Metal-grating-outcoupled, surface-emitting distributed-feedback diode lasers

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The theoretical analysis of antiphase, surface-emitting, complex-coupled, distributed feedback (SE-CC-DFB) lasers is presented. The specific configuration chosen for analysis is relatively simple: a metallic second order grating placed atop a diode-laser structure. This type of SE-CC-DFB structure can be fabricated by a lift-off and evaporation process; can operate in a single-lobed, orthonormal beam with a rather uniform near-field intensity pattern, and external differential quantum efficiency, η_d , values in excess of 30%. The dependence of the gain threshold on grating duty cycle for both the symmetric and antisymmetric (longitudinal) modes is presented and discussed. The external differential quantum efficiency for the symmetric mode is found to steadily increase with grating length at the expense of the degree of near-field-pattern uniformity. © 1996 American Institute of Physics. [S0003-6951(96)00345-2]

Complex-coupled, distributed-feedback (CC-DFB) edge-emitting lasers consisting of periodic variations of both the refractive index and gain have recently received considerable theoretical and experimental attention as potential light sources in advanced optical-communication systems.^{1–9} We have previously reported on the theoretical analysis of in-phase, second-order, surface-emitting CC-DFB lasers.¹⁰ In this letter, we present a treatment of antiphase (i.e., excess gain preferentially placed in low-index regions), CC-DFB lasers. The device analyzed is simply composed of a metallic second-order Bragg grating placed atop a diode-laser structure. We show that an antiphase, surface-emitting (SE-CC-DFB) laser can provide a single-lobed, orthonormal far-field radiation profile as well as a symmetric, nearly uniform near-field intensity pattern.

While we have already demonstrated¹⁰ that in-phase type SE-CC-DFB devices can fundamentally favor symmetric (i.e., single-lobe) mode operation, the designed structure involves a biharmonic-like grating, a feature impractical to fabricate and incorporate into a semiconductor-laser device. Therefore, knowing that resonant-optical-waveguide (ROW) arrays¹¹ are analogous to second-order antiphase, CC-DFB lasers,¹² we proceeded to analyze antiphase-type SE-CC-DFB's; which, as shown below, can be designed to be made in practical configurations. In particular, we choose to analyze a metal-grating second-order DFB, due to its simplicity of fabrication, and no need to process the semiconductor material itself. The latter feature is particularly attractive if one has to make GaN-based blue/green diode lasers.¹³

Metal-grating first-order, loss-coupled DFB lasers have already been demonstrated,¹⁴ with excellent results (i.e., single-longitudinal-mode operation with good side-mode suppression ratio and no danger of self-pulsation, since light absorption in the metal is nonsaturatable). However, those devices were edge emitters. Here we present an analysis of a second-order metal-grating DFB laser that primarily acts to

efficiently outcouple light in a direction orthonormal to the wafer plane.

The longitudinal cross section of the studied SE-CC-DFB structure is schematically shown in Fig. 1. The design utilizes a multi-quantum-well active region (at $\lambda_0 = 0.98 \mu\text{m}$), and a second-order metallic grating for both feedback and outcoupling mechanisms. The rectangular-profiled Bragg grating, which can simply be fabricated by standard techniques,¹⁵ consists of gold (i.e., $n_{\text{Au}} = 0.1 + i6.54$) and 300-Å-thick zirconium (i.e., $n_{\text{Zr}} = 3.42 + i1.31$). Zr was chosen over other metals (e.g., Ni, Ti, Al) since it combines a relatively high real part of the refractive index with relatively low optical absorption (at $\lambda_0 = 0.98 \mu\text{m}$). Thus strong radiation outcoupling can occur with minimal penalty in absorption loss. An alternative high-index, absorptive structure is a combination of 200-Å-thick Ti atop 100-Å-thick GaAs. Although Au has a higher optical absorption coefficient than Zr, due to its extremely low index, light hardly samples Au, while deeply penetrating in the high-index Zr regions. Thus an antiphase grating (i.e., high modal gain in low effective-index regions) is created.

We have assumed that the structure supports propagation of only the fundamental transverse electric (TE) mode and has perfectly antireflection-coated facets. For the structure

FIG. 1. Schematic diagram of metal-grating-based second order, surface-emitting antiphase CC-DFB laser structure. Light generated in the active region is reflected mainly by the low-index Au regions and absorbed primarily in the high-index Zr regions.

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FIG. 2. Dependence of total loss coefficients, for the symmetric ($\alpha_S = \alpha_{\text{rad}} + \alpha_{\text{metal},S}$) and antisymmetric ($\alpha_A = \alpha_{\text{metal},A}$) solutions of an infinitely long grating as a function of the grating duty cycle, σ (i.e., ratio of the width of the low-loss grating region, here Au, to the grating period). The radiation loss for the symmetric mode is shown as well.

shown in Fig. 1, the effective-index difference, Δn_{eff} , is 0.004 and the local modal-gain difference, $\Delta \alpha_{\text{metal}}$, is 127 cm^{-1} . Following the numerical approach of Noll and Macomber,¹⁶ the governing equations for the slowly varying modal amplitudes of forward $[A^+(z)]$ and backward $[A^-(z)]$ traveling waves are obtained as:

$$\frac{d}{dz}A^+ = C_1A^+ + C_2A^-, \quad (1)$$

$$-\frac{d}{dz}A^- = C_3A^+ + C_4A^-, \quad (2)$$

where the coupling coefficients provide information about feedback, radiation, and metal losses as well as the oscillation characteristics.¹⁶ Due to the symmetric nature of the structure, the amplitudes of the field solutions are longitudinally symmetric or antisymmetric about the center of the grating.

