Measurements of the α factor of a distributed-feedback quantum cascade laser by an optical feedback self-mixing technique

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We demonstrate measurements of the α factor of a distributed-feedback quantum cascade laser (QCL) by using a newly modified self-mixing interferometric technique exploring the laser itself as the detector. We find a strong dependence of the α factor on the injection current, ranging from −0.44 at 120 mA to 2.29 at 180 mA, which can be attributed to the inherent physics of QCLs. © 2006 Optical Society of America

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Today, quantum cascade lasers (QCLs) have evolved to be among the most important light sources in the mid-infrared (MIR) to far-infrared (FIR) wavelength range. The lasing transition in QCLs occurs between subsequently cascaded quantized energy levels within the conduction band. Hence the emitted wavelength does not depend on the energy bandgap as in conventional semiconductor lasers, but it is determined by the energy difference of discrete levels in the conduction band originating from the bandgap-engineered design of the laser device.[1] With the advent of this new type of laser structure, a series of questions on the laser performance and the relevant physical mechanisms have been brought up. For example, it has been found experimentally, and verified theoretically, that the scaling behavior of the intensity noise as a function of the emitted power is different with respect to interband lasers, resulting directly from the cascaded level scheme and the different carrier lifetime.[2,3] The linewidth enhancement factor (α factor) determines the dynamics of semiconductor lasers, because it accounts for the coupling between amplitude and phase of the light as defined in Eq. (1),

$$\alpha = -\frac{\partial \chi_r / \partial n}{\partial \chi_i / \partial n}. \tag{1}$$

Here, χ_r and χ_i are the real and the imaginary parts of the susceptibility, respectively, and n is the carrier density.[4] The α factor therefore describes how gain and refractive index change with respect to each other when the carrier density varies.[5] From the very beginning of the first technological realizations of QCLs, there has been an urgent need to measure the α factor of QCLs and to check whether the particular level scheme gives rise to a different physics, e.g., if QCLs exhibit an α factor close to zero as expected for a nondetuned atomiclike level scheme. The standard technique used for interband semiconductor lasers is the Hakki–Paoli method, which relies on measuring the wavelength shift of the longitudinal laser modes below threshold. However, this method gives only access to α values below threshold, and for low α values its accuracy may be affected by temperature effects.[6] An approach based on injection locking[7] is the only method, to date, that has been applied to QCLs above threshold.

Our purpose in this paper is fourfold. First, we apply the self-mixing (SM) technique to the MIR spectral range using QCLs. Second, by directly using the laser itself as a detector instead of an external photodetector, we are able to obtain nice and clean SM signals. Third, by applying a modified analysis method, we are able to extract the α factor from the measurement of these waveforms for different injection currents. Finally, possible explanations for the obtained strong dependence of the α factor on injection current are discussed to motivate detailed research on the band structure of QCLs.

The so-called SM technique has recently been successfully applied to determine the α factor of semiconductors lasers.[8] The experimental setup is depicted in Fig. 1. A part of the emitted laser light is diffusely backreflected into the laser cavity. The intracavity mixing signal depends on the phase difference between the lasing and the backreflected light. The phase difference can be changed periodically, if, for example, the reflecting target is mounted on a loudspeaker that is driven by a sinusoidal signal. The resulting intensity modulated power emitted by the laser represents the so-called SM signal. The interferometric SM fringes show an asymmetry from which the α factor can be deduced. The influence of α

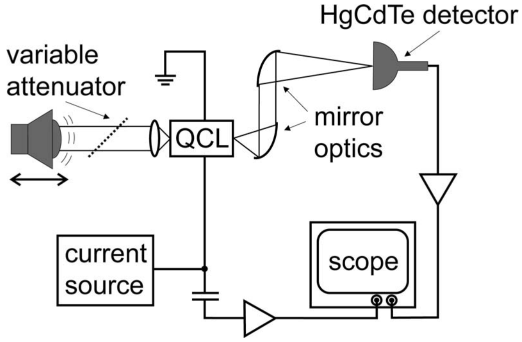

Fig. 1. Schematic of the experimental setup.

on the SM signal is depicted in Figs. 2(a)–2(c). Therefore with an appropriate analysis of the SM signal, it is possible to extract the α factor from this waveform.[8–11]

