Piezoacoustic modulation of gain and distributed feedback for quantum cascade lasers with widely tunable emission wavelength

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Due to the piezoelectric properties of III–V materials, an acoustic wave propagating along the optical axis of a unipolar laser produces a periodic modulation of the carrier density and the optical gain, sufficient for providing distributed feedback (DFB) with a mode suppression ratio exceeding 30 dB. In contrast to bipolar lasers, the piezoelectric modulation of unipolar carrier density is not accompanied by a degradation of the average gain. Inasmuch as the acoustic frequency can be easily changed, the wavelength of the main DFB mode can be tuned in a wide range. This property should be very attractive for spectroscopic applications of the quantum cascade laser. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1543232]

The quantum cascade laser (QCL) is a promising candidate for midinfrared atmospheric spectroscopy in the 3–12 μm wavelength range.[1] Recent reports have demonstrated broadband emission[2] in the wide range of 5–8 μm and single-mode distributed feedback (DFB) operation with the side-mode suppression ratio exceeding 30 dB.[3] Generally, most trace-gas sensing applications also require reasonable operational tunability of the lasing wavelength, which at this time can be achieved only by varying the heat-sink temperature and/or pumping current. This approach has the drawback of a limited tuning range, which seldom exceeds a few hundred nanometers.[3]

In this work, we discuss the possibility of an ultrabroadband tuning of the QCL lasing wavelength by means of piezoacoustic modulation of the optical gain in the laser active region. Since the acoustic impedance of the laser ridge and the substrate are similar, a piezoelectric transducer can be attached to a flat crystal facet, so that the generated bulk acoustic wave partially penetrates in the laser active region (see Fig. 1). The acoustic wave propagating along the optical axis of a unipolar laser produces a sinusoidal modulation of the carrier density. Since the optical gain is linear in carrier density, this does not affect the average gain over a modulation period but does provide a distributed feedback for the optical wave. This is to be contrasted with the situation in bipolar interband lasers, where the longitudinal piezoelectric field would spatially separate electrons and holes, thus degrading the average material gain.

Acoustic waves in piezoactive A_3B_5 semiconductors are practically immune to the layered layout of multiple quantum well (QW) heterostructures.[4] We shall, therefore, confine our estimates below to bulk acoustic waves, e.g., a shear wave with a [110] propagation direction, suitable for zincblende symmetry. Surface acoustic waves may ultimately provide a better option in terms of mode separation per input acoustic power, but this case would require special design consideration to account for the overlap of the wave with the laser active region.

To estimate the efficiency of the resulting DFB coupling, we consider a one-dimensional scalar problem, assuming uniformity in the y direction and neglecting the charge density redistribution along the z axis related to the vertical electron transport. The wave equation for the acoustic displacement u and the continuity equation for electron density in drift–diffusion approximation describe the piezomodulation of the electron density N:

$$\rho \frac{\partial^2 u}{\partial t^2} = C \frac{\partial^2 u}{\partial x^2} - \beta \frac{\partial E}{\partial x}, \tag{1}$$

$$\frac{\partial N}{\partial t} = -\frac{\partial}{\partial x}\left(N \mu E - D \frac{\partial N}{\partial x} \right). \tag{2}$$

The electric field E of the piezoacoustic wave obeys the Gauss law, which is of the form

$$q(N - N_0) = \beta \frac{\partial^2 u}{\partial x^2} + \varepsilon \frac{\partial E}{\partial x}. \tag{3}$$

The term with $E\, \partial N/\partial x$ in (2) leads to nonlinear effects and can be neglected for A_3B_5 semiconductors with weak piezocoupling. In the linear approximation, with $\partial/\partial t = j\omega_{\mathrm{ac}}$ and $\partial/\partial x = -jk_{\mathrm{ac}}$, we eliminate electric field E and arrive at the following relation between the amplitudes of charge density modulation $\tilde{N} = N - N_0$ and acoustic displacement u_{ac}:

$$q\tilde{N} = -\frac{\beta k_{\mathrm{ac}}^2 u_{\mathrm{ac}}}{1 + j\omega_{\mathrm{ac}}\tau_M + \lambda_D^2 k_{\mathrm{ac}}^2}. \tag{4}$$

