP grating. Furthermore, the upper layer of GaAs planarizes at ~0.05 μm above the grating peaks, thus providing a flat reflecting surface, upon metallization with Au, that insures effective collection of all light outcoupled by the grating. The second-order SE-CC-DFB is terminated with first-order DBRs. Combinations of first- and second-order gratings have been previously reported, with first-order DBRs used for laser oscillation and a second-order grating used as a passive outcoupler. Such a combination can be fabricated in a one-step process using direct-write e-beam or x-ray lithography. Saturation of the absorbing regions at high drive levels is not of concern for two reasons: (1) the quantum-well absorber is curved and in close proximity (0.05–0.1 μm) to the metal contact, thus allowing for easy replacement of the carriers used in absorption; and (2) other designs involve metal gratings which by nature are nonsaturable absorbers.

For the case where no first-order DBR reflectors are present, the numerical method developed by Noll and Macomber was used to find the coupling coefficient, \( \kappa = j \kappa_i + \kappa_g \), where \( \kappa_i \) and \( \kappa_g \) are the gain and index coupling coefficients, respectively, for an infinitely long grating, and then the coupled-mode theory (CMT) was used to solve for the modes of a finite structure. The boundary conditions used for the CMT are found by assuming that no light is entering the grating longitudinally from either end. The analysis for the case when DBR reflectors are present is done the same way, only using different boundary conditions. The boundaries are assumed to be the two interfaces of the second- and first-order gratings. The amount of light entering at each second-order grating end is simply the amount of field at the end of the second-order grating multiplied by the field amplitude reflectivity of a DBR reflector, \( \rho \). Because the active region and the absorbing grating extend into the DBR regions, there is absorption which limits the maximum achievable \( \rho \) value to \( \approx 80\% – 85\% \). Due to a large \( \Delta n \) value of 1.4 × 10^{-2} (i.e., strong coupling) relatively short DBR regions (70–100 μm) should be adequate. Furthermore, the DBR regions will be pumped over half their lengths, resulting in a relatively small penalty (<10%) in overall efficiency.

Before presenting the results of the analysis involving DBR reflectors, we should define the important parameters. The gain threshold is defined as

\[
\eta_{\text{th}} = \alpha_{\text{rad}} + \alpha_{\text{edge}} - \kappa g \delta_{\text{st}},
\]

(1)

where \( \alpha_{\text{rad}} \) is the surface emission loss, \( \alpha_{\text{edge}} \) is the edge emission loss, and \( \delta_{\text{st}} \) is the relative depth of the standing wave pattern. The external differential quantum efficiency is defined as

\[
\eta_D = \frac{\alpha_{\text{rad}}}{g + \alpha_i},
\]

(2)

where \( \alpha_i \) is the internal cavity loss, which is assumed to be 3 cm^{-1}. Finally, we define a parameter we call “aspect ratio” characterizing the longitudinal near-field profile of the surface emission. The aspect ratio is defined as the near-field intensity at the center of the SE-CC-DFB divided by the near-field intensity at one end of the SE-CC-DFB (at the second-order/first-order grating interface). Thus, the aspect ratio quantifies the degree of nonuniformity of the near-field intensity profile — a large aspect ratio corresponds to a highly nonuniform near field while unity aspect ratio corresponds to a perfectly flat near-field intensity profile.

