Plasma etching for fabrication of low-dissipation single-mode quantum cascade lasers

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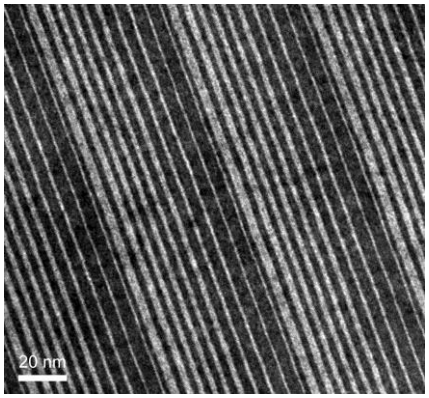
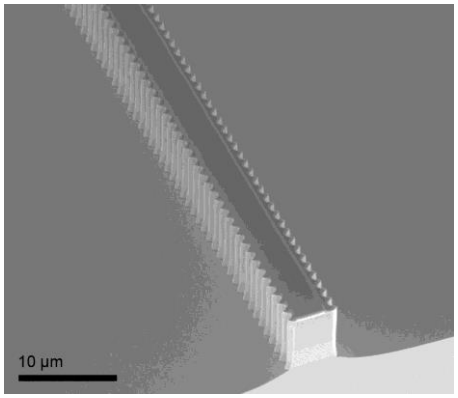
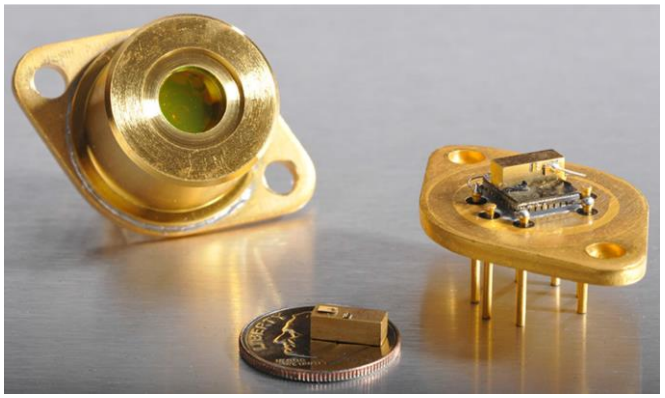
Nanotech 2017: Pushing the Limits

July 19, 2017







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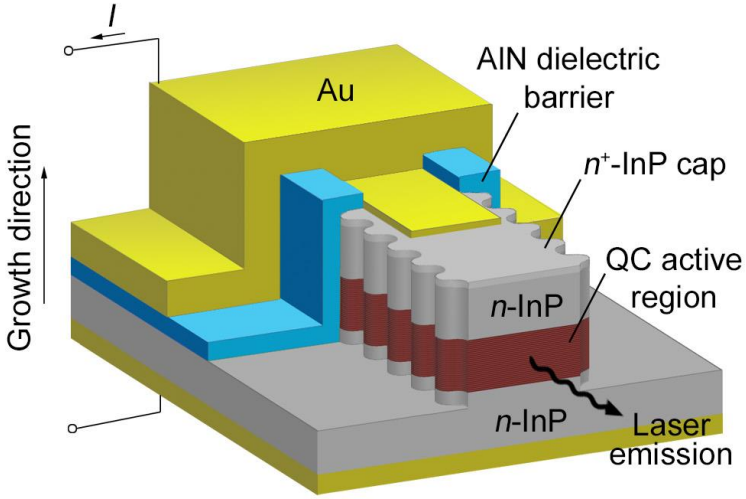
Motivation: Low-power-consumption long-wavelength lasers

