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Optical sideband generation up to room temperature with mid-infrared quantum cascade lasers

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Abstract: Room temperature sideband generation on an optical carrier is demonstrated using mid-infrared quantum cascade lasers. This is achieved via an enhancement of the nonlinear susceptibility via resonant interband and intersubband excitations, compensating the large phase-mismatch.

OCIS codes: (190.0190) Nonlinear Optics; (140.5965) Semiconductor lasers, quantum cascade

The combined nonlinear optical properties of intersubband and interband transitions in quantum wells have received considerable attention owing to their enhanced susceptibilities compared to bulk properties and potential applications in devices such as optical switches and modulators. Indeed efficient non-linear wave mixing between a near-infrared (NIR) pump (interband resonance) in presence of an intense terahertz (THz) beam (intersubband resonance) in quantum wells systems has been previously demonstrated for the generation of optical sidebands [1]. However, the THz radiation is provided by a Free Electron Laser (FEL). Recently, we have demonstrated [2, 3] that sidebands can be realized using the combined resonant interband and intersubband nonlinearities of a compact and practical device – the quantum cascade laser (QCL) [4]. These previous demonstrations have been performed using THz QCLs and thus inherently limited to cryogenic temperatures. In this work, through appropriate design of the waveguide and the interband excitation, we demonstrate the resonant nonlinear process up to room temperature using mid-infrared (MIR) QCLs.

Figure 1 shows a schematic of the process. The MIR QCL laser transition, E_{QCL}, occurs within the conduction band between the highlighted green states (E_3-E_2). An external near-infrared beam (NIR) E_{NIR} is coupled into the QCL cavity. This excitation promotes electrons from the valence band to above the lowest lying conduction band states (E_2, E_1), resulting in a resonant enhancement of the second order non-linearity and hence permitting frequency mixing. As a result the difference frequency (or sideband) E_{NIR}-E_{QCL} is generated below the bandgap and is therefore not absorbed. This virtual state corresponds to a compromise between the increase in the nonlinearity and the interband losses. This permits the generation of the difference frequency at, for example, E_{NIR}-E_{QCL}=1.48eV for E_{NIR}=1.615eV and E_{QCL}~135meV (~9µm), i.e. separated from the pump by the QCL photon energy

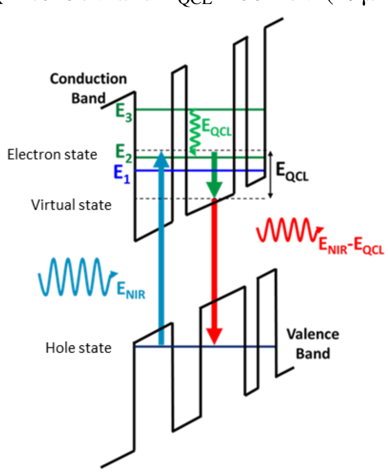

Figure 1: Schematic of the resonant nonlinear optical process for the generation of the difference frequency.

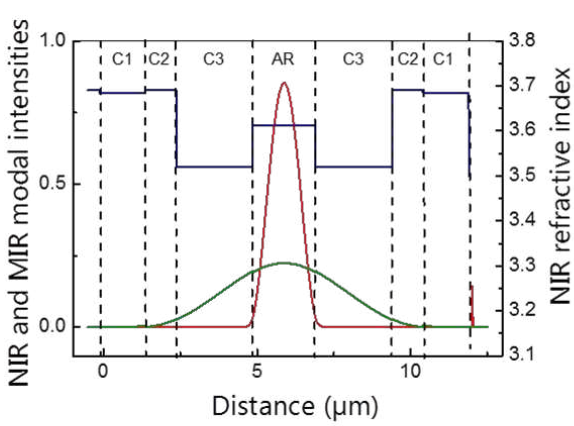

Figure 2: Dual Wavelength QCL waveguide. NIR refractive index profile (blue) and guided modes in the MIR (green) and NIR (red). Layer C3 is an AlGaAs layer with a lower refractive index than the active region (AR).

