Regrowth-free mid-infrared distributed feedback quantum cascade lasers with sub-watt power consumption

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ABSTRACT

We report on room-temperature, continuous-wave operation of single-mode quantum cascade lasers designed for minimal threshold power consumption in the 4 to 10 µm spectral range. Narrow-ridge distributed feedback lasers were developed with plasma-etched sidewall corrugations and infrared-transparent dielectric cladding, enabling fabrication without any epitaxial steps beyond the initial growth of the planar laser wafer. The devices exhibit single-mode emission with stable, mode-hop-free tuning and side-mode suppression greater than 25 dB. We demonstrate packaged single-mode devices with continuous-wave threshold power consumption near 1 W above room temperature.

Keywords: Quantum cascade lasers, distributed feedback lasers, infrared absorption spectroscopy

1. INTRODUCTION

Over the past two decades, many development efforts in the area of quantum cascade (QC) lasers have focused on achieving watt-level output power and high wall-plug efficiency [1-3]. However, for *in situ* spectroscopy applications, output power requirements are typically on the order of a milliwatt [4]. By nature, *in situ* instruments must also often be field-deployable, which levies the additional requirement of low power consumption. Key examples include mid- to long-wavelength laser absorption spectrometers used to measure gas abundance and isotopic composition on airborne and space-based platforms [5-7]. Here, we describe the development of single-mode QC lasers with power consumption on the order of 1 W and emission wavelengths relevant to atmospheric science.

Recently, other researchers have reported on QC lasers with continuous-wave (CW) power dissipation near 1 W using buried distributed feedback (DFB) gratings [8] as well as sidewall buried-heterostructure (BH) regrowth [9,10]. We present lasers emitting at 4.8 µm and 7.4 µm that are competitive with the lowest-dissipation BH QC lasers; however, we employ a process that requires no epitaxial processes after the initial growth of the laser structure [11]. This approach has the potential to reduce fabrication costs and also enables the implementation of more versatile cavity designs. In particular, we demonstrate a sidewall-grating DFB scheme where the grating is defined by planar lithography, which affords fine control over the grating profile. By engineering the grating interaction in single-mode cavities, and with the ability to define narrow, vertically etched waveguide ridges, we have produced QC lasers with stable, mode-hop-free emission and CW threshold power consumption at and below 1 W.

2. LASER FABRICATION AND PACKAGING

Devices were fabricated using the process described in Ref. 11. For lasers emitting near 4.8 µm, we employed a double-phonon-resonance QC active region design adapted from Evans, *et al.* [12], while for longer-wavelengths devices, a non-resonant extraction design was used [1]. Figure 1 shows a scanning electron micrograph of a laser ridge after etching through the QC active region of a 4.8 µm device, as well as a micrograph of a completed device. First-order sidewall gratings with an approximately sinusoidal profile were defined with a modulation amplitude calculated to provide moderate over-coupling for a cavity length of 1 mm, as described in Ref. 11. After defining the laser ridges, the

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structures were coated with a low-index dielectric to optically and electrically isolate the waveguide sidewalls from the electroplated Au top contact. This allows the laser ridge to be narrow (smaller than the free-space wavelength) while maintaining strong confinement of the optical mode in the active region. For lasers emitting at wavelengths below 5 µm, SiN_x is a suitable dielectric; however, for devices operating at longer wavelengths, AlN was found to have lower optical absorption with a similar refractive index, resulting in comparable confinement factors. Finally, dielectric high-reflectivity (HR) back facet coatings were deposited to reduce cavity loss and threshold current.