Here, $\tau_M = \varepsilon / qN_0\mu$ is the Maxwell relaxation time and $\lambda_D^2 = D\tau_M = \varepsilon k_B T / q^2 N_0$ is the Debye screening length. Typically, the QCL active region is doped at the level of about $N_0 \sim 10^{17}$ cm^{-3}. Using the material constants for InGaAs (Ref. 5) with electron mobility $\mu \sim 10^3$ cm^2/V s at room temperature, we estimate $\tau_M \approx 10^{-13}$ s and $\lambda_D \approx 2\times10^{-6}$ cm. According to Faist *et al.*,[6] in the lasing wavelength range $\lambda \sim 5-8$ μm the effective modal refractive index is about $n_{\mathrm{eff}} \sim 3.2$, so that the spatial periodicity of the gain modulation, which for the main Bragg mode equals half the wavelength of light in the medium, $\omega_{\mathrm{ac}} = \lambda/2n_{\mathrm{eff}}$, should be about 1 μm, corresponding to the acoustic wave frequency in the

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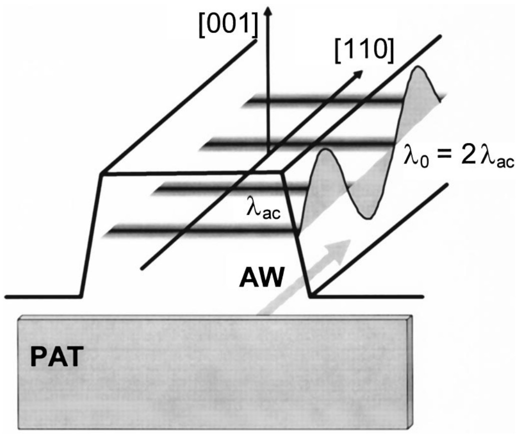

FIG. 1. Piezoacoustic-DFB modulation geometry. Bulk-like shear acoustic wave (AW) is generated by a piezoacoustic transducer (PAT) attached to a facet. Alternatively, assuming a fine-line lithography fabrication, the design may comprise a micro-PAT on the laser ridge facet, or even a surface acoustic wave generator via a transducer deposited on the ridge sidewall. For zinc-blende III–V materials the preferable propagation direction for the piezoacoustic wave is [110]. For wurtzite III–V nitrides propagation conditions are isotropic in (001) plane.

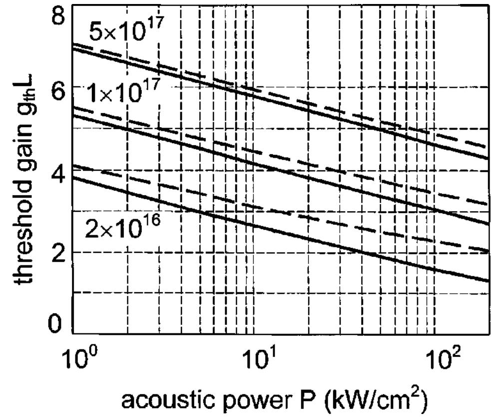

FIG. 2. Threshold gain vs acoustic power for different levels of the average electron concentration in the QCL active region. Material parameters of InGaAs have been used:[5] $\varepsilon=14$, density $\rho=5$ g/cm^3, shear acoustic wave velocity $V_{ac}=(C_{44}/\rho)^{1/2}=3\times10^3$ m/s, and piezoelectric constant $\beta=\beta_{14}=0.1$ C/m^2.