The active region of the QCL used in this work was a GaAs/AlGaAs quantum well system designed for laser action around 9µm [5]. To ensure that the resonant nonlinearity is excited, it is critical that the NIR light is guided within the active region. However, standard waveguide designs based on plasmon-enhanced guiding layers [5] do not ensure this as the active region has a lower refractive index than the surrounding GaAs cladding layers. A new waveguide has been designed through the addition of AlGaAs based cladding layers (layer C3 in fig. 2) around the active region to confine the NIR mode in the active region. Figure 2 shows the simulations of the MIR (9.2µm) (green line) and NIR (770nm) (red line) modes as well as the refractive index of the layers in the NIR domain. The MIR mode is similar to a standard waveguide and NIR mode is confined within the active region with a 100% overlap and an overlap of ~40 % with the MIR mode.

The experimental scheme is similar to that described in reference [2]. A low power NIR beam (~mW) is coupled into a QCL that is mounted in a cryostat and the out-coupled beam is analysed using a NIR spectrometer. Figure 3 shows the typical spectrum that is obtained with a NIR pump at 1.615eV (~770nm), greater than the effective bandgap, E_g (the lowest electron-hole transitions). The QCL is held at 210K. The sideband (the difference frequency) is clearly observed at E_{NIR}-E_{QCL}=1.48eV, separated exactly from the pump by the QCL photon energy. The inset of figure 3 is a zoom of the generated sideband with several modes corresponding to QCL Fabry-Perot spectrum. The efficiency of the process is estimated at ~ 10^{-3} %, considerably less than that observed for THz QCLs. The reasons for this large difference is a result of a much larger phase mismatch and a lower susceptibility owing to a detuning from an exact double resonant geometry when compared to the THz. From the efficiency, the second order susceptibility, $\chi^{(2)}$, is estimated to be 10^3pm/V, an order of magnitude larger than the bulk susceptibility.

The effect of the QCL operating temperature is shown in Figure 4. On the left axis is the intensity of the sideband and on the right the maximum QCL power measured using a pyroelectric detector as a function of temperature. The same tread is observed with an approximately linear decrease in both sideband and QCL output power. Sideband generation is observed up to 295K, limited by the maximum operating temperature of the QCL. This illustrates that the temperature does not influence the nonlinear process involved in the sideband generation and remains proportional to the output power of the QCL, even though broadening of the transitions is expected to reduce the nonlinear susceptibility.

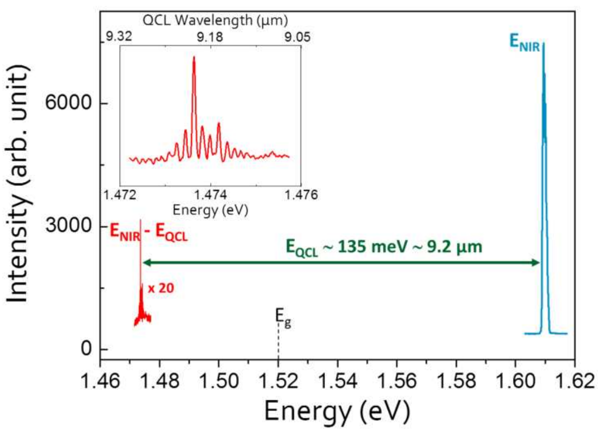

Figure 3: NIR spectrum showing sideband at the difference energy. E_g is the effective gap. The QCL is held at a temperature of 210K. The inset is a zoom of the sideband.

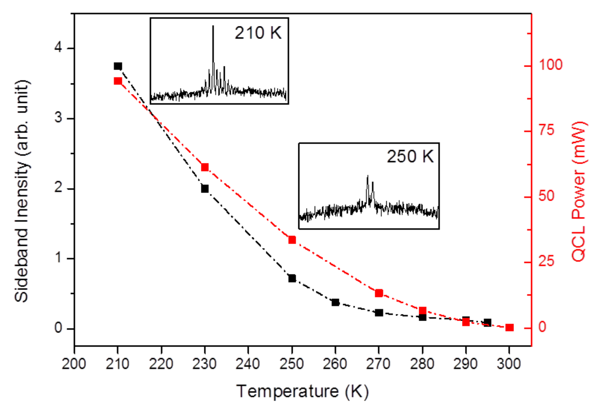

Figure 4: QCL power (red) and sideband integrated intensity (black) as a function of temperature. Insets shows the sideband spectrum at 210 K and 250 K.

To conclude, sideband generation at room temperature has been demonstrated using MIR QCLs. As well as the understanding of resonant nonlinear interactions in active mediums with gain, this work can be applied to all-optical communication networks for large wavelength shifts between telecom bands, to the stabilization of the QCL to a frequency comb or to the detection of MIR QCL emission using mature NIR techniques.

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