Room-temperature operation of index-coupled distributed-feedback 4.75 µm quantum cascade lasers fabricated without epitaxial regrowth

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Abstract: We demonstrate single-mode distributed-feedback quantum cascade lasers at 4.75 µm with etched index-coupled surface gratings and spin-on dielectric infilling. We observe continuous wave laser emission at room temperature with 5 W of electrical power consumption.

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Laser absorption spectroscopy has emerged as one of the most important applications for semiconductor quantum cascade (QC) lasers, particularly in the mid-infrared spectral regime where many gases of interest exhibit fundamental absorption features [1]. For manned spaceflight in particular, the National Aeronautics and Space Administration has identified environmental monitoring as a key technology development area. Laser absorption spectrometers have the potential to match or exceed the sensitivity of electrochemical sensors presently used aboard the International Space Station, and laser-based detectors are capable of long-duration maintenance-free operation without consumable components.

To realize an effective laser-based absorption spectroscopy instrument, the laser source should produce stable single-mode emission with enough tunability to span at least one target gas absorption line. This has prompted the development of several schemes for suppressing multimode operation, the most compact and mechanically robust of which employs an integrated distributed-feedback (DFB) grating. Over the past several years, DFB QC lasers have been demonstrated using both loss-coupled metallic gratings [2,3] and index-coupled semiconductor structures [4,5]. For low input power operation, which is particularly important for portable gas detection instruments, buried heterostructure devices with etched index-coupled gratings have been the most successful [5]; however, fabrication of buried gratings relies on epitaxial regrowth, which adds significant processing complexity and capital equipment cost. Here, we demonstrate room-temperature continuous wave (CW) operation of DFB QC lasers at 4.75 µm with high-aspect-ratio etched surface gratings that have been planarized using spin-on dielectric material. This process enables the fabrication of gratings with sufficient coupling for single-mode emission with relatively short cavity lengths, without the need for lossy metallic gratings or buried gratings with regrown epitaxial layers. The laser emission wavelength can be tuned across distinct fundamental absorption lines of carbon monoxide (CO) by varying the injection current, and the devices consume approximately 5 W of electrical power, making them suitable for portable CO monitoring instruments.

Strain-balanced QC laser structures based on the design reported by Evans, *et al*. [6] were grown on InP substrates using molecular beam epitaxy. Lightly doped (2×10^{16} cm^{-3}) 2-µm-thick InP cladding layers were grown below and above the active region to minimize absorption loss from the substrate and top contact layers. First-order diffraction gratings were patterned by electron-beam lithography with a lateral width of 3 µm, and the gratings were etched in an anisotropic $Cl_2/H_2/CH_4$ inductively coupled plasma (ICP) process to a depth of nearly 2 µm, as shown in Fig. 1(a). The etched gratings were then coated with a spin-on polyimide precursor and cured at 350 °C. The polyimide was etched back to the top of the gratings using CF_4/O_2 reactive-ion etching, and Ti/Pt/Au ridge contacts were deposited over the grating regions. An additional lithography and ICP etching process was used to define 5-µm-wide ridges, with the gratings centered between the ridge sidewalls. The ridges were coated with SiN_x using plasma-enhanced chemical vapor deposition, and the SiN_x was stripped away from the ridge contacts. Finally, 10 µm-thick Au contacts were electroplated over the ridges, and individual lasers were cleaved into 2 mm bars. For testing, individual lasers were attached epitaxy-side up to Au-coated Cu submounts using AuSn eutectic solder.

The CW light output and current-voltage characteristics of a DFB QC laser with a grating pitch of 760 nm and polyimide infilling are shown in Fig. 1(b). Near room temperature, the maximum output power corresponds to an injection current density of 4.6 kA/cm^2 with input power of 5.3 W. The laser emission spectra in Fig. 1(c) are shown along with calculated transmission spectra for various concentrations of CO at standard temperature and pressure over an interaction length of 25 cm. Adjusting heat-sink temperature and sweeping the injection current can tune the laser emission wavelength across two distinct ro-vibrational CO absorption lines.

The DFB QC lasers reported here employ low-loss index-coupled gratings and were fabricated without epitaxy beyond the initial wafer growth. The lasers exhibit promising CW performance near room temperature with relatively low input power. The grating geometry, facet reflectivity, and mounting configuration of the devices can be optimized to further reduce power consumption, making these DFB QC lasers a promising technology as light sources for low-cost portable laser absorption spectrometers.