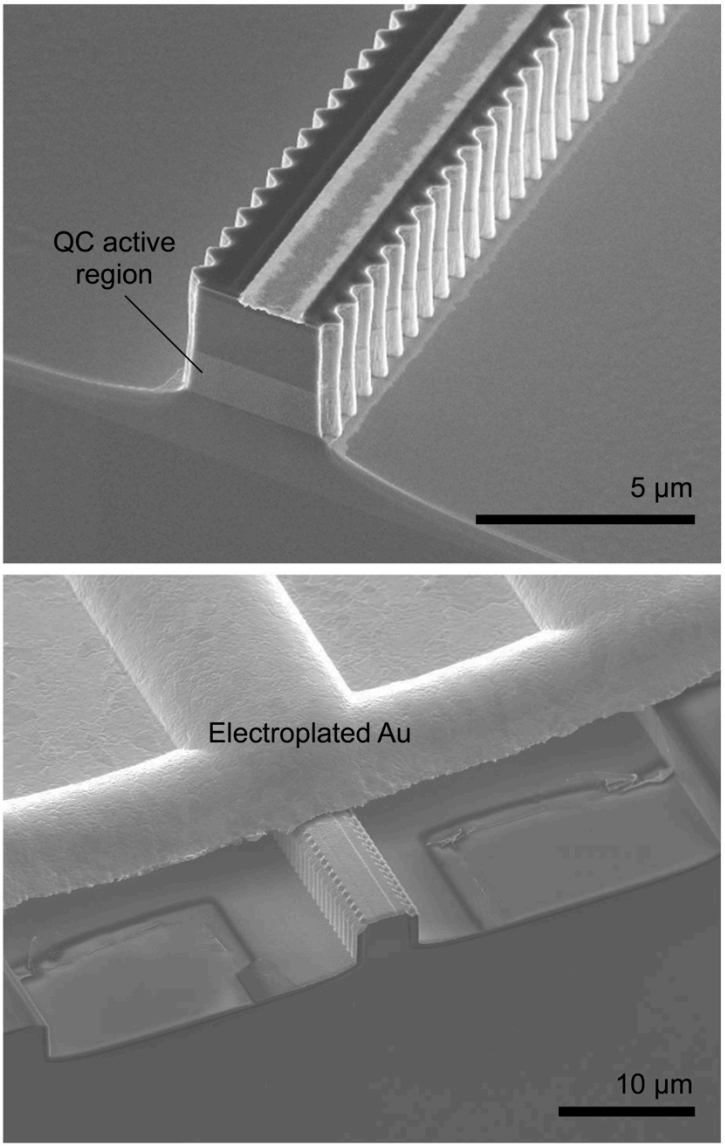

Figure 1. (Top) Scanning electron micrograph of a QC laser ridge with DFB sidewall gratings. The structure is shown with a narrow metal top contact stripe that was deposited on the laser wafer surface prior to lithographically patterning the waveguide. (Bottom) Micrograph of the emission facet of a completed QC laser designed to emit near 4.8 µm. The ridge was coated with SiN_x, which was removed from the top of the ridge prior to electroplating the top Au contact. Photoresist was used to prevent electroplating where the laser substrate was cleaved to form the end facets of the laser cavity.

For *in situ* instrument applications, lasers have been packaged in hermetically sealed, temperature-controlled TO-3 enclosures as well as custom packages designed for integration with specific instrument platforms. For the TO-3 module, an individual laser chip was mounted to a CuW submount using AuSn eutectic solder and then epoxied to a thermoelectric cooler (TEC). The low dissipation of the QC lasers, combined with operability at and above room temperature, enables the use of these enclosures with significantly smaller form factor compared with standard high-heat-load QC laser packages. The TO-3 format also allows for integration of ZnSe collimating lenses inside the package. Lasers in various stages of packaging are shown in Fig. 2.

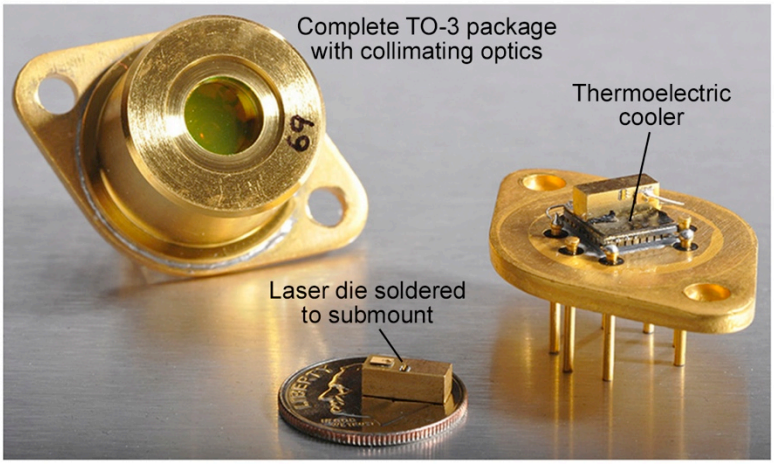

Figure 2. QC laser chips prepared for packaging in TO-3 modules. A 1-mm-long laser die is shown soldered to a submount. Mounted devices are also shown integrated on a TO-3 header with a TEC and thermistor for temperature control, and hermetically sealed with an internal collimating lens.