Previously, we have shown¹⁰ that a SE-CC-DFB laser can oscillate in a symmetric mode when the modal-gain difference between the symmetric and antisymmetric modes due to optical-field (longitudinal) overlap with the gain/loss grating overcomes the modal-gain difference based on radiation losses. Thus, to ensure symmetric-mode lasing, our designed structure must guarantee that the antisymmetric modes on either side of the symmetric (lasing) mode experience more metal-absorption losses (the radiation losses for antisymmetric modes are rather small) than the total loss of the symmetric lasing mode due to the radiation outcoupling and metal absorption.

In order to obtain the trends in modal behavior it is useful to study the behavior of the two modes characterizing an infinite-length grating:¹⁶ one symmetric (*S*), and one antisymmetric (*A*). Shown in Fig. 2 are the total loss coefficients for these modes as a function of the duty cycle σ (i.e., ratio

FIG. 3. Mode spectrum of the structure shown in Fig. 1 for $\sigma=0.33$, and a $600\text{-}\mu\text{m}$ -long grating (*S*: symmetric mode, *A*: antisymmetric mode).

of the width of the low-index, low-loss region to the grating period). As expected the *A* mode has no radiation loss, while the *S* mode has losses due both to metal absorption as well as to radiation. By using the *A* and *S* solutions,¹⁶ it is easy to show that for $\sigma=0.5$ the two modes have similar (longitudinal) field overlap with the high-index, lossy regions, and thus similar absorption losses. However, as σ decreases to 0.25 the *A*-mode absorption losses significantly increase due to increased field overlap with the high-index, lossy regions. By contrast, the *S*-mode field overlap with the lossy region stays basically the same as σ varies, which explains the relative constancy of its absorption losses.

Now, returning to a finite-length grating, we show in Fig. 3 the gain threshold, g_{th} , versus the Bragg frequency deviation, δ , for the first six longitudinal modes for a structure of the cross section shown in Fig. 1, $600 \mu\text{m}$ long, and with a duty cycle value, σ , of 0.33. It is evident that the mode favored to lase is of the symmetric type. The gain-threshold difference between the symmetric lasing mode and the nearest antisymmetric mode is about 7 cm^{-1} , which is adequate discrimination for single-mode operation. The relatively high gain threshold (i.e., 74 cm^{-1}) is due to the metal losses. Since for an efficient surface-emitting device high radiation outcoupling is desired, relatively large metal losses are unavoidable, and as a result, a relatively high gain threshold is required. That is why a multi-quantum-well active region is necessary.

The near- and far-field radiation patterns of the two modes with lowest gain thresholds are shown in Figs. 4(a) and 4(b), respectively. The lasing mode has a symmetric, fairly uniform near-field pattern, and a corresponding single-lobed far-field pattern. The η_d value for this device is 27.2%. A perfectly uniform near-field profile was obtained at the Bragg resonance¹⁰ by varying the device length, but then η_d drops to 18%.

The dependence of the gain threshold for the first symmetric and antisymmetric modes as a function of duty cycle, σ , is illustrated in Fig. 5. Now we can clearly see the trends displayed in Fig. 2 for infinite-length-grating modes. When

FIG. 4. Relative intensity of: (a) near-field and (b) far-field radiation patterns for the two modes of Fig. 3 of lowest gain thresholds.

intermodal discrimination based on metal loss is larger than that based on radiation losses, the symmetric mode is favored to lase (i.e., for $\sigma \leq 0.36$). The discrimination increases with decreasing σ , but at some price in η_d . Specifically η_d decreases from 27% to 23% as σ decreases from 0.36 to 0.25.

Next, the η_d of the symmetric mode versus the grating length is shown in Fig. 6. For an antisymmetric mode η_d decreases with increasing length,¹⁶ since an antisymmetric finite solution asymptotically reaches the nonradiating anti-

FIG. 5. Dependence of gain thresholds on the grating duty cycle, σ , for the two modes of Fig. 3 of lowest gain thresholds.

FIG. 6. Dependence of the external differential quantum efficiency of the symmetric lasing mode on the grating length ($\sigma = 0.33$).

symmetric infinite-length solution.¹⁶ In marked contrast, the η_d of the symmetric mode increases with the grating length, as shown in Fig. 6. Such behavior is expected for devices for which the outcoupled light output is proportional with the device length.¹⁷ It should, however, be noted that as the grating length increases, the nonuniformity of the near-field intensity also increases, making the device vulnerable to gain spatial hole burning and subsequent multimoding. Thus, a tradeoff between the η_d value and the degree of near-field uniformity has to be reached.

In conclusion, we have shown that employing a metal grating atop a semiconductor structure can result in single-lobe lasing with good uniformity of the near-field profile and moderately high values for the external differential quantum efficiency. Such devices are expected to radiate in a stable, single mode to cw powers in the 10–100 mW range, thus vastly surpassing the single-mode power capability of vertical-cavity surface emitters (i.e., ≈ 1 mW cw).

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