Usually the SM signal is detected by a photodetector, preferentially the monitor photodiode in housing-mounted laser diodes. In this experiment the QCL was located in a cryostat, and thus the rear photodiode had to be placed far away from the laser chip. This allowed some light backscattered from the moving external reflector to interfere with the light emitted by the rear facet of the laser. To avoid a modification of the SM signal because of that interference, we chose an alternative approach, exploring the laser itself as a photodetector. The use of a laser as a photodetector was pioneered in the near-infrared regime some years ago, directly benefiting from the amplification performance of weak signals.[12–14] Furthermore, for QCLs, the in-principal capability to serve as a conventional photodetector under reverse bias has been demonstrated successfully.[15] The SM signals, obtained by a HgCdTe photovoltaic detector placed at the rear facet of the laser, where a carefully adjusted aperture guaranteed a clean mixing geometry, and the SM signal obtained from the amplified ac voltage signal of the QCL itself are shown in Figs. 2(d) and 2(e), respectively. Each interferometric fringe corresponds to a movement of the loudspeaker of one-half wavelength. These results demonstrate that an excellent SM signal can be obtained, using the QCL as an active detector. It is therefore not necessary to use an additional photodetector. Hence we obtained a very simple setup with only the laser, a lens, and the target.

For the measurements we used a $10\ \mu\mathrm{m} \times 1000\ \mu\mathrm{m}$ distributed-feedback (DFB)-QCL emitting at $5.45\ \mu\mathrm{m}$. The facets were left uncoated, also giving access to the emitted light from the rear facet. The laser was mounted in a cryostat and operated in a continuous-wave regime at liquid nitrogen temperature. The laser threshold amounts to 115 mA at 82 K. More detailed information about this QCL structure can be found elsewhere.[16] The beam emitted from the front facet was collected by a ZnSe lens and focused onto a diffusely reflecting target glued onto the loudspeaker. The feedback strength was changed by a variable attenuator. The length of the external cavity was $L=0.3$ m, and the loudspeaker was driven by a sinusoidal signal at 10 Hz.

The SM signals reflect the dynamics of the semiconductor laser subjected to optical feedback, as determined by the Lang–Kobayashi theory.[9,10,17] A steady-state analysis of the Lang–Kobayashi equations shows that the shape of the SM waveform is determined by the α factor and the feedback strength. The analysis of the SM waveform for QCLs has been modified to account for the regime of small α factors, which inherently causes a low effective optical feedback strength. The method is based on the evaluation of the asymmetry of the fringes. This asymmetry is determined by measuring certain time intervals from the waveform as depicted in Fig. 2(e). The α factor is obtained via $\alpha=(t_M/T-0.5)/(t_Z/T-0.5)$, similarly to what was found in Ref. 11. Several waveforms with different feedback strengths were acquired at each injection current for measurement of the α factor. Figure 3 shows the experimentally determined value of the α factor as a function of the injection current. We find that α amounts to −0.44 for an injection current of 120 mA, close to threshold, and increases to 2.29 for an injection current of 180 mA. We find a zero crossing at approximately 140 mA. These results confirm that the α factor of a QCL is very close to zero at threshold, as predicted by an atomiclike level scheme.[1] However, our results also demonstrate a significant increase of the α factor of QCLs beginning from small negative values at threshold to high positive values at higher injection currents. This is a remarkable difference with respect to near-infrared

