Microwatt-level terahertz sources based on intra-cavity difference-frequency generation in mid-infrared quantum cascade lasers

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Abstract: We report 5THz quantum cascade laser sources based on intra-cavity difference-frequency generation in dual-wavelength mid-infrared quantum cascade lasers. Our devices produce microwatt-level terahertz output at 80K and approximately 200nW output at 250K.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (190.4223) Nonlinear wave mixing; (140.5960) Semiconductor lasers.

The terahertz (THz) spectral range (λ=30-300μm) has been long devoid of compact electrically pumped room temperature semiconductor sources. Despite recent progress with THz quantum cascade lasers (QCLs), existing devices still require cryogenic cooling [1]. An alternative way to produce terahertz radiation at room temperature is with difference-frequency generation (DFG) in a nonlinear optical crystal using infrared or visible pump lasers. Recently, we reported a new type of THz QCL sources based on intra-cavity DFG in dual-wavelength mid-infrared (mid-IR) QCLs with giant optical nonlinearity monolithically integrated in the active region [2]. Since mid-IR QCLs have been shown to operate continuous-wave (CW) above room temperature and since the optical nonlinearity for the DFG process is not expected to significantly deteriorate with temperature, this approach can lead to a room-temperature electrically-pumped compact CW semiconductor THz source.

The power of the THz DFG output at frequency $\omega=\omega_1-\omega_2$ is given by the expression

$$W(\omega=\omega_1-\omega_2)\propto\left|\chi^{(2)}\right|^2\times W(\omega_1)W(\omega_2)\times l_{coh}^2, \tag{1}$$

where $l_{coh}=1/(k-(k_1-k_2))^2+(\alpha/2)^2)$ is the coherence length, $W(\omega_i)$ and $\vec{k}_i$ are the power and the wave vector of the beam at frequency ω_i, respectively, and α stands for the losses at the DFG frequency. It follows from Eq. (1) that, for more powerful THz DFG output, one needs to increase the powers of the pumps $W(\omega_1)$ and $W(\omega_2)$, optical nonlinearity $\chi^{(2)}$, and/or the coherence length. Our first proof-of-principle device [2] produced only nanowatt-level THz power output at 80K and operated only up to 150K. Here, we report THz DFG QCL sources with improved performance that produce microwatt-level THz power output at 80K and are operable up to thermoelectric-cooler temperatures. The improvements in THz power output have been achieved by increasing optical nonlinearity and the coherence length through improvements in both active region and waveguide designs.

Our devices are based on an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure grown by molecular beam epitaxy, with an upper InP waveguide cladding re-grown by metalorganic chemical vapour deposition. The active region consists of two sections: a 30-period structure based on the bound-to-continuum design with integrated optical nonlinearity, emitting at 9.1 μm, and a 20-period structure based on the two-phonon design, emitting at 10.6 μm, separated by a 100 nm-thick InGaAs spacer doped to 3×10^{16} cm^{-3}. Similar to Ref. [2], only the bound-to-continuum section possesses giant optical nonlinearity for DFG; however, its optical nonlinearity is estimated to be approximately 25% higher than that in Ref. [2]. The waveguide design in our new devices has also been improved. First, we reduced doping in the active region from 6.5×10^{16} cm^{-3} down to 5×10^{16} cm^{-3} and used a very low-doped InP substrate and upper waveguide cladding, doped to 9×10^{16} cm^{-3} and 5×10^{16} cm^{-3}, respectively. Second, the waveguide layer structure was designed to facilitate the phase matching for the DFG process. We estimate the coherence length for the DFG process in our new structures to be approximately 80μm, a factor of 4 improvement relative to that in Ref. [2]. The conduction band diagram of a single period of the QCL structure with integrated optical nonlinearity is shown in Fig. 1a and the waveguide design, along with the THz waveguide mode profile, is shown in Fig. 1b.

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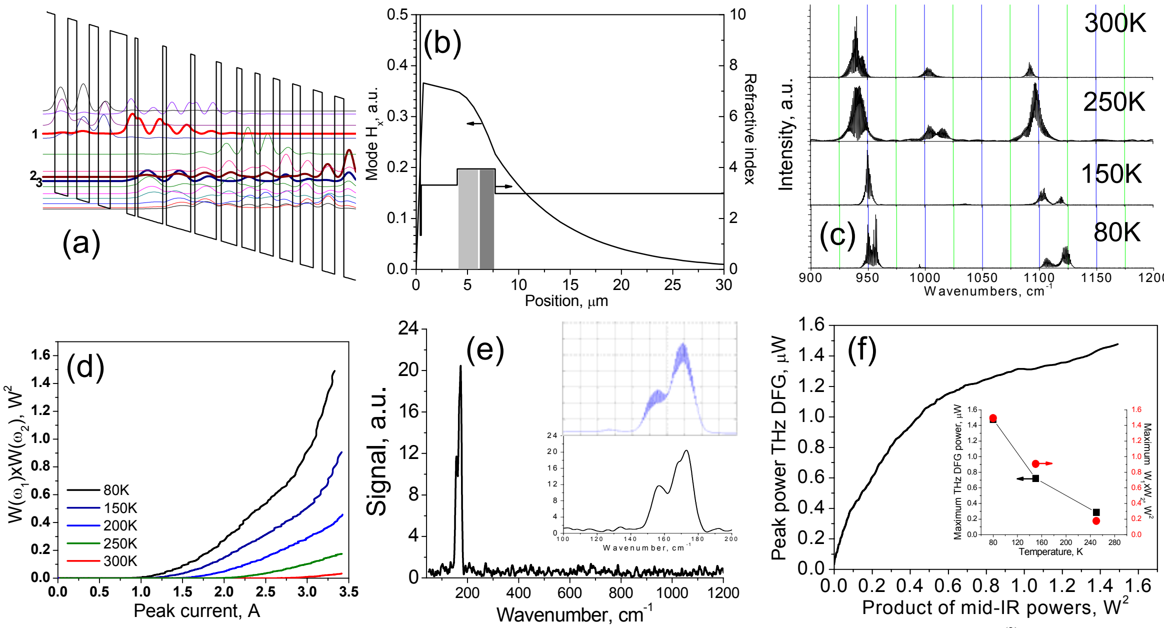

Fig. 1. (a) Conduction band diagram of a bound-to-continuum section of the active region with integrated $\chi^{(2)}$. The upper laser state and two lower laser states with the largest contributions to $\chi^{(2)}$ are labelled 1, 2, and 3, respectively. (b) The waveguide refractive index profile and the THz waveguide mode in our devices. The bound-to-continuum and two-phonon active region sections are shown in light and dark grey, respectively. The mid-IR modes have dielectric confinement in the active region. (c) Mid-IR emission spectra of a representative device at various temperatures. (d) The product of the mid-IR pump powers for a representative device at different temperatures. (e) THz DFG emission spectrum of a representative device at 80K. Upper inset: a simulated THz DFG emission spectrum; lower inset: a zoom-in of the measured THz DFG spectrum. (f) Dependence of the THz DFG output power on the product of mid-IR powers. Inset: dependence of the maximum DFG THz power output (left axis) and the product of the mid-IR pump powers (right axis) on temperature.

The devices were processed as deep-etched 25-μm-wide and 2-mm-long ridge lasers; their back facet was coated with a high-reflection coating. Measurements were done in pulsed mode with 60 ns pulses at a 250 kHz repetition rate. Radiation was collected using two 2"-diameter parabolic mirrors: one with a 5 cm focal length to collect light from the device and the other with a 15 cm focal length to refocus it onto a thermopile or MCT detector for mid-IR measurements or a He-cooled calibrated Si bolometer for THz measurements. The data was corrected for an estimated 70% and 20% collection efficiency for mid-IR and THz powers, respectively. Spectra were taken with a Fourier transform spectrometer. For THz measurements, mid-IR radiation was blocked using filters. Our devices operated at dual wavelength up to room temperature, see Fig. 1(c). For a typical device, the product of the maximum output pump powers, $W(\omega_1)\times W(\omega_2)$, was measured to be approximately 1.5W^2 at 80K and still ~0.2W^2 at 250K, see Fig. 1(d). The THz emission spectrum at 80K of a typical device is shown in Fig. 1(e), where we also compare the measured THz emission spectrum with the one obtained by simulating DFG process using mid-IR spectra. Finally, Fig. 1(f) shows the dependence of the THz DFG power on the product of the mid-IR pump powers. The dependence is not linear due to the varying multimode nature of the mid-IR pumps and the changes in optical nonlinearity with bias voltage. The THz DFG conversion efficiency is ~1μW/W^2. Also shown in Fig. 1(f) are the dependences of the THz power output and the product of mid-IR powers on temperature. The data indicates that THz DFG conversion efficiency in our devices is not significantly affected by temperature.

Work is currently underway to improve the power of THz DFG QCL sources further by increasing the optical nonlinearity in the active region and incorporating it in both sections in the active region, further reducing waveguide doping in order to achieve longer coherence length, and employing surface emission schemes.

This work was supported by AFOSR under Contract No. FA9550-05-1-0435 (Gernot Pomrenke). Sample growth was partly done in the University of Neuchatel. The authors would like to acknowledge help of Nicolas Hoyler.

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