2.10 Mode structure of two-section, coupled-cavity quantum-cascade lasers

A conventional semiconductor ridge laser consists of a single resonant Fabry-Pérot cavity formed by the gain medium embedded between two reflecting facets. The facets (mirrors) cause the optical feedback, which generate the light round trips within the gain medium. Lasing occurs if for one round trip the gain is larger than the optical losses and the total phase shift is a multiple of 2π. In two-sectioned, coupled-cavity (TSCC) lasers, the cavity is divided into a front (f, length L_f) and a back (b, L_b) subcavity (Fig. 27). Both subcavities, which have to lase at the same energy and same time, are separated from each other by a gap of width L_g, which is small compared to the wavelength of the THz and mid-infrared (MIR) light. Therefore, both subcavities are strongly coupled. Adjustments of the individual values of the cavity gain using separate electrical contacts and the degree of freedom enabled by the three-terminal geometry allow additional control of the light interference during the round trip and therefore of the laser output spectrum. Effects of laser-mode monitoring or pulsation of lasing can be studied in conventional semiconductor TSCC lasers. In these interband or *p-n* junction lasers, the stimulated photon emission causes a pinning of the inversion population for increasing current above the threshold, while in quantum-cascade lasers (QCLs), the inversion population is predominantly determined by electron-LO phonon scattering so that it increases with increasing current. This distinct behavior causes different laser-mode properties for both types of semiconductor lasers. Consequentially, we have to investigate whether or not a monitoring of the laser modes in TSCC QCLs is possible for THz and MIR region.

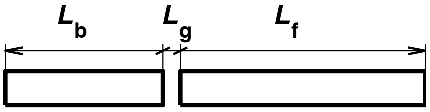

Fig. 27. Two-section, coupled-cavity QCL.

We studied GaAs/$Al_{0.15}Ga_{0.85}As$ THz and GaAs/$Al_{0.45}Ga_{0.55}As$ MIR QCLs, both with plasmon-assisted waveguides grown by molecular-beam epitaxy. The laser spectra were recorded at 7 K under pulsed operation using Fourier transform spectroscopy. The gap [$L_g = (350 \pm 50)$ nm] was fabricated by cleaving the laser ridge and refilling the gap with photoresist.

Figure 28 shows the THz spectra of two QCLs with single laser ridges on the bottom and two TSCC QCLs in parallel operation on the top with the length of the laser ridges indicated. The mode structure of single ridge lasers is characterized by a Gaussian-like envelope with minor deviations due to inhomogeneities within the laser ridge, and a mode spacing $\Delta\nu$, which is inversely proportional to the length of the laser ridge. Therefore, $\Delta\nu(L_0) = \Delta\nu(L_0/2)/2$ as shown in Fig. 28. For THz TSCC QCLs, we have always observed that the mode spacing is determined by the total length of both subcavities, $\Delta\nu \propto (L_f + L_b)^{-1} \approx L_0^{-1}$ independent on the driving current I through the front, back or both cavities. However, the peak intensity of neighboring lasing modes varies strongly depending on the ratio between the length of both coupled subcavities (L_f/L_b). For $L_f = L_b$, every second mode is strongly suppressed, while the adjacent ones are enhanced, whereas for $L_f \neq L_b$ several modes disappear (or are enhanced) in

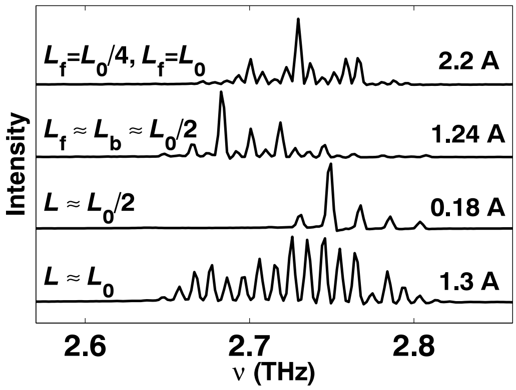

Fig. 28. Lasing spectra of THz QCLs with a single ridge (two spectra on the bottom, $L_0 = 4200$ nm) and of THz TSCC QCLs for parallel operation (two spectra on the top). The lengths of the laser ridges and the driving currents are indicated.

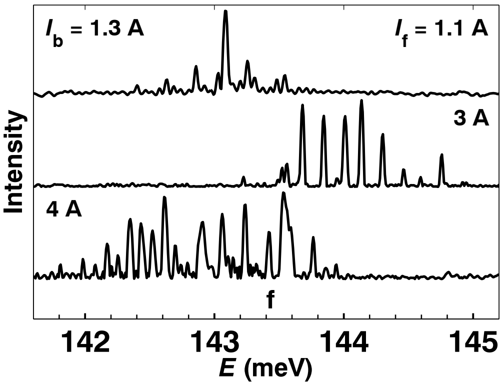

Fig. 29. Lasing spectra of a MIR TSCC QCL with L_f = 1197 nm and L_b = 2060 nm for lasing of the backside cavity (bottom), front cavity (middle) as well as operation of both cavities (top). The driving currents are indicated in the figure.

a periodic way as clearly observed in the uppermost spectrum in Fig. 28.

In contrast to THz QCLs, a larger manifold of intensity modulations and mode spacings can be achieved for MIR TSCC QCLs by selecting appropriate driving currents through a single or both subcavities. Figure 29 shows spectra for a laser with $L_f \neq L_b$, where the one on the bottom was recorded for lasing of the backside subcavity. The spectrum exhibits two features. On the left-hand side, modes with a spacing determined by the backside cavity $\Delta\nu_{\mathrm{left}}(\mathrm{f:off,b:on}) \propto L_b^{-1}$ are present. On the right-hand side (indicated by ”f”), a mode group appears where the mode spacing is determined by the front cavity $\Delta\nu_{\mathrm{right}} \propto L_f^{-1}$, which does not lase, but the laser light from the lasing backside cavity is transmitted through this cavity to the front facet. If only the front cavity lases (spectrum in the middle), the mode spacing is predominantly determined by this cavity $\Delta\nu(\mathrm{f:on,b:off}) \propto L_f^{-1}$. In the case where both subcavities lase, the mode spacing can be attributed to the total length of both subcavities $\Delta\nu_{\mathrm{left}}(\mathrm{f:on,b:on}) \propto (L_f + L_b)^{-1}$ and the peak intensities of neighboring modes exhibit periodic modulations (spectrum at top).

We demonstrated that THz TSCC QCLs allow a static manipulation of the lasing mode intensities due to a control of the ratio L_f/L_b, while for MIR TSCC QCLs the mode spacing can additionally be modified by controlling I_f and I_b. The observed mode features can be explained by interference effects of the light during the round trip in the two-sectioned coupled-cavity QCL. Different mode controlling of THz and MIR TSCC QCLs is assumed to be due to the very different wavelength of THz and MIR radiation, but may also be caused by different optical losses in both types of QCLs. We expect that TSCC QCLs offer a promising potential for a dynamical mode manipulation by a controlled variation of the width and refractive index of the refilled gap between both subcavities. Finally, TSCC QCLs may be a powerful tool for the investigation of effects such as the onset of lasing in THz and MIR QCLs.

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