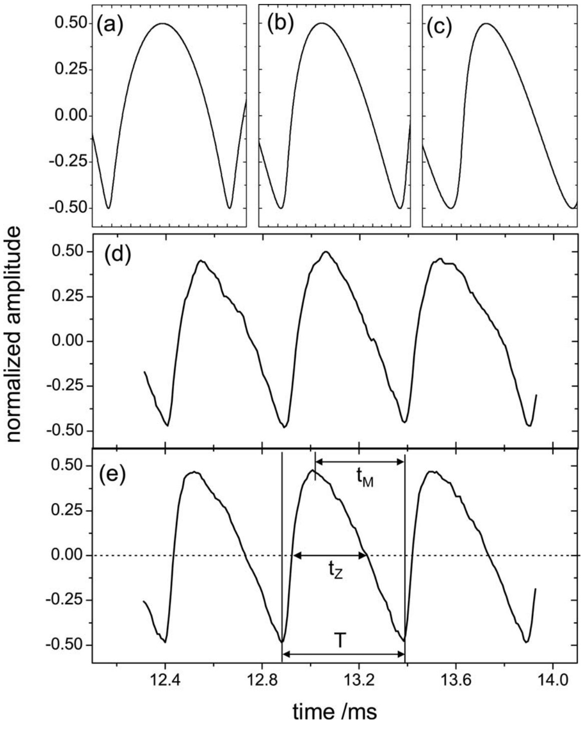

Fig. 2. Top, calculated SM signals with the same feedback strength, but different α factors: (a) $\alpha=0.25$, (b) $\alpha=1$, and (c) $\alpha=2.75$. Middle and bottom: Experimentally obtained normalized waveforms from the signal of (d) a HgCdTe photovoltaic detector and (e) from the voltage drop across the QCL. The time intervals required for the determination of the α factor are also shown in (e).

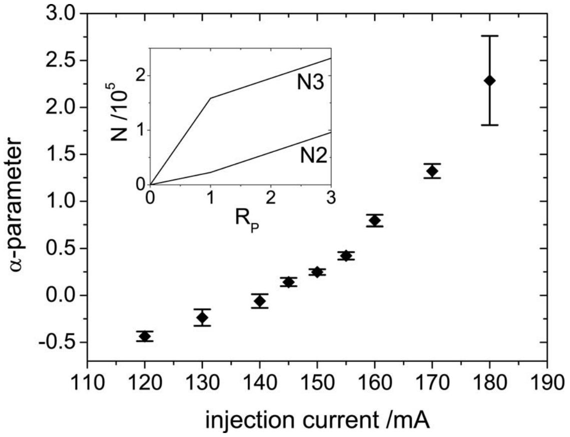

Fig. 3. Measured α factor as a function of the injection current of a DFB-QCL. The threshold current is $I_{\text{thr}}=115$ mA. The inset shows the dependence of the carrier population of the upper (N3) and lower (N2) laser level on the pump parameter $R_P=I/I_{\text{thr}}$.

interband semiconductor lasers, for which α is expected to be approximately constant.[5]

The zero crossing of the α factor can be explained by a change of the sign of the differential refractive index[6]; the strong increase of α, however, needs more explanation. A possible reason for this increase could be the detuning effects of the resonator mode with respect to the gain curve. It is known that for interband semiconductor lasers a relative redshift of the resonator mode with respect to the gain peak results in an increase of the α factor.[18] For QCLs, an increase of temperature as well as an increase of injection current results in a redshift of the gain spectrum.[19] However, the shift of the spectral position of the gain curve due to an increase of the temperature is about 2.5 times larger than the shift of the resonator mode of the DFB grating. As this results in an relative blueshift, the α factor should decrease with increasing injection current. Thus detuning effects cannot explain the observed behavior. However, one possible explanation can be found in the inherent structure of the QCL. From a steady-state analysis of the rate equations of QCLs with an equivalent three-level scheme,[3] we find that the carrier densities of the upper and lower laser levels both increase above threshold with increasing injection current, even though the difference of both densities above threshold remains constant, accounting for gain clamping. This behavior follows from the rate equations for QCLs and is depicted in the inset of Fig. 3. It is in contrast to interband semiconductor lasers, where the carrier density is pinned above threshold. The monotonic increase of the carrier density certainly influences the material susceptibility, and thus it alters the α factor. A final statement of whether the particular QCL design or detuned intersubband transitions contribute to the effect cannot be given yet. Thus detailed band structure calculations are needed to identify the concrete mechanisms that can explain our experiment.

In conclusion, we have applied the SM technique to the MIR spectral range with QCLs. We have shown experimentally that we were able to obtain reliable SM signals, using the laser simultaneously as a light source and detector with possible applications to interferometric measurements in the MIR and FIR. We have used a modified analysis technique to extract the α factor from the signal for different injection currents. Finally, the obtained strong dependence of the α factor on the injection current motivates deeper research on the physics of QCLs.

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