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View online: http://dx.doi.org/10.1063/1.4869561

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Design for high-power, single-lobe, grating-surface-emitting quantum cascade lasers enabled by plasmon-enhanced absorption of antisymmetric modes

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(Received 1 January 2014; accepted 12 March 2014; published online 3 April 2014)

Resonant coupling of the transverse-magnetic polarized (guided) optical mode of a quantum-cascade laser (QCL) to the antisymmetric surface-plasmon modes of 2nd-order distributed-feedback (DFB) metal/semiconductor gratings results in strong antisymmetric-mode absorption. In turn, lasing in the symmetric mode, that is, surface emission in a single-lobed far-field beam pattern, is strongly favored over controllable ranges in grating duty cycle and tooth height. By using core-region characteristics of a published 4.6 μm-emitting QCL, grating-coupled surface-emitting (SE) QCLs are analyzed and optimized for highly efficient single-lobe operation. For infinite-length devices, it is found that when the antisymmetric mode is resonantly absorbed, the symmetric mode has negligible absorption loss (~0.1 cm⁻¹) while still being efficiently outcoupled, through the substrate, by the DFB grating. For finite-length devices, 2nd-order distributed Bragg reflector (DBR) gratings are used on both sides of the DFB grating to prevent uncontrolled reflections from cleaved facets. Equations for the threshold-current density and the differential quantum efficiency of SE DFB/DBR QCLs are derived. For 7 mm-long, 8.0 μm-wide, 4.6 μm-emitting devices, with an Ag/InP grating of ~39% duty cycle, and ~0.22 μm tooth height, threshold currents as low as 0.45 A are projected. Based on experimentally obtained internal efficiency values from high-performance QCLs, slope efficiencies as high as 3.4 W/A are projected; thus, offering a solution for watt-range, single-lobe CW operation from SE, mid-infrared QCLs. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4869561]

Grating-coupled surface-emitting lasers (GCSEL) are attractive sources due to easy packaging, lack of emitting-facet heating and subsequent degradation, ability to reach 1 W diffraction-limited continuous-wave (CW) power, and the potential for obtaining multi-watt CW diffraction-limited power when combined with single-lateral-mode, high-index-contrast photonic-crystal structures.

Research on GCSELs started in the early 1970s and was focused on near-infrared (IR)-emitting devices. It was found for TE-polarized lasers that, in accordance with theory, the longitudinal mode favored to lase is the antisymmetric one (i.e., a mode whose far-field pattern consists of two lobes) due to its inherent low radiation loss and subsequent low threshold gain. Several approaches have been proposed and demonstrated for realizing operation in a single-lobed beam with the most successful ones being those involving no penalty in efficiency: central grating π phase shift or chirped grating corresponding to a π phase shift.

With the advent of quantum cascade lasers (QCLs) in the mid 1990s, GCSEL analysis turned to devices generating transverse-magnetic (TM)-polarized light. SE distributed-feedback (DFB) grating, mid-IR-emitting QCLs include: two-dimensional (2-D) photonic-crystal structures, air-metal/semiconductor gratings, metal/semiconductor gratings for emission only through the substrate, and all-semiconductor gratings. By and large, the antisymmetric mode was found to be favored to lase, just like for TE-polarized GCSELs, with two exceptions: (a) excitation of a 2nd-order DFB region from a 1st-order DFB laser, which gave a single, diffraction-limited beam only for short (≤200 μm) apertures and (b) an edge- and surface-emitting device that provided 100 mW CW surface-emitted power in a near-diffraction-limited beam, with significant power being edge emitted, and occasional two-lobed beams due to uncontrolled facet reflections. 500 mW CW surface-emitted power was reported from ring-cavity devices, but operating multimode. More recently, ring-cavity GCSE QCLs have provided a symmetric-like, multilobe beam pattern, as a result of employing two π phase shifts and a linear-polarization scheme. THz SE-DFB QCLs have been found to operate in the antisymmetric mode as well with the solution for single-lobed operation being either a central π phase shift or symmetric-mode selection via dual-slit unit-cell gratings, chirped gratings from their centers to their edges. Furthermore, by using resonant leaky-wave coupling, 2-D GCSE THz QCLs emitting in diffraction-limited beams have been demonstrated.

