Terahertz sources based on difference-frequency generation near exit facets in dual-wavelength mid-infrared quantum cascade lasers

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Abstract: We report novel quantum cascade laser sources based on difference-frequency generation in nonlinear sections localized near exit facets. This new approach allows for infrared-to-terahertz conversion efficiencies above $1mW/W^2$. Experimentally, devices operating at 4THz are discussed.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (140.3070) Infrared and far-infrared lasers; (190.4223) Nonlinear wave mixing; (190.5970) Semiconductor nonlinear optics including MQW.

1. Introduction

The terahertz (THz) spectral range (λ=30-300μm) is still devoid of compact electrically pumped room temperature semiconductor sources. Despite recent progress of THz quantum cascade lasers (QCLs), existing devices still require cryogenic cooling [1,2]. An alternative way to produce terahertz radiation at room temperature is to use difference-frequency generation (DFG) in a nonlinear optical crystal pumped by infrared or visible lasers. Recently, we reported a new type of THz QCL source based on intra-cavity DFG in dual-wavelength mid-infrared (mid-IR) QCLs with giant optical nonlinearity monolithically integrated in the active region [3,4]. The most advanced devices fitted with a silicon microlens to improve THz radiation out-coupling and collimation demonstrated 5 THz power output of 7μW at 80K and 300nW at room temperature [4]. To be useful for applications, the power output of these devices needs to be improved to a milliwatt level and above.

Devices in Refs. [3,4] utilized optical nonlinearities of mid-IR QCL pump sections. This approach produces large resonant intersubband optical nonlinearities with population inversion and generates optical gain, instead of loss, in the laser cavity [3,4]. However, this approach can only create relatively modest values of optical nonlinearities for DFG, of the order of 4×10^4 pm/V, due to relatively small values of population inversion density in mid-IR QCLs ($\sim2\times10^{15}$ cm^{-3} [4]) and relatively broad laser transition linewidths [4]. In comparison, a simple resonant multi-quantum-well (MQW) structure, without population inversion, can have THz DFG optical nonlinearities above 10^6 pm/V for THz DFG [5]. An example of such a structure is shown in Fig. 1(a). In this work we will demonstrate that one can integrate resonant nonlinear MQW structures near the exit facet of dual-wavelength mid-IR QCLs to produce room-temperature THz DFG QCL sources with mid-infrared-to-terahertz conversion efficiencies above $1mW/W^2$. This number should be compared to conversion efficiencies of $\sim5\mu W/W^2$ for the devices in Ref. [4].

2. Device design and preliminary results

The new device structure and its fabrication steps are shown in Fig. 1 (b-d). Preliminary experimental results presented here were obtained with $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ QCLs grown by the molecular beam epitaxy. Initially a structure that consists of a 3.1μm-thick dual-wavelength active region followed by a 500nm-thick MQW nonlinear section is grown on an InP substrate doped to $\sim5\times10^{16}$ cm^{-3}, see Fig. 1(b). The active region consists of two stacks of two-phonon-resonance QCL structures, each containing 25 stages designed to emit at λ_1=8.5μm and λ_2=10μm. The nonlinear section contains 18 repetitions of the MQW structure, shown in Fig. 1(a), designed to have resonant nonlinearity for DFG between λ_1 and λ_2. The nonlinear susceptibility of this structure for THz DFG is estimated to be 1.24×10^6 pm/V using the expression for $\chi^{(2)}$ in Ref. [4] and assuming transition linewidth of 10meV full width at half maximum. In the next processing step we selectively remove most of the nonlinear MQW layer on top of the active region and leave only a 70μm-long section of it that will be positioned at the exit facets of the final devices, see Fig. 1(c). Then an InP upper waveguide cladding (4μm-thick layer n-doped to 4×10^{16} cm^{-3}, followed by a 200nm-thick layer n-doped to 5×10^{18} cm^{-3}) is overgrown on the structure, Fig. 1(d), and the wafer is processed into QCLs with 25μm-wide ridges using an established dry-etching-based fabrication process. The processed wafer is finally cleaved into laser bars with ~3mm-long devices that have nonlinear sections positioned near the output laser facet. The coherence length for a DFG process in our devices is estimated to be in the range 50-100μm.

The optical loss for the TM_{00} laser mode in a 70μm-long section with a MQW layer is calculated to be 127 cm^{-1} assuming intersubband transition linewidths with full width at half maximum of 10meV. The absorption loss effectively reduces the front laser facet reflectivity from 28% to 5%, which leads to a 3cm^{-1} increase in 'mirror' losses of for a 3mm-long laser. To alleviate this problem one may use shorter nonlinear sections, longer laser bars, or a DFB grating in a laser waveguide for optical feedback. In our first proof-of-principle devices we etched a 5μm-wide trench, defined by dry etching, to separate the nonlinear section from the rest of the laser and provide optical feedback, as shown in Fig. 1(e). Using finite difference time domain simulations we see that this approach results in only 15% of the pump powers coupling into the nonlinear section as the trench scatters most of the transmitted laser radiation into the substrate. We will improve the coupling efficiency of the pump radiation in the next generation of devices.

The preliminary experimental results, obtained in pulsed mode at 80K, are presented in Fig. 2. Fig. 2(a) shows the current-voltage (I-V) and mid-IR light output-current (L-I) characteristics of a reference structure that was cleaved without a nonlinear section. All our devices have a voltage defect of ~10V that appears to be the result of a wafer surface oxidation prior to top waveguide cladding overgrowth. This issue currently prevents reliable operation of the lasers at room-temperature. We expect to fix this problem in the next generation of devices. Fig. 2(b) shows the fundamental and THz emission spectra of a device with a 70μm-long nonlinear section at 80K. A THz emission line is clearly seen. We estimate the maximum peak power of THz DFG output to be ~300nW, corrected for the collection efficiency. Using the product of maximum pump powers from Fig. 2(b) and assuming 15% pump coupling efficiency into the nonlinear section, we obtain THz DFG conversion efficiency ~30μW/W^2. We expect that this number may be further improved to over 1mW/W^2 through optimization of the waveguide and nonlinear section designs in our devices, and by improving the THz radiation outcoupling efficiency using a silicon microlens [4].

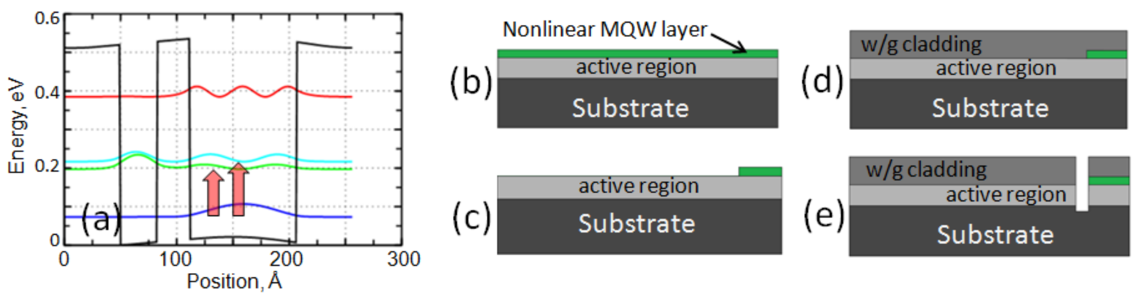

Fig. 1. (a) Conduction band diagram of one period of a MQW structure with giant nonlinearity for THz DFG. Red arrows refer to mid-IR pump transitions. The layer sequence for this structure is is **9.0**/2.0/**1.1**/4.6 nm, where AlInAs barriers are shown in bold. The center 6 nm of a 10 nm barrier is n-doped to 4.3×10^{17} cm^{-3}. (b)-(e) Steps in fabricating the devices as discussed in the text.

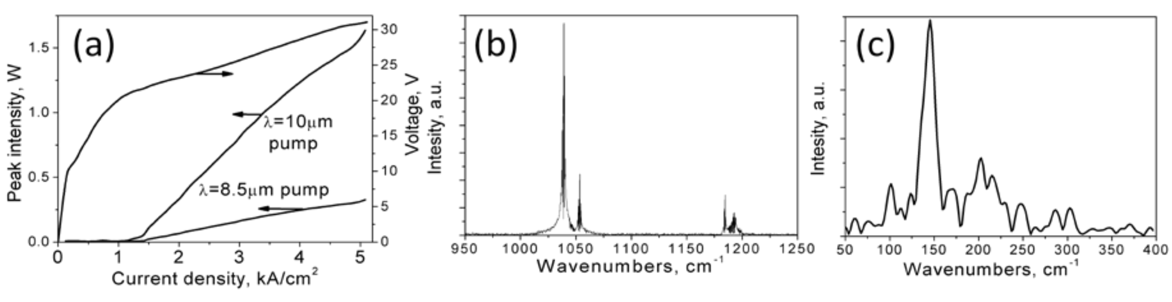

Fig. 2. (a) I-V and L-I characteristics of a reference structure without the nonlinear sections. The data is corrected for an estimated 30% collection efficiency of our setup. (b) and (c) Mid-IR and THz emission spectra of a device with the nonlinear section. The measurements are performed using 50ns current pulses at 800kHz repetition rate at 80K.

3. References

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