Figure 3(a) is a graphical representation of the results of the calculation of the aforementioned parameters for the structure of Fig. 2, and for a surface-emitting grating length of 500 μm. The graph shows, for the symmetric mode, how \( \eta_{\text{th}} \), \( \eta_D \), and the aspect ratio vary as the DBR amplitude reflectivity \( \rho \) is varied from 0% to 95%. Most notable is how quickly the aspect ratio approaches the ideal value of 1. It is also notable that in the case where \( \rho = 50\% \) and \( \rho = 85\% \). The reason why \( \eta_{\text{th}} \) and \( \eta_D \) vary so little with \( \rho \) can be seen from Fig. 3(b) and from Eqs. (1) and (2). The surface loss (\( \alpha_{\text{rad}} = 6.5 \text{ cm}^{-1} \)) and the absorption loss \( \kappa g \delta_{\text{st}} = 8.7 \text{ cm}^{-1} \) in the second-order DFB region are independent of \( \rho \). Only the edge loss varies with \( \rho \). In the first case, when \( \rho = 0 \), there is almost no field at the ends of the SE-CC-DFB, and so the edge loss is small (\( \alpha_{\text{edge}} = 2.8 \text{ cm}^{-1} \)). In the case where \( \rho = 50\% \), the field at the edges and therefore the edge loss is larger (\( \alpha_{\text{edge}} = 6.3 \text{ cm}^{-1} \)). This causes only a relatively small increase in \( \eta_{\text{th}} \) and decrease in \( \eta_D \), since \( \alpha_{\text{edge}} \) is relatively small compared with \( \alpha_{\text{rad}} \). Finally, when \( \rho = 85\% \), the field at the edges is large, but since the amplitude reflectivity is high, most of the field is reflected back into the structure and therefore, again the edge losses are small (\( \alpha_{\text{edge}} = 3.1 \text{ cm}^{-1} \)); and \( \eta_{\text{th}} \) and \( \eta_D \) are back to what they were for \( \rho = 0 \). The results show that one can drastically reduce the aspect ratio without paying a penalty in gain threshold or slope efficiency. That is, high near-field uniformity and high \( \eta_D \) are simultaneously achievable. However, it should be noted that phase mismatches at the second-order/first-order grating interface. Thus, the aspect ratio quantifies the degree of nonuniformity of the near-field intensity profile — a large aspect ratio corresponds to a highly nonuniform near field while unity aspect ratio corresponds to a perfectly flat near-field intensity profile.
first-order grating interfaces can cause severe near-field distortions. We find that phase mismatches of up to $\pm \pi/10$ are tolerable, in that the resulting near-field distortions are not enough to prevent symmetric-mode lasing to high drive levels. As mentioned above, e-beam grating fabrication has allowed successful operation of devices with second-order/first-order grating interfaces. Should phase mismatches prove to be a problem the solution would be to use separate contact pads for the DBR reflectors so as to adjust the phase via carrier-induced changes in the dielectric constant.

Figure 4 shows how the gain thresholds of the symmetric mode and the nearest antisymmetric mode, $g_{th,S}$ and $g_{th,A}$, vary with $\rho$. The maximum modal discrimination occurs when $\rho = 50\%$. However the aspect ratio at that point is not adequate for high power single-mode operation. As $\rho$ approaches $100\%$ the modal discrimination approaches zero and the aspect ratio approaches 1. Therefore one must find a value of $\rho$ between $50\%$ and $100\%$ which provides suitable modal discrimination and low aspect ratio. For the device of Fig. 2, with a $500\mu m$-long SE-CC-DFB section, we choose $\rho = 85\%$. This gives a modal discrimination value, $\Delta \alpha$, of $3.3 \mathrm{cm}^{-1}$ and an aspect ratio of 1.1; while $g_{th} = 18 \mathrm{cm}^{-1}$ and $\eta_D = 30\%$. The $\Delta \alpha$ value is considered adequate since the near-field profile for $\rho = 85\%$ is virtually uniform and thus multimoding via longitudinal GSHB is highly unlikely. A simple single-spatial-mode structure in the lateral direction (e.g., ridge guide) together with the proposed structure should thus provide $\geq 100 \mathrm{mW}$ cw surface-emitted, stable, single-mode power.

These results have important implications for the development of 2D high-power surface emitters. A ROW array is a structure for which all elements of a lateral array of anti-guides equally couple with one another (i.e., parallel coupling) and thus the device has a uniform near-field intensity profile. The combination of the ROW array with the SE-CC-DFB with DBR reflectors will then result in a device with a uniform near field in both the lateral as well as the longitudinal directions; i.e., in two dimensions. The far field of such a device will be single lobed and normal to the surface. A device with a $20\times20$ array (or $100 \mu m$ aperture) and a $500\mu m$-long SE-CC-DFB, being immune to GSHB and possessing strong (lateral) built-in index guiding, has the potential for providing greater than $1 \mathrm{W} \mathrm{cw}$ stable, diffraction-limited power.

We have shown here that the addition of first-order DBR reflectors at the ends of a SE-CC-DFB laser drastically reduces the near-field nonuniformity, while the gain threshold and external differential quantum efficiency are relatively unaffected. Such devices should provide $>100 \mathrm{mW}$ of stable power from (latterally) single-mode devices. Furthermore, by combining this structure with a ROW array one can create a two-dimensional surface emitter of uniform intensity profile, which has the potential of providing greater than $1 \mathrm{W} \mathrm{cw}$ power in a stable, single-lobed beam pattern.

**Diode Laser Arrays**