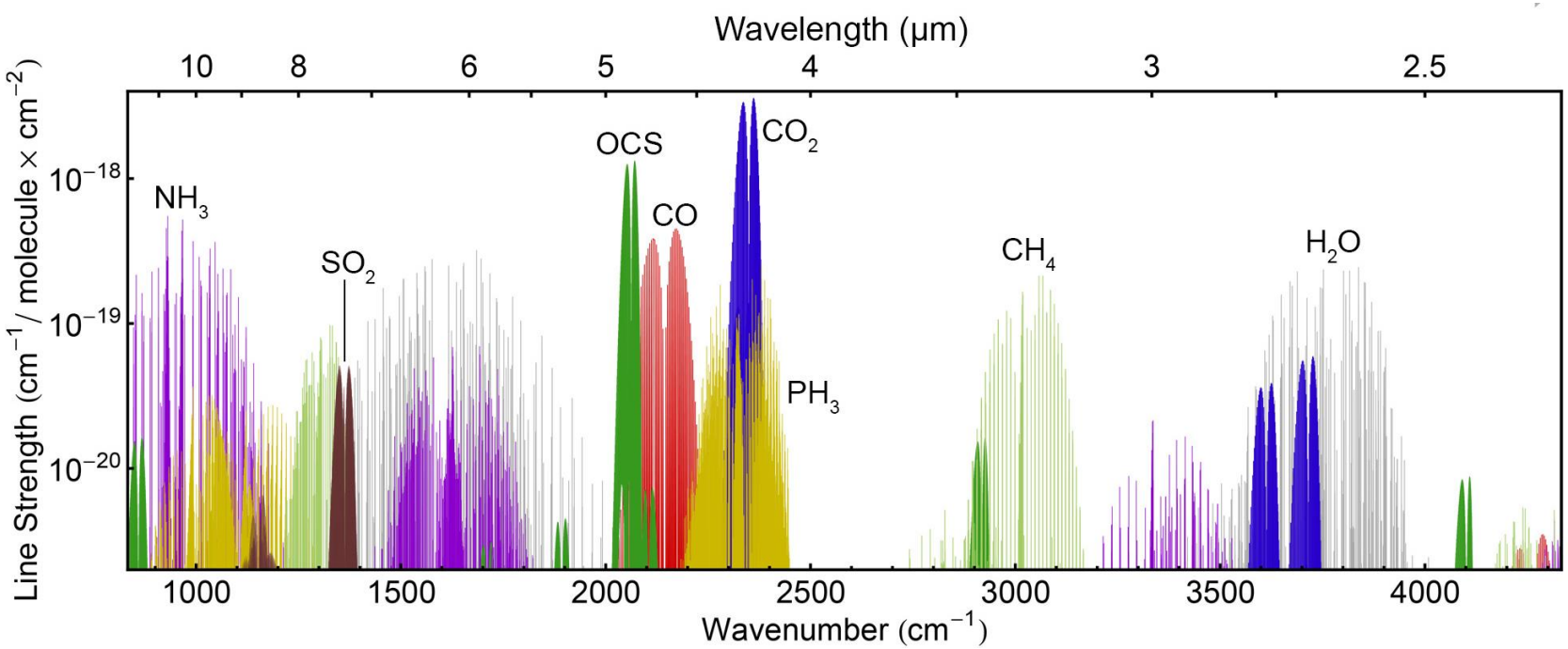
In situ Tunable Laser Spectrometer (TLS) instruments require single-mode laser sources to probe molecular absorption lines

Typical spacecraft power budgets cannot accommodate commercially available long-wavelength laser modules (laser chip + cooler)

Anisotropic etching enables fabrication of quantum cascade lasers with minimal device area, leading to reduced operating current, as well as distributed feedback gratings

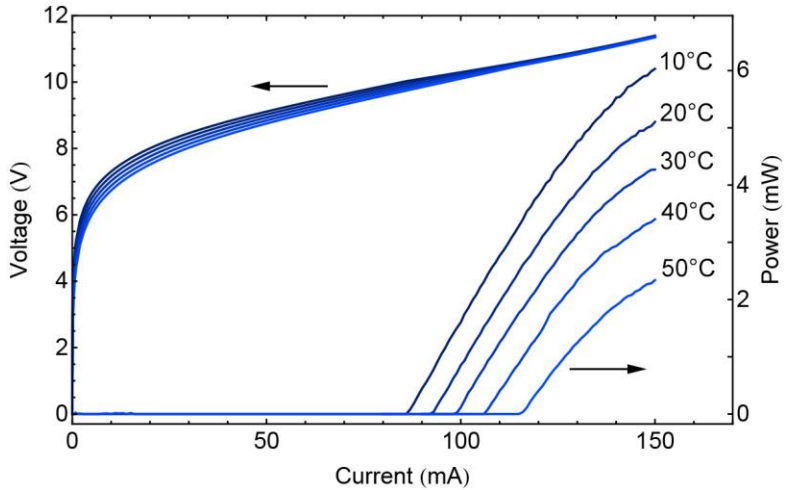


Molecular absorption in the mid-infrared regime



