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High order optical sideband generation with Terahertz quantum cascade lasers

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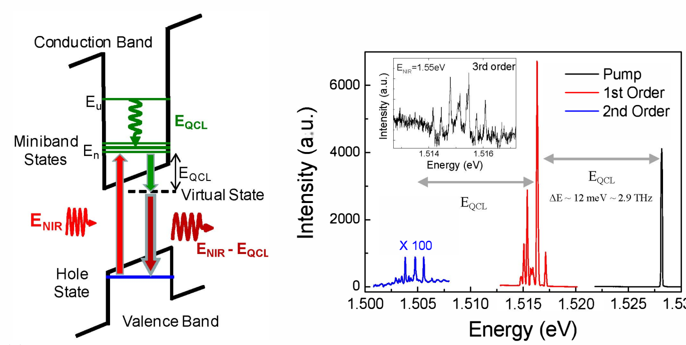
***Abstract* – Optical sidebands are generated by difference frequency mixing between a resonant bandgap near-infrared beam and a terahertz (THz) wave. This is realized within the cavity of a THz quantum cascade laser using resonantly enhanced non-linearities. Multiple order optical sidebands and conversion efficiencies up to 0.1% are shown.**

The nonlinear optical properties of intersubband and interband transitions in quantum wells has recently 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 probe (interband resonance) in presence of an intense terahertz (THz) beam (intersubband resonance) in quantum wells systems has been already demonstrated [1,2]. However, the THz radiation was provided by a Free Electron Laser (FEL). In this work, we demonstrate [3] that these types of high order nonlinear processes can be realized using the resonant interband nonlinearities of a compact and practical device – the quantum cascade laser (QCL) [4].

Figure 1a shows a schematic of the process. The THz QCL laser transition E_{QCL} occurs within the conduction band between the highlighted green states (E_u-E_n). A near-infrared beam (NIR) E_{NIR} is coupled into the QCL cavity resulting in a bandgap excitation from the confined hole state. The geometry results in a resonance enhancement of the second order non-linearity permitting non-linear frequency mixing. As a result the difference frequency E_{NIR}-E_{QCL} is generated via a virtual state below the bandgap and is therefore not absorbed. This concept permitted the generation of the difference frequency at $E_{NIR\text{-}QCL}$= 1.5171 eV (λ=817nm) with E_{NIR}=1.53eV, i.e. separated from the pump E_{NIR} by exactly the photon energy of the THz QCL (operating at f=2.78 THz, E_{QCL}~12meV). When the QCL is taken above laser threshold, the difference frequency is observed for pump excitations over a range of few meV (1.523eV < E_{NIR} < 1.534eV). A resonant behaviour is found for the conversion efficiency with a maximum of 0.13% observed for pump energies of 1.527eV, comparable to those obtained in FEL experiments [3].

We have also demonstrated high order terahertz (THz) frequency sidebands (up to 3[rd] order) within the THz QCL i.e. $E_{NIR}\pm nE_{QCL}$ with integer n>1. This was achieved with a double metal QCL cavity to enhance the intracavity power density, approaching those used in FEL studies. Figure 1b shows the typical sideband spectra observed with the QCL above laser threshold. Each sideband was investigated as a function of THz input power. The 1[st] order sideband intensity shows a linear dependence with THz power corresponding to a single THz photon, while the second order sideband has a quadratic dependence implying a two THz photon interaction and hence a third order susceptibility. We show that the first and second order sidebands correspond to an enhanced second and third order susceptibility, respectively, that are two orders of magnitude greater than the bulk value.

The perspectives of this work include tuning the interband resonances to the telecom window using mid-infrared InP-based QCLs. The latter operate at room temperature and would allow wavelength shifting between different telecommunication bands.



(a)

(b)

Fig. 1a) Schematic of the resonant non-linear process for the generation of the difference frequency (E_{NIR} – E_{QCL}) in a QCL operating at E_{QCL}. A NIR pump E_{NIR} is tuned in resonance with interband transitions. This allows the generation of a lower energy beam at E_{NIR}-E_{QCL} via a virtual state below the material bandgap. **b)** Pump laser spectrum through QCL and spectrum of the below bandgap generated sidebands at the generated differences, E_{NIR}-E_{QCL} and E_{NIR}-2E_{QCL}. The third order sideband E_{NIR}-3E_{QCL} is shown in the inset.

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