Resonant Nonlinear Optics in Coupled Quantum Wells: From Lasers to Detectors

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ABSTRACT

It was recently shown that the active region of a quantum cascade (QC) laser can be integrated with a coupled quantum well (QW) structure designed for the nonlinear conversion of laser light into coherent radiation at a different frequency. In other words, the laser field serves as an intracavity optical pump for the desired nonlinear optical interaction. This approach allows one to fully utilize giant resonant optical nonlinearities associated with intersubband transitions in coupled quantum wells. In particular, sum-frequency and second-harmonic generation have been achieved in InGaAs/AlInAs/InP and GaAs/AlGaAs material systems. These processes can have high enough efficiency to be interesting for practical applications, with second-harmonic generation demonstrated at milliwatt power levels.

Here we discuss strategies to utilize resonant second-order nonlinearities in coupled QWs for nonlinear mid-infrared (mid-IR) sources and detectors that would be competitive with existing devices based on "direct" lasing and photodetection. This talk will mainly concentrate on two examples: short-wavelength mid-IR sources and mid/far-IR up-conversion detectors.

The first example is second-harmonic generation in the 2.5-3.5 μm wavelength range in QC lasers based on high band-offset heterostructures: InAs/AlSb and strain-balanced InGaAs/AlInAs. Existing semiconductor lasers in this spectral range include narrow-gap and type-II diode lasers, interband cascade lasers and, more recently, InAs-based InAs/AlSb QC lasers. They are making impressive progress but still suffer from several intrinsic problems that make them not as efficient as longer-wavelength InP-based QC lasers or near-IR diode lasers.

Intracavity second-harmonic generation provides a natural way to convert radiation from the sweet spot of QC lasers around 5-7 μm wavelengths where they are very efficient into the hard-to-reach 2.5-3.5 μm wavelength range. We present specific InAs/AlSb and strain-balanced InGaAs/AlInAs QC structures for second-harmonic generation designed in the spirit of the simplest and efficient vertical cascade design (see, e.g., Malis et al. EL 40, 1586 (2004) and APL 84, 2721 (2004)) and show that milliwatt output powers can be reached under the condition of partial modal phase matching.

Another example that we consider is detection of mid/far-IR radiation by frequency up-conversion into the near-IR range via quasi-resonant sum-frequency generation in coupled QW structures. Standard semiconductor photodetectors utilize photon absorption due to an interband, intersubband, or impurity transition. At low photon energies they suffer from high dark current due to thermal excitations. Cryogenic cooling is usually required for high detectivity. An alternative detection scheme is based on frequency up-conversion into the near-IR/visible range. This approach allows one to employ superior visible/near-IR detectors: avalanche photodiodes and photomultipliers that have low dark counts and background noise and operate at room temperature in the single-photon counting regime. Unfortunately, the efficiency of nonlinear up-conversion of weak signals is low in the continuous-wave regime. It can be improved by employing high-power pulsed lasers, but the resulting system becomes costly and bulky.

We present an up-conversion detector scheme that utilizes a near-resonant cascade of interband and intersubband transitions in coupled QW structures. A near-IR laser pump, slightly detuned from the interband transition, is mixed with a mid/far-IR signal resonant to the intersubband transition in the same structure, generating near-IR sum-frequency radiation. Such structures, when integrated with phase-matched semiconductor waveguides, can yield high nonlinearity and high up-conversion efficiency in a relatively narrow spectral range of the order of 10 meV determined by the transition linewidth. Up-conversion detectors can be designed for both collinear and perpendicular pump and signal beams. We present specific structures based on GaAs/AlGaAs and InGaAs/AlInAs QWs for both geometries and calculate expected detectivities of such detectors.

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