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Origin of terminal voltage variations due to self-mixing in a terahertz frequency quantum cascade laser

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1. Introduction

The use of quantum cascade lasers (QCLs) for laser feedback interferometry (LFI) has received significant attention since it enables a wide range of sensing applications without requiring a separate detector, and hence simplifies experimental apparatus [1]. LFA (based on the self-mixing effect) refers to the partial reinjection of the radiation emitted from a laser after reflection from a target; the injected radiation field then interacts with the intra-cavity field causing measurable variations of the QCL terminal voltage.

The theory of LFI with conventional laser sources is well studied and explained by the Lang–Kobayashi model [2, 3]. However, while this enables the dynamic state populations and light interaction to be modelled, a linear relationship between the change in cavity light power, ΔP, and terminal voltage variation is commonly assumed, i.e. $V_{SM} \propto \Delta P$ [4, 5]. This is not strictly applicable to QCL structures since carrier transport is dominated by the mechanisms of electron subband alignment, intersubband scattering and photon driven transport between subbands with energy separations that change with applied bias (terminal voltage). We present experimental results of a QCL which departs significantly from this assumed linear behavior. We observe strong enhancement of the self-mixing signal in regions where the local gradient of the current-voltage (I–V) curve increases.

We explain the origin of this signal using an extended density matrix (DM) approach [6] which accounts for coherent transport and interaction of the optical light field with the active region. The model is used to calculate the I–V characteristics of a bound-to-continuum (BTC) terahertz (THz) QCL and predict the effect of light variation on terminal voltage at a fixed drive current. This approach is shown to predict the experimental signal with good agreement.

2. Experimental and theoretical method

An experimental LFI system was configured, in which a 2.9 THz QCL was driven using a dc current source. The radiation was collimated using an off-axis paraboloid and reflected back along the same optical path into the QCL cavity using a planar mirror. The resulting interference between the intra-cavity and reflected THz fields gave rise to changes in the photon and electron density within the laser cavity, and this was observed as a self-mixing (SM) perturbation, V_{SM}, to the terminal voltage. The phase of the reflected field was adjusted by oscillating the path length between the QCL and the target, hence generating a periodic SM signal.

In our QCL electron transport model, the applied electric field (corresponding to voltage) and cavity loss are inputs, while current is a calculated output. To account for this an inverse interpolation of the data was performed to determine the equivalent applied field across the device for each current and cavity loss value.

The effect of external optical feedback was interpreted through a cavity loss change (ΔL) ansatz. Calculating the change in loss while accounting for changing emission frequency, mode formation and dynamic effects is beyond the scope of the present work where the origin of terminal voltage is of interest. The magnitude of the SM signal, V_{SM}, at each current (when the laser is on) is calculated as

$$V_{SM}(I) = |V(I,L_{FR}) - V(I,L_{FR} + \Delta L)| \qquad (1)$$

where L_{FR} is the free-running loss found to be $16\,\text{cm}^{-1}$ by fitting the threshold current of the DM model with experiment. Two ΔL values are used: one which approximates a 5% reinjection of optical light field injected to the cavity ($-0.3\,\text{cm}^{-1}$) and a value used to fit with the experimental signal ($-1.4\,\text{cm}^{-1}$). The measured V_{SM} represents the peak amplitude observed during the oscillating target sweep with a constant driving current [4].

3. Results

The comparison of calculated and experimental peak self-mixing signal is shown in Fig. 1(a). Theoretical results using a loss change of -1.4 cm^{-1} shows best agreement with experiment over a wide range of current densities. At 257 A/cm^2 the predicted SM signal increases sharply to 0.58 V however the experimental value maximum is 0.16 V. We attribute this to the laser reaching an early current saturation and negative differential resistance (NDR) region, causing oscillation of the applied bias field and the laser turning off. Before this occurs, the differential resistance of the device increases, and voltage must vary over a larger range to maintain the drive current as stimulated emission current varies, leading to a larger self-mixing voltage. An expression for this phenomenon (referred to as a "hybrid" approach) is

$$V_{SM}(I) = \left(\frac{dV_{FR}}{dI}(I) \frac{dI}{dL} \frac{dL}{dP} \right) \Delta P \qquad (2)$$

where $\frac{dV_{FR}}{dI}$ is the differential resistance of the free-running QCL. The terms dI/dL and dP/dL are the response of current and optical power to changing cavity loss, and are extracted from the DM model output. It is found that best agreement is achieved with a loss change of 0.5 cm^{-1} as shown in Fig. 1(b).
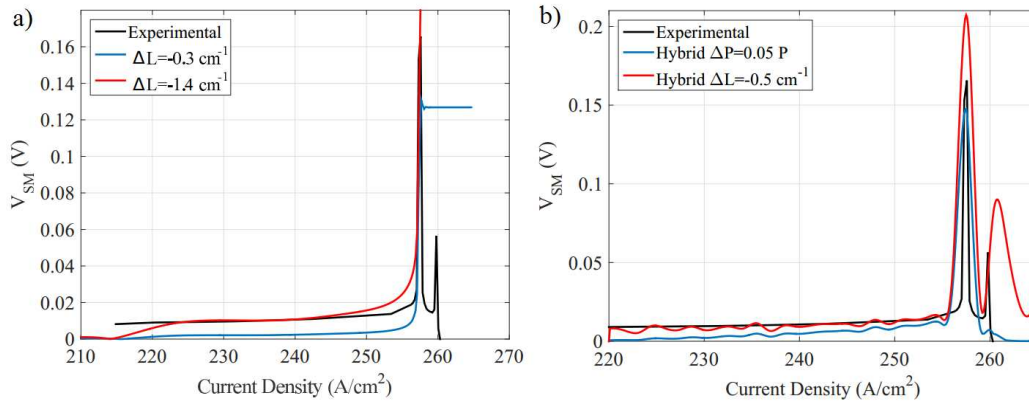

Fig. 1. (a) Comparison of experimental and theoretical peak self-mixing signal using Eq. 1. (b) Comparison of experimental and hybrid approach using experimental I–V curve as in Eq. 2. This uses values of dI/dL=-1.5 A/cm and dP/dL=-0.5 mW·cm extracted from the DM model output.

4. Conclusion

We have presented the results of a DM model applied to a BTC QCL structure. Its inclusion of light interaction with the cavity allows the current response of the QCL to be calculated and therefore the effect of changing loss to be investigated. LFI is a promising application of QCLs since it allows the QCL to be used as both a source and detector. By applying the model to this application an explanation for the origin of terminal voltage variations is presented for QCLs. We propose that the bias voltage varies to maintain the constant drive current while stimulated emission current changes with cavity loss. By combining experimental I–V data of a QCL with DM output parameters excellent agreement is obtained for the magnitude of peak self-mixing signal and the QCL drive current at which it occurs. This model could be used to design and evaluate QCLs tailored to have large sensitivities at desired wavelengths.

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