Linewidth enhancement factor of terahertz quantum cascade lasers

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The linewidth enhancement factor (LEF) of terahertz quantum cascade lasers is measured using an optical feedback self-mixing technique. As expected, a much lower LEF is found than is common for interband lasers, but instead of the predicted value of zero, the LEF depends on the laser conditions and can be as high as 0.5. The measured value tends to increase with increasing current. Cross absorption within the laser active region is suggested as a possible cause for the nonzero LEF observed. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2883950]

The mechanism for light emission in a terahertz quantum cascade laser (QCL) is unusual because the light originates from intersubband transitions, rather than electron-hole recombination. Since the original demonstration of terahertz QCLs in 2002,[1] the performance of these devices has shown rapid improvement, with high powers[2] achieved and a maximum operating temperature of 164 K.[3]

The linewidth enhancement factor (LEF) (also known as the α-factor) is a dimensionless parameter used in semiconductor lasers to describe the coupling between the gain and the refractive index.[4] Finite values of α will cause the laser linewidth to increase above the Schawlow–Townes limit, since the intensity noise arising from both gain fluctuations and spontaneous emission is also coupled into frequency noise. The LEF also affects properties of the laser such as its modulation response and sensitivity to external optical feedback, as well as being important in the description of the gain dynamics of the device. In conventional diode lasers the LEF is typically $\sim 3-7$, and arises because the two bands involved in the laser transition have opposite curvature in k-space, resulting in a spectrally asymmetric differential gain. In contrast, both laser subbands of a QCL are within the conduction band, and exhibit the same reciprocal space curvature. It has thus been predicted that QCLs should display a symmetric differential gain and a zero LEF.[6]

The LEF of midinfrared QCLs has been reported in various publications,[5,7] but so far, an experimental study in terahertz devices is lacking. In part, this is because the most common method of determining the LEF is through measurement of the sidebands arising from modulation of the laser. This requires very fast detectors with a high dynamic range, which are not yet generally available in the terahertz. Here, we report the use of an optical feedback self mixing technique to measure the LEF of a terahertz QCL. A schematic diagram of the experimental setup is shown in Fig. 1(a). The light emitted from one of the laser facets was collimated using a $f/1.5$ picarin lens, and reflected off a gold mirror, so that the reflected beam was refocussed by the lens and incident upon the laser facet. The phase of the optical feedback could be varied by moving the mirror along the optical axis, using a computer controlled translation stage. A variable aperture within the beam path allowed the level of optical feedback to be changed.

In this configuration, a small modulation of the emitted power is caused by the optical feedback. The laser output power as a function of mirror position is determined by the LEF and by the feedback parameter C, which describes the level of the effective external optical feedback. This is defined as[8]

$$C = \varepsilon \frac{L_{\mathrm{ext}}\sqrt{1+\alpha^2}}{L_{\mathrm{las}} \cdot n} \frac{\sqrt{R_{\mathrm{ext}}}(1-R_{\mathrm{facet}})}{\sqrt{R_{\mathrm{facet}}}}, \quad (1)$$

where L_{las} and L_{ext} are the lengths of the laser and the external beam path, n is the effective refractive index of the optical mode in the laser, and R_{facet} and R_{ext} are the reflectivities of the laser facet and the external mirror. ε is a dimensionless constant which accounts for losses due to the spatial mode mismatch between the laser waveguide mode and the reflected light, as well as atmospheric absorption, slight mis-

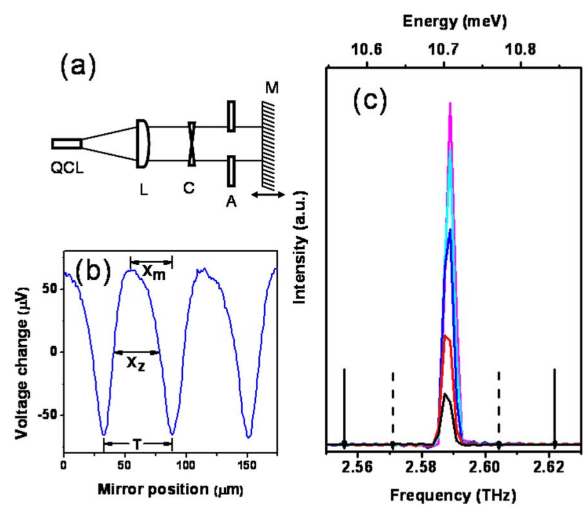

FIG. 1. (Color online) (a) Schematic diagram of the experimental setup used. (b) A representative trace obtained from the self-mixing experiment, showing the definition of X_m, X_z, and T. (c) Spectra measured from sample B under cw operation. From smallest to highest peak, the spectra were measured at 220, 240, 260, 280, and 300 mA. Solid and dashed arrows mark the expected position of longitudinal and transverse side modes respectively.

