Monte-Carlo Analysis of the Nonlinear Susceptibility in Quantum Cascade Laser Structures for THz Difference Frequency Generation

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Recently, the possibility to integrate giant artificial nonlinearities into the quantum cascade laser (QCL) active region by appropriate quantum design has become highly attractive for various applications. In particular, THz difference frequency generation (DFG) has opened a door to compact, semiconductor-based THz sources operating at room temperature [1–4]. While conventional THz QCLs only work under cryogenic conditions, this approach takes advantage of the fact that efficient mid-infrared (MIR) QCLs for room temperature operation are readily available. THz DFG at a frequency *f*1-*f*2 is here achieved by using a dual-stack active region design with MIR lasing modes at *f*1 and *f*2 which pump a giant optical nonlinearity integrated into one or both active regions. An attractive feature is the inherent wide THz tuning capability, with a maximum demonstrated frequency range of 1.2–5.9 THz [2,3]. However, THz DFG structures still suffer from low room temperature THz output powers of up to 3 µW in continuous-wave and 1.4 mW in pulsed mode [4].

The generated THz power is proportional to |χ(2)|2, where χ(2) represents the effective second order susceptibility of the DFG process. Hence, a further systematic development of DFG sources requires a thorough understanding of the optical nonlinearity and its dependence on the operating parameters. Detailed modelling is very important in this context, especially since |χ(2)| is hardly accessible to direct experimental measurement. Here we use a recently developed numerical approach which combines carrier transport Monte-Carlo simulations of the active regions and electromagnetic modelling of the MIR and THz optical fields [5].



**Fig. 1**. (a) Temperature dependence of (a) the MIR pump powers and THz power and (b) |χ(2)| and waveguide loss. (c) |χ(2)| in a widely tunable THz DFG structure as a function of applied bias and frequency detuning.

Fig. 1(a) shows the temperature dependence of the MIR pump powers and the generated THz power for a DFG structure with THz outcoupling through the front facet [1]. The simulation results (lines) agree well with experimental room temperature data (crosses) [1], validating our simulation approach. The corresponding simulated nonlinear susceptibility and waveguide loss are displayed in Fig. 1(b), confirming the experimentally estimated values (crosses) [1]. Both quantities exhibit only a moderate temperature dependence, indicating that the strong degradation of the THz output power is largely due to the decrease in MIR pump powers. Apart from the temperature dependence of |χ(2)|, also its spectral characteristics is important especially for widely tunable THz DFG structures. In Fig. 1(c), the simulated nonlinear susceptibility of such a design [2,3] is shown as a function of applied bias and THz frequency. |χ(2)| is close to its maximum value over an extended frequency and bias range, indicating that the tuning range is not limited by the optical bandwidth of the nonlinear susceptibility.

**References**

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