3. LASER PERFORMANCE

Packaged lasers were characterized for output power and emission wavelength as well as to determine overall power consumption. Figure 3 shows the CW current-voltage characteristics and output power for a single-mode QC laser designed to target OCS absorption lines near 4.823 µm for isotopic measurements [13]. The laser was found to dissipate 707 mW at threshold with a submount temperature of 20 °C, and the laser power consumption was approximately 1.6 W near maximum output power. In addition, the threshold current was relatively insensitive to current, enabling operation above room temperature. The measured emission spectrum for the laser is plotted as a function of current in Fig. 4. The laser exhibited stable, single-mode tuning over the entire characterized range of current and temperature. The observed side-mode suppression ratio was at least 25 dB, limited by the noise level of the Fourier-transform infrared spectrometer used to collect the laser spectra.

The single-mode QC laser represented in Figs. 3 and 4 was packaged in a TO-3 enclosure with a TEC, and the overall module power consumption is plotted in Fig. 5 at various laser submount temperatures. In all cases, the TO-3 can was in thermal contact with a heat sink at 20 °C. As expected, due to the heat dissipated by the laser chip, the TEC must operate in cooling mode at a laser temperature of 20 °C. The total module power consumption at threshold falls to 749 mW for a laser temperature of 30 °C, indicating that the laser itself is generating sufficient heat to maintain the temperature differential with the heat sink. The module was most efficient near the maximum output level of the laser at a submount temperature of 40 °C. While other factors must be taken into account, such as the temperature dependence of the TEC efficiency, we observe that a laser temperature 10 to 20 °C higher than the heat-sink temperature is optimal for minimizing module power consumption for the laser-TEC combination chosen here. In this regime, the overall module power consumption remains below 2 W over the entire CW operating range of the packaged laser. We compare this with

the total module power consumption of approximately 6 W for the 3.27 µm interband cascade (IC) laser source currently operating on the Tunable Laser Spectrometer instrument on the Mars Science Laboratory rover [5]. While IC lasers, in particular, have seen substantial improvement in threshold power consumption and high-temperature operability in recent years [14,15], we draw this comparison simply to show that the QC lasers presented here are compatible with existing *in situ* planetary science instrument platforms.

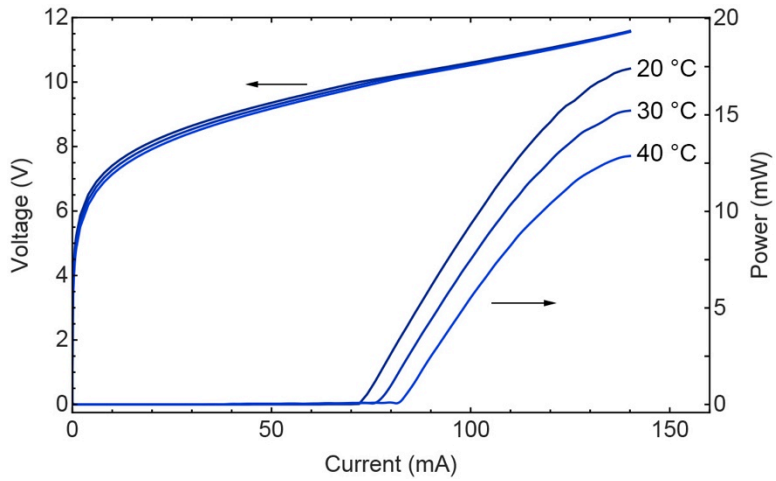

Figure 3. Continuous-wave output power and compliance voltage measured for a 4.82 µm DFB QC laser as a function of current and submount temperature. The laser ridge was 4-µm-wide and 1-mm-long. The laser was uncoated on the emission facet and HR coated on the back facet.

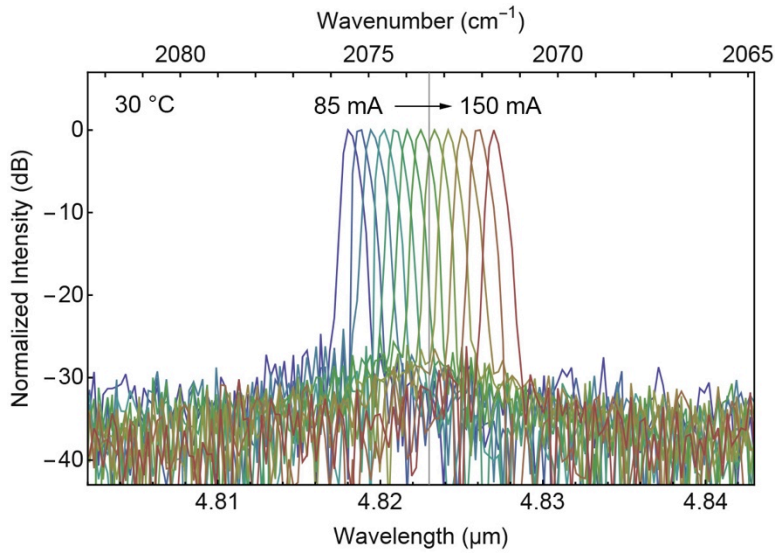

Figure 4. Emission spectra collected from the device represented in Fig. 3 as a function of current. This particular device was designed for detection of OCS isotopologues near 4.823 µm, which is in the middle of the laser tuning range at a submount temperature of 30 °C.