range of 2–3 GHz. It follows that for all doping concentrations of interest $\omega_{ac}\tau_M \ll 1$ and temporal dispersion can be safely neglected, while the spatial dispersion accounted for by the term $\lambda_D k_{ac}$ is tangible for low-doped QCL. The amplitude of the acoustic displacement u_{ac} is related to acoustic power P transported by the wave per unit cross section of the acoustic beam, $P=\frac{1}{2}\rho\omega_{ac}^2 V_{ac} u_{ac}^2$. The inverse subband population in the active quantum wells of the QCL, N_2-N_1, is determined by the interplay between the intersubband relaxation time τ_{21} and the time of the lower lasing state depopulation $\tau_{1\,\mathrm{out}}$. These relaxation times are primarily determined by phonon scattering, and hence, they are not significantly affected by electron density modulation. The relative modulation of the population and the optical gain modulation can thus be estimated as

$$\xi=\frac{\tilde{g}}{g}\approx\frac{\tilde{N}_2-\tilde{N}_1}{N_2-N_1}\approx\frac{\tilde{N}}{N_0}\approx\frac{\beta k_{ac}}{qN_0(1+\lambda_D^2 k_{ac}^2)}\left(\frac{2P}{\rho V_{ac}^3}\right)^{1/2}. \quad (5)$$

For the material parameters of InGaAs and $\lambda_{ac}\sim1\ \mu$m, $P\sim10$ kW/cm^2, and $N_0\sim10^{17}$ cm^{-3}, this gives $\xi\sim0.05$, which confirms the validity of our small-signal approximation.

According to the linear theory of DFB lasers,[7] the DFB coupling coefficient $\kappa=\frac{1}{2}(k_0\tilde{n}+j\tilde{g})$ and the propagation parameter $\gamma=\pm\sqrt{\kappa^2+(g-j\delta)^2}$ satisfy the dispersion equation

$$\kappa=j\gamma/\sinh(\gamma L). \quad (6)$$

Here, L is the laser cavity length, and $\delta=k-k_0=n_{\mathrm{eff}}(\omega-\omega_0)/c$ is the detuning from the main Bragg mode $k_0=k_{ac}/2$. Tilded quantities, $\tilde{n}$ and $\tilde{g}$, represent the modulation amplitudes of the refractive index and optical gain, respectively. The DFB dispersion equation [Eq. (6)] determines the threshold gain value g_{th} required for lasing in a specified DFB mode, and gives also the mode detuning δ.

Owing to the near parallelism of the QCL subbands, the differential gain peak is not shifted away from the peak of the optical gain spectrum, in contrast to interband lasers. The resonant depolarization effect further compensates the inhomogeneous line broadening, induced by the subband nonparabolicity.[8–10] Refractive index modulation, related to the differential gain by the Kramers–Kronig transformation, nearly vanishes when a laser operates at the maximum of the differential gain spectra,[11] hence, we can consider purely gain coupling ($\tilde{n}\approx0$, κ imaginary) a good approximation for the QCL with piezomodulation.

Gain coupling is preferable for DFB operation since in this case the main optical resonance occurs exactly at the Bragg condition ($\delta=0$). This eliminates the mode uncertainty in the vicinity of the Bragg wavelength,[7] and hence, improves the single-mode yield. This regime is also immune to the facet reflection.[12] DFB QCLs with predominantly gain coupling were implemented by Faist *et al.*[6] In the gain-coupled regime, the DFB dispersion equation takes the form

$$\frac{\xi}{2r}\sinh(g_{th}Lr)=1, \quad r=\sqrt{\left(1-i\frac{\delta}{g_{th}}\right)^2-\frac{\xi^2}{4}}. \quad (7)$$

Combined with the above estimate of gain modulation factor ξ, this gives the dependence of normalized gain threshold $g_{th}L$ on acoustic power P and/or electron concentration N_0. The calculated gain threshold is shown in Fig. 2 by the solid lines. For week piezocoupling, which is the case for A_3B_5 semiconductors, the dependence of the threshold gain on both the acoustic power and the mean electron concentration in the active region is logarithmic, which can be readily seen from the dispersion equation. In our linear approach, the piezomodulation strength increases in the low concentration limit, so that for $N_0\sim2\times10^{16}$ cm^{-3} we find very reasonable values of the gain threshold about $g_{th}\sim20$ cm^{-1} at $P\sim20$ kW/cm^2 and for $L\sim1$ mm. The dashed curves in Fig. 2 represent the gain threshold for the next Bragg resonance, which is detuned by about $\delta L\approx\pi$ from the main mode.[7] It is readily seen that the relative change of the gain threshold of about $\sim10\%$ can be easily achieved even for $N_0\sim10^{17}$ cm^{-3}, resulting in the mode-suppression ratio in excess of 30 dB.[13]

An excessively high level of acoustic power will affect such device performance as heat removal and adhesion between the substrate and device mount. To diminish the acoustic power, surface acoustic waves can be employed in-

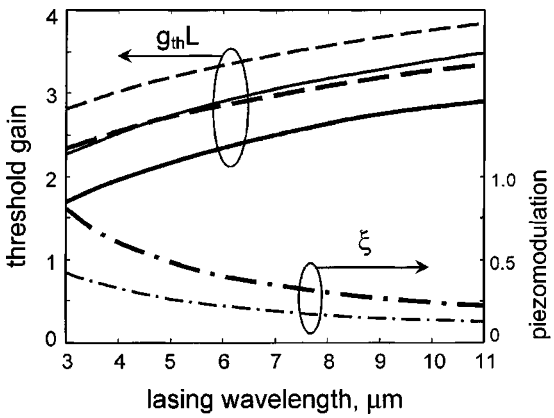

FIG. 3. Spectral dependence of the gain threshold $g_{th}L$ and mode selectivity for QCL implemented in two material systems, based on In(Al)GaAs (thin lines) and GaAlN (thick lines). Solid lines: gain thresholds for the main Bragg modes; dashed lines: threshold gain for the next mode. Two lower curves (dash-dotted lines) represent piezomodulation strength ξ. The assumed acoustic power and doping level are, respectively, 5 kW/cm^2 and 5×10^{16} cm^{-3} for both systems. Material parameters used for the GaAlN-based system are: dielectric constant $\varepsilon=5$, mass density $\rho=5$ g/cm^3, shear acoustic wave velocity $V=(C_{44}/\rho)^{1/2}=4\times10^3$ m/s, piezoelectric constant $\beta=\beta_{14}=0.4$ C/m^2, and $n_{\mathrm{eff}}=2.3$.

stead of bulk waves by using an interdigital transducer deposited on the ridge sidewall. Alternatively, the acoustic power requirements can be further relaxed by using stronger piezoelectrics, such as III–V nitrides, which have attracted recent attention as a promising material system for the implementation of QCLs in a wide frequency range.[3,14] Piezocoupling in nitride-based heterostructures is several times stronger than in the traditional III–V materials.[15] Figure 3 compares the gain thresholds for In(Al)GaAs- and GaAlN-based piezo-DFB QCLs. For both material systems the DFB mode selectivity remains practically unchanged in a wide range of lasing wavelengths λ, which also allows laser tuning throughout the entire frequency range of positive net modal gain [compare with the record 6% tunability in coupled cavity QCLs (Ref. 16)]. For low concentrations $N_0 \approx (2\div5)\times10^{16}$ cm^{-3} the nitride-based QCL even enters the regime of a strong ($\xi\approx1$) electron density modulation, most preferable for the DFB action. In this regime one can satisfy the condition $\kappa L\approx1$, which provides for uniform distribution of the radiation intensity throughout the waveguide,[7] thus ensuring optimum performance in slope efficiency and threshold current. Alternatively, the full modulation regime can be achieved by using surface acoustic waves (cf., e.g., hybridization techniques[17,18]) with strong piezoelectric materials deposited, for example, on the sidewall of the laser ridge. The sidewise layout of the transducer may have the advantage of uniform gain modulation in different stages of the multilayer QCL structure. A detailed discussion of the design will be the subject of a separate publication.

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