Here, we present a GCSE QCL mid-IR-emitting structure with inherent suppression of the antisymmetric modes that allows symmetric-mode lasing at low (<0.5 A) threshold currents and high (>3 W/A) slope efficiencies. The device relies on the antisymmetric modes being strongly absorbed due to resonant coupling of the (guided) optical mode to the antisymmetric surface plasmon mode of a metal/semiconductor grating. In addition, the DFB grating is bounded by 2nd-order

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The antisymmetric surface plasmon mode at the interface(s) of a 2nd-order metal/semiconductor has its H-field intensity nulls occur in the middle of the grating troughs and peaks [see example in Fig. 1(b)]. For an infinite-length grating with Ag for metal, InP for semiconductor and designed to be the 2nd-order DFB grating for a published30 4.6 μm-emitting QCL structure, we plot in Fig. 1(a) the wavevector of the plasmon as a function of grating duty cycle, defined as the percentage of metal in a grating period, and grating tooth height. A thin white line indicates the plasmon-wavevector curve corresponding to 4.6 μm wavelength, λ; that is, where the DFB-QCL structure’s optical-mode propagation constant matches the plasmon-propagation constant, and thus resonant coupling occurs between the two modes. We show in Fig. 1(b) the plasmon H-field intensity for a grating of 39% duty cycle and 0.217 μm tooth height (λ = 4.6 μm).

Next, we consider the DFB-QCL structure for which the (transverse) optical mode couples to the grating surface-plasmon modes. Coupling to the antisymmetric and symmetric plasmon modes results in antisymmetric (A) and symmetric (S) longitudinal modes of the structure. We choose a 40-period, 4.6 μm-emitting QCL structure30 of 75% transverse optical-confinement factor Γ. The grating period a is fixed to be that ratio of the vacuum wavelength (4.6 μm) to the effective refractive index of the transverse mode, such that the 2nd-order Bragg-diffraction condition is met. For this 2nd-order DFB-QCL structure, we show in Fig. 2 the dispersion curves, at 39% grating duty cycle, for the A and S modes as a function of tooth height, h. As seen from the inserted pictures, in the case of the A mode for h < 0.217 μm the guided mode couples in-phase with the antisymmetric plasmon mode, while for h > 0.217 μm the guided mode couples out-of-phase with the antisymmetric plasmon mode. The S mode couples weakly to the symmetric plasmon mode, as evidenced by negligible field at the grating interfaces. (However, the S-mode couples strongly to the grating and is effectively outcoupled over a large range in h [Fig. 3(b)].) Such modal behavior is somewhat similar to that for the modes of 1st-order metal/semiconductor DFB structures31 in that the A and S modes qualitatively behave like the 1st-order DFB modes whose H-field maxima occur on the grating troughs and peaks, respectively (Fig. 3 in Ref. 31).

Fig. 3(a) shows the A-mode loss as a function of grating height and duty cycle. We superimpose the white line from Fig. 1(a) on the locus of maximum-loss points, to highlight that the latter corresponds to resonant coupling between guided and plasmon modes. The losses for the A and S modes are shown in Fig. 3(b) as the grating height varies, when the duty cycle is 39%. The A-mode loss is only absorption loss which is peaked at resonance (i.e., at h = 0.217 μm). The S mode has both surface-emission (coupling coefficient κ = 0.193 – i9.231 cm⁻¹) and absorption losses; the latter being negligible (~0.1 cm⁻¹) due to weak optical-mode coupling to the symmetric plasmon mode. We note that significantly enhanced absorption of incident TM-polarized light, due to strong coupling to a surface-plasmon mode of a
Next, we study finite-length, buried-heterostructure devices with DBR gratings at the ends of the DFB grating (Fig. 4), just as for high-power, near-IR GCSELS. A longitudinal cross-section is shown in the inset. The 40-period InGaAs/InAlAs core region of a high-CW-power, 4.6 $\mu$m-long, DFB/DBR QCL is considered. Atop an InP cladding layer a metal/semiconductor grating is placed. To control the tooth height, a 10 nm-thick InGaAs etch-stop layer is introduced between the InP cladding layer and the grating. At the top of the semiconductor portions of the grating, a 50 nm-thick n$^-$-InP layer is added to ensure good electrical contact, and a 2 nm-thick Ti layers are inserted between metal and semiconductor for good adhesion.