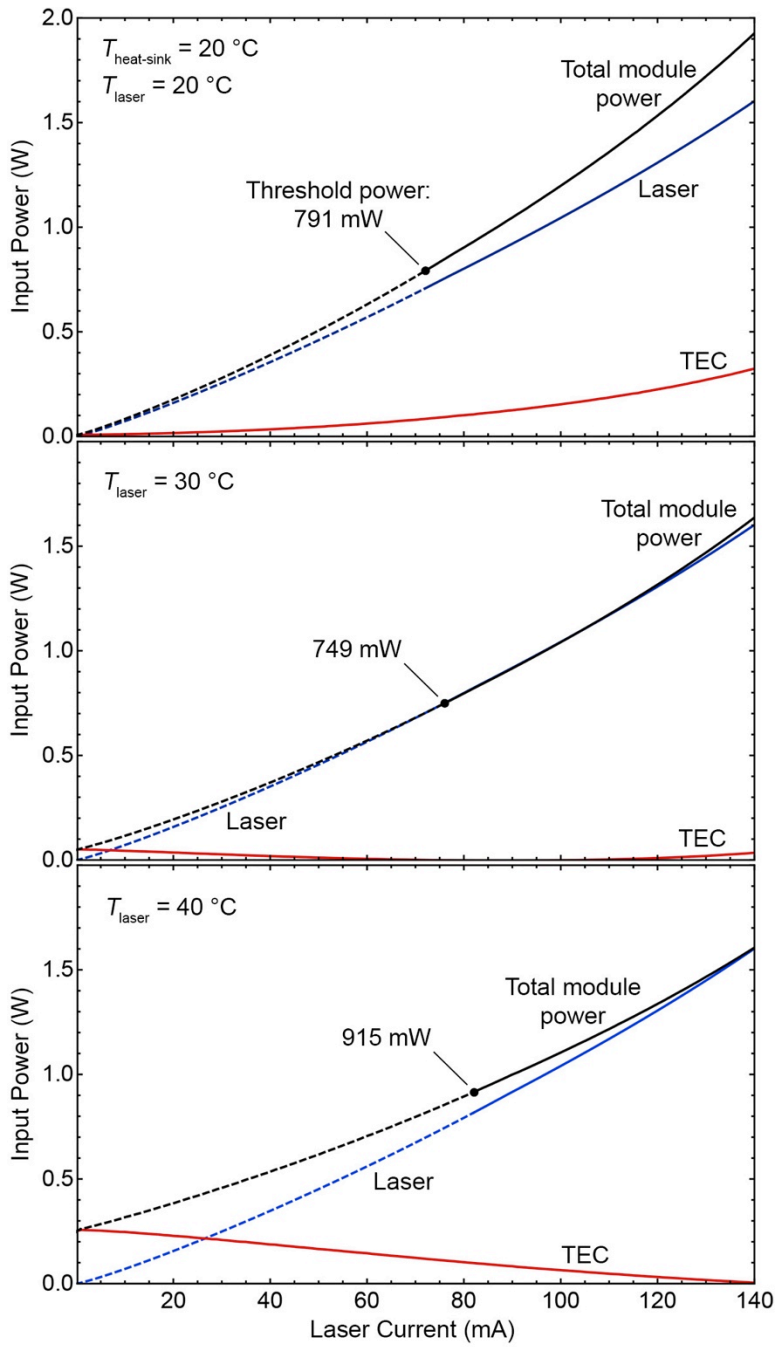

Figure 5. Measured module power consumption for a single-mode QC laser in a TO-3 package. The package was attached to a heat sink at 20 °C while the laser submount temperature was varied using the internal TEC. The total input power is shown along with the power contribution for both the TEC and laser. The dashed portions of the module and laser power curves indicate below-threshold levels.