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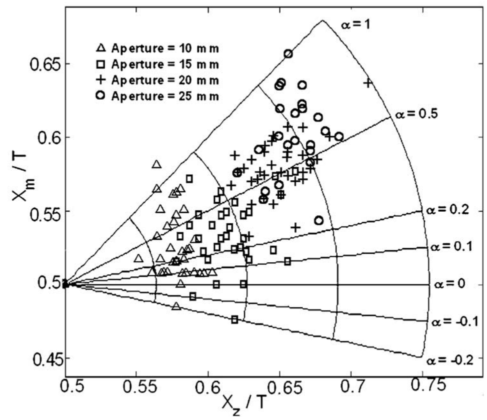

FIG. 2. Self-mixing data measured at a range of different aperture sizes, plotted on the X_m, X_z plane. All measurements were carried out at the same current, 380 mA.

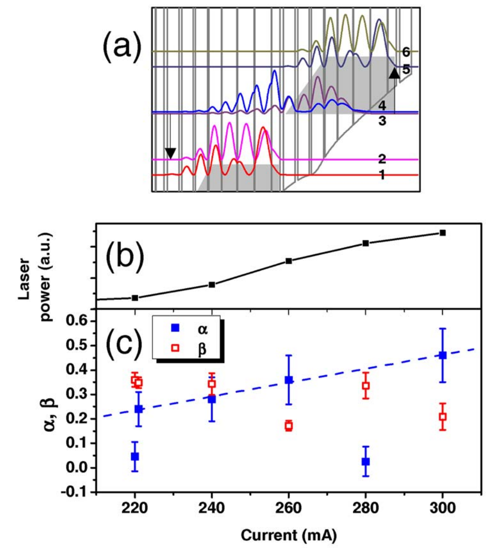

FIG. 3. (Color online) (a) Calculated band diagram of the laser structure under operating bias. For clarity, selected energy levels only are shown, with the grey shading denoting the position of the miniband. (b) Light output measured from the laser as a function of the current. (c) α-values measured from sample B at a range of different currents, plotted on the same horizontal scale. Open symbols show the values of β obtained from the same data.

alignments of the optical components, etc. Instead of measuring the laser output power, we found that the signal to noise ratio could be improved by recording the voltage across the device (when driven in constant current mode). An optical chopper was placed in the beam path and the change in laser voltage solely due to the external optical feedback was isolated using a lock in amplifier. By moving the mirror in steps rather than continuously, our method differs slightly from that used in previous reports of this technique, where the mirror used was mounted on a loudspeaker and the output signal visualized on an oscilloscope.[5] This was made possible because the very long wavelength of terahertz radiation reduces the sensitivity of the experimental setup to mechanical vibrations. In the special case where $\alpha=0$, both output power and voltage will be a periodic and even function (almost sinusoidal) of the mirror position. For finite values of α, where $C<1$, the trace becomes asymmetric and skewed to one side, as can be seen in Fig. 1(b).

Two Fabry–Pérot (FP) devices were used for the measurements, both fabricated from the same wafer and emitting close to 2.55 THz ($\lambda \sim 116$ μm). Sample A had a cavity length of 2.0 mm, with threshold current of ~340 mA, while sample B had a 1.18 mm long cavity and threshold current of ~150 mA. This latter device was used for the current dependent measurements, since its very low threshold allowed it to be operated in continuous wave over its full dynamic range without causing excessive heating of the sample above its operating temperature of ~20 K. The structure used a bound to continuum design, which has been fully detailed elsewhere,[9] and a plasmon waveguide, to facilitate the coupling of light back into the cavity. Sample A lased on a single longitudinal mode close to threshold, while single mode operation was observed from sample B under all investigated conditions as shown in Fig. 1(c).

Figure 2 shows the data measured from laser A close to threshold, while varying the size of the aperture within the external beam path. The values of X_m and X_z as defined in Fig. 1(b) were evaluated from each feedback period and normalized to the overall period T. Both the LEF and C can be obtained from the position of the datapoint on the plot. C is given by the distance from the (0.5,0.5) point and α is related to the angle between the line connecting the datapoint to (0.5,0.5) and the horizontal.[5] A clear trend of increasing C with aperture size can be seen, as would be expected. It is also obvious from the figure that the data are not consistent with a zero value for the LEF, but are instead clustered about the $\alpha=0.5$ line.

One possible origin for the nonzero value of α is related to the effects of parasitic absorption between states in the structure which are not directly involved in the laser transition. Figure 3(a) shows the calculated band diagram for the laser under operating bias, together with selected subbands. The laser transition has a predicted energy and dipole moment of 9.6 meV and 10 nm, respectively, and takes place between levels 4 and 2. The absorptive transition between levels 3 and 5 is close in energy (9.3 meV), but with a smaller dipole moment of 4 nm. Because of the finite width of the transitions, this can provide a small amount of cross absorption at the laser energy. The lower state for this transition is known as the injector level, since it is the ground state of the injection miniband, where most of the carriers are expected to reside. A recent detailed study of the photoluminescence properties of a QCL fabricated from the same wafer has shown evidence for a progressive increase in the population of high-lying states with increasing current.[10] Since the number of charge carriers within the device is fixed, this implies a reduction in the electronic population of the injector level, and hence in the expected cross absorption. This cross absorption results in a positive contribution to the differential gain curve at lower energy than the laser transition, not because of the existence of gain at that energy, but because of a reduction in the losses with increasing current. The resulting asymmetric differential gain will imply a nonzero LEF. This hypothesis however, has to be verified studying different active region designs.

Next, the LEF was measured as a function of the bias current through the laser; sample B was used for these measurements. Figure 3(b) shows the output power measured from the laser at each of these currents, while the α-values measured are shown in Figure 3(c). Each data point is obtained by averaging the results from at least nine feedback periods, to reduce the statistical error. Two data points were measured at 220 mA current, using aperture diameters of 20 (upper point) and 25 mm; otherwise, a 25 mm aperture was used. Below 220 mA, the effects of self-mixing were too weak to be reliably measured. The data show a general increasing trend with current. This behavior is analogous to that observed in mid-IR QCLs,[5] which was attributed to an increase in the carrier density in the active region. In our case it could also be due to the blue Stark shift of the gain curve with respect to the lasing mode observed for this structure. But the increase is also consistent with the model outlined above, since we expect the coupling of the injector level to higher lying states to become more efficient with increasing electric field, meaning that the cross absorption losses decrease more rapidly, making the differential gain spectrum more asymmetric.

There are, however, two datapoints for which α is much lower. These appear to be reliable, and at present we have no good explanation for them. Based on Eq. (1), we define the parameter $\beta = C/\sqrt{1+\alpha^2}$. This is only dependent on the details of the experimental setup, and hence should not change with current. The open symbols in Fig. 3 show the average values of β for the data gathered at each current level. It can be seen that these anomalous datapoints are well within the range of variation of β, confirming the reliability of the data.

The value of α for a given device can be changed by mode-hopping onto a different FP mode, thus, shifting the position of the laser energy with respect to the gain peak. However, we do not consider this to be a probable explanation for the two outlying points in Fig. 3(c). The laser spectrum was measured before each set of data, immediately after changing the current. The results are shown in Fig. 1(c), where it is evident that the device was emitting on the same longitudinal mode for all current levels. We expect the laser cavity to have a free spectral range of ~33 GHz, based on a refractive index of 3.9 obtained from the FP spectra of longer devices fabricated from this wafer. The solid arrows in Fig. 1(c) show the expected position of the adjacent FP modes, based on this, while the dashed arrows show the expected position of the higher order transverse modes. The spectrometer resolution should be clearly sufficient to resolve the appearance of these modes, suggesting that the origin of these two anomalous datapoints does not lie in mode-hopping of the laser.

In conclusion, we have used an optical feedback self mixing technique to measure the LEF of a terahertz QCL. Depending on the conditions, we obtain values of α up to ~0.5, which we attribute to the effects of cross absorption within the laser active region. We also find a general trend for increasing α with drive current.

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