For finite-length devices, the coupled-mode theory for 2nd-order metal/semiconductor gratings is employed together with the matrix method for DFB/DBR structures adjusted for TM-polarized light. More specifically, COMSOL is used to calculate the eigenfrequencies of the symmetric and antisymmetric modes for an infinite-length DFB structure. The real and imaginary parts of these are converted into detuning and loss parameters, both in units of cm$^{-1}$, and then inserted into the equations for calculating the coupling coefficient and correction factor. Then, we use the transfer-matrix method to solve for the grating-related (intensity) loss coefficient, $2\alpha$, which is part of the local threshold gain (i.e., in the DFB region) $g_{th}$, which, for interband-transition devices, is given by

$$g_{th} = 2\alpha + \frac{x_i}{\Gamma_g},$$

where $x_i$ is the internal cavity loss and $\Gamma_g$ is the percentage of field intensity residing in the DFB region. However, for QCLs one has to take into account the backfilling-current density which, multiplied by $\Gamma_g$, are routinely subsumed with $x_i$ as being parts of a “waveguide” loss coefficient $x_m$ in the threshold-current density formula for Fabry-Perot-cavity devices: $J_{th} = (x_m + x_g)/\Gamma_g$ where $x_m$ is the mirror loss and $g$ is the differential gain. Since backfilling and carrier leakage occur only in the DFB region, the $g_{th}$ equation for SE DFB/DBR QCLs is

$$g_{th,q} = 2\alpha + x_m + \left(\frac{1}{\Gamma_g} - 1\right)x_i,$$

For $x_m$, we take the experimental value obtained by Lyakh et al.: 3.3 cm$^{-1}$, and for $x_i$ we take a value of 0.5 cm$^{-1}$, typical of state-of-the-art, high-power 4.5–5.0 $\mu$m-emitting QCLs. The modal threshold gain $G_{th,q} = \Gamma_g g_{th,q}$. Then, the threshold-current density is

$$J_{th} = \frac{G_{th,q}}{\Gamma_g} = \frac{g_{th,q}}{\Gamma_g}.$$
An S mode is clearly favored to lase over two adjacent A modes, which have $g_{th,q}$ values 23.1 cm$^{-1}$ and 23.9 cm$^{-1}$ higher than the S mode. These large intermodal-discrimination values are dominated by the strong absorption of the A modes. For the S mode, by using Eq. (3) and the $g$ value experimentally obtained by Lyakh et al., we obtain a $J_{th}$ value of 1.84 kA/cm$^2$.

Fig. 5(b) shows the $g_{th,q}$ values for the S and the two adjacent A modes as a function of grating height, at 39% duty cycle. The A modes reach $g_{th,q}$ maxima at values corresponding to resonant coupling of the guided mode to the anti-symmetric plasmon mode, at their respective oscillation wavelength. The intermodal discrimination is $\geq 10$ cm$^{-1}$ over a 0.030 $\mu$m-wide variation in tooth height, which is quite achievable by using a stop-etch layer. Fig. 5(c) shows the intermodal discrimination as a function of duty cycle and tooth height. Thin black lines indicate where the intermodal discrimination is 10 cm$^{-1}$; thus, defining a curved-stripe-shaped domain over which the intermodal discrimination is $\geq 10$ cm$^{-1}$. For a fixed duty cycle, intermodal discrimination is $\geq 10$ cm$^{-1}$ over a 0.030 $\mu$m-wide variation in tooth height (e.g., over the 0.202–0.232 $\mu$m range in tooth height at 39% duty cycle). This can easily be achieved by using the InGaAs stop-etch layer. For a fixed tooth height, intermodal discrimination is $\geq 10$ cm$^{-1}$ over a 2%-wide variation in duty cycle (e.g., over the 38%–40% range in duty cycle at 0.217 $\mu$m tooth height). For a grating of 1.44 $\mu$m period, this corresponds to controlling the tooth width within 0.03 $\mu$m, which can be achieved with e-beam lithography.