As mentioned in the previous section, we have extended the design approach implemented for single-mode QC laser emitting near 4.8 µm to longer wavelengths. In particular, we present performance data for a laser emitting near 7.42

μm, which was designed to probe absorption lines of SO_2 [13]. Figure 6 shows the CW current-voltage and output power for a single-mode laser with a cavity length of 1 mm and uncoated facets. The threshold current is higher than the shorter-wavelength devices, resulting in threshold power consumption of 1.0 W at 20 °C, but the device exhibited comparable output power. In Fig 7, the laser emission spectrum is plotted as a function of current at 30 °C. The device produced stable, single-mode output over the entire operating range measured with no evidence of side modes above the noise level of the spectrometer used to collect the emission spectra.

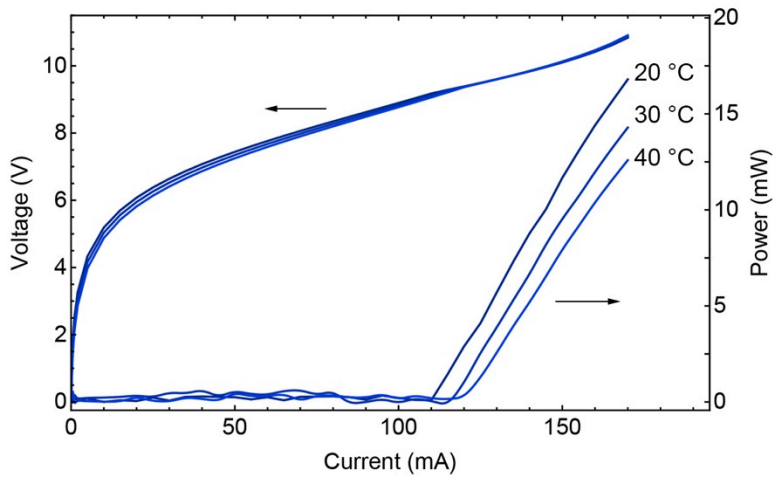

Figure 6. Continuous-wave output power and compliance voltage measured for a 7.42 μm DFB QC laser as a function of current and submount temperature. The laser ridge was 5.2-μm-wide and 1-mm-long with uncoated facets.

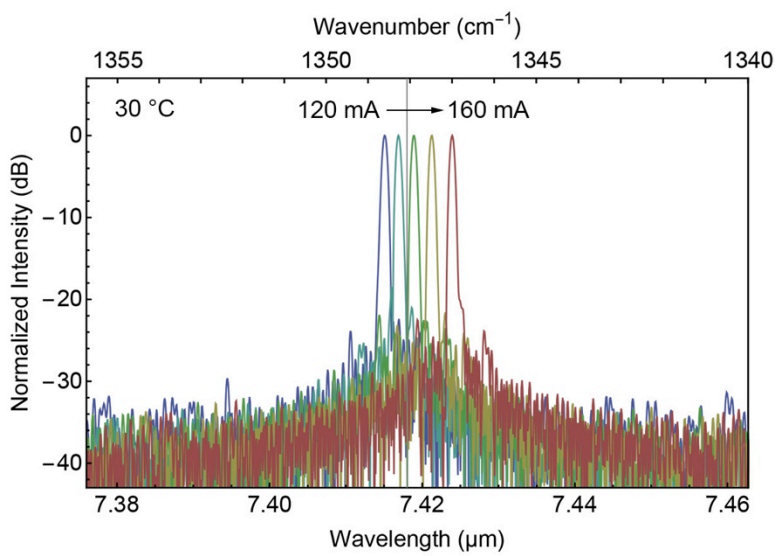

Figure 7. Emission spectra collected from the device represented in Fig. 6 as a function of current. This particular device was designed for detection of SO_2 isotopologues near 7.418 μm, which is in the middle of the laser tuning range at a submount temperature of 30 °C.

4. SUMMARY

The performance data presented here show that QC lasers can be optimized to achieve single-watt-level CW module power consumption for use in power-sensitive applications. We have employed a regrowth-free fabrication process that enables the implementation of versatile sidewall-grating designs and narrow waveguide ridges with high modal confinement. We have fabricated low-dissipation single-mode lasers operating at wavelengths up to 7.5 µm, and work is ongoing to extend our approach to 10 µm. For laser absorption spectrometers, in particular, the single-mode QC lasers presented here are competitive with shorter-wavelength interband lasers previously integrated with airborne and space-based instrument platforms in terms of both power dissipation and spectral stability. Ultimately, the availability of low-power-consumption QC lasers in mid- to long-wavelength infrared regime will create new opportunities to perform highly accurate *in situ* measurements of the abundance and isotopic composition of various molecules relevant to planetary science and environmental sensing.

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