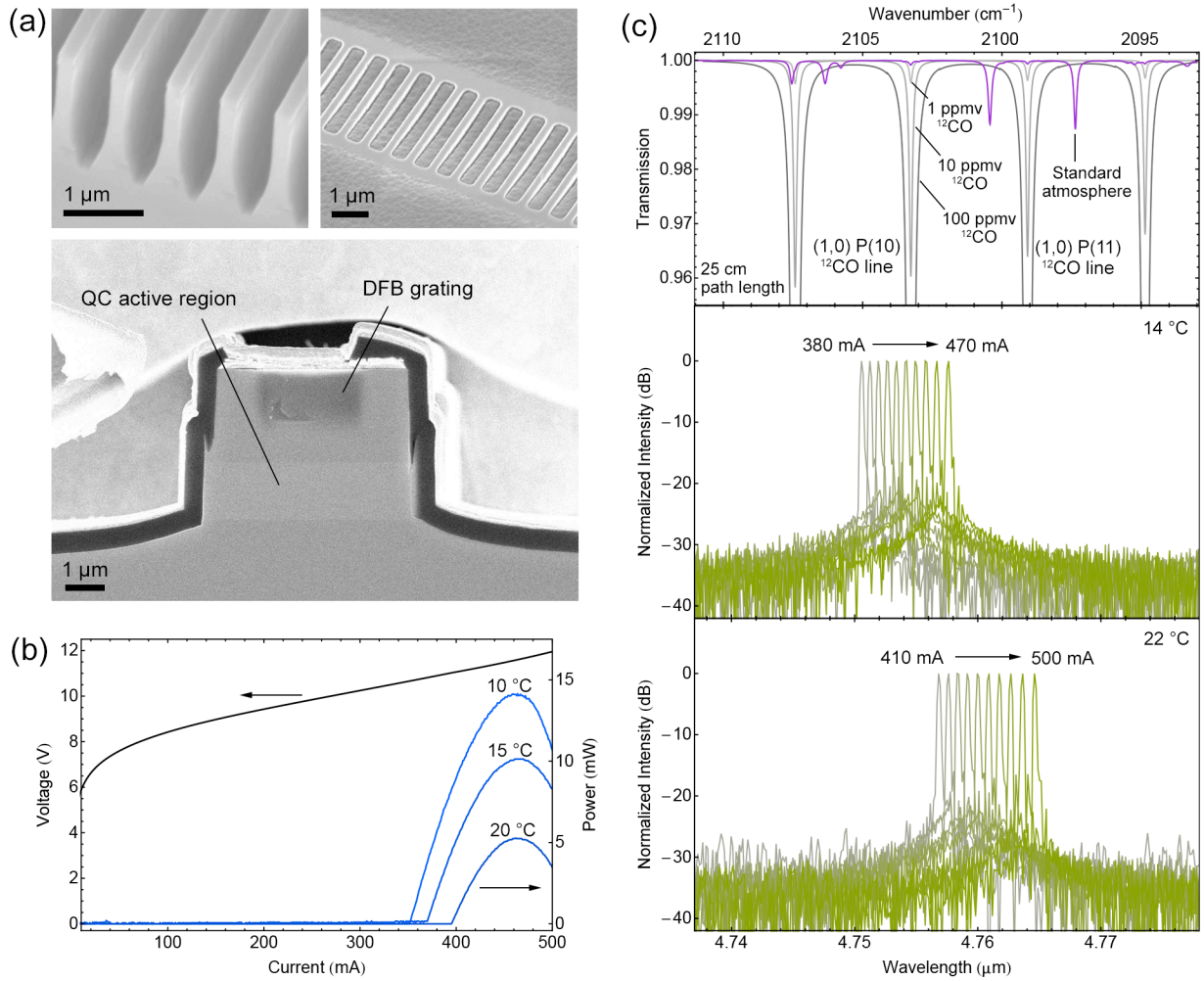

Figure 1. (a) Scanning electron micrographs of fabricated DFB QC devices, showing a high-aspect-ratio etched grating structure, a grating after polyimide infill and planarization etching, and the emission facet of a completed laser. (b) CW light-current-voltage performance of a 2-mm-long DFB QC laser with uncoated facets. (c) Laser emission spectra at two different heat-sink temperatures shown over a range of injection current, in increments of 10 mA. For reference, the top panel indicates the position of CO absorption lines near 4.75 µm.

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