A study over the ranges: 37%–41% in duty cycle and 0.202–0.232 $\mu$m in grating height, within the $\geq 10$ cm$^{-1}$ domain, reveals that the grating outcoupling efficiency decreases by at most 15% (i.e., from 40% to 34%), 40% outcoupling efficiency is obtained for 38%, 39% and 40% duty cycle at 0.202 $\mu$m, 0.217 $\mu$m and 0.232 $\mu$m grating height, respectively. Thus, the chance of getting outcoupling efficiencies close to 40% is high. Finally, if the grating height is controlled, via the etch-stop layer, to be within the 0.03 $\mu$m range, the range of acceptable duty-cycle values is 4%: from 37% to 41%; thus, the actual tolerance in grating-tooth width is 0.06 $\mu$m, which can be controlled via e-beam lithography.

Figs. 6(a) and 6(b) show the radiated near-field intensity and the envelope of the guided-field intensity profiles for S and A modes, when the grating duty cycle and tooth height are 39% and 0.217 $\mu$m. The $R_0$ value is only 2, as required to ensure single-longitudinal-mode operation to high drive levels.

For the A modes the guided-field intensity in
the DFB region is fairly uniform, yet peaks in the center of the DFB region. Considering this, the fact that the intermodal discrimination is $>20\,\text{cm}^{-1}$ and that $R_0 = 2$, it is quite reasonable to assume that longitudinal spatial hole burning is unlikely to cause multimoding at high drives above threshold. Fig. 6(c) is the S-mode far-field beam pattern: a single lobe.

As for the differential quantum efficiency, the equation for GCSELSs, modified for QCLs is

$$\eta_d = \eta_i \frac{\zeta_{\text{surf}}}{G_{th}} N_p = \eta_i N_p \frac{\zeta_{\text{surf}}}{2k_{lg}} + \eta_i N_p,$$  

(4)

where $\zeta_{\text{surf}}$ is the surface radiation loss; $\eta_i$ is the internal differential efficiency per period, the product of $\eta_p$, the differential pumping efficiency, and $\eta_{tr}$, the transition differential efficiency; and $N_p$ is the period number. The $\zeta_{\text{surf}}/G_{th}$ term, known as outcoupling efficiency, is 40% in this case. While for devices with suppressed carrier leakage (i.e., $\eta_i$ close to unity) the $\eta_i$ value is theoretically $\sim0.85$, the best reported experimental values are in the 0.70–0.79 range. Then, taking $N_p = 40$, $\lambda = 4.6\,\mu\text{m}$, and assuming an AR-coated window and negligible substrate absorption, the estimated slope efficiencies are 3.0–3.4 $\text{W}/\text{A}$, values comparable to best reported pulsed, single-facet values from 4.6 $\mu\text{m}$-emitting devices. Furthermore, for devices with $R_0 = 2.5$ the outcoupling efficiency increases to 48%; then, the slope efficiencies are in the 3.6–4.1 $\text{W}/\text{A}$ range. Since gain spatial hole burning is not well understood in QCLs, we chose to analyze the more conservative case of $R_0 = 2$, but that does not mean that devices of $R_0 = 2.5$ are not possible candidates for single-mode operation to watt-range powers.

Using the estimated threshold and slope-efficiency values (i.e., 0.45 A and 3.4 $\text{W}/\text{A}$), the projected peak pulsed power at 3× threshold is 3.06 W. The coherent power can be increased via resonant leaky-wave coupling of GCSE devices in the lateral direction. In fact, we have recently demonstrated in-phase mode lasing of five resonant leaky-wave-coupled QCLs. Then, considering that typically $\sim67\%$ of the coherent power is emitted in the array main far-field lobe, for a five-element phase-locked array of DFB/DBR QCL coherent powers in excess of 10 W become possible.

In conclusion, a type of grating-surface-emitting laser is presented that offers efficient single-lobe lasing due to the antisymmetric modes being strongly absorbed via TM-mode resonant coupling to surface plasmon modes. By employing a published QCL-core structure, we find that DFB/DBR devices can lase in a single-lobe pattern with threshold currents as low as 0.45 A and slope efficiencies as high as 3.4 $\text{W}/\text{A}$. Thus, the devices hold potential for watt-range CW coherent-power emission delivered reliably, since emitting-facet heating and subsequent degradation are avoided.

This work was supported under Navy Contract No. N68335-11-C-0432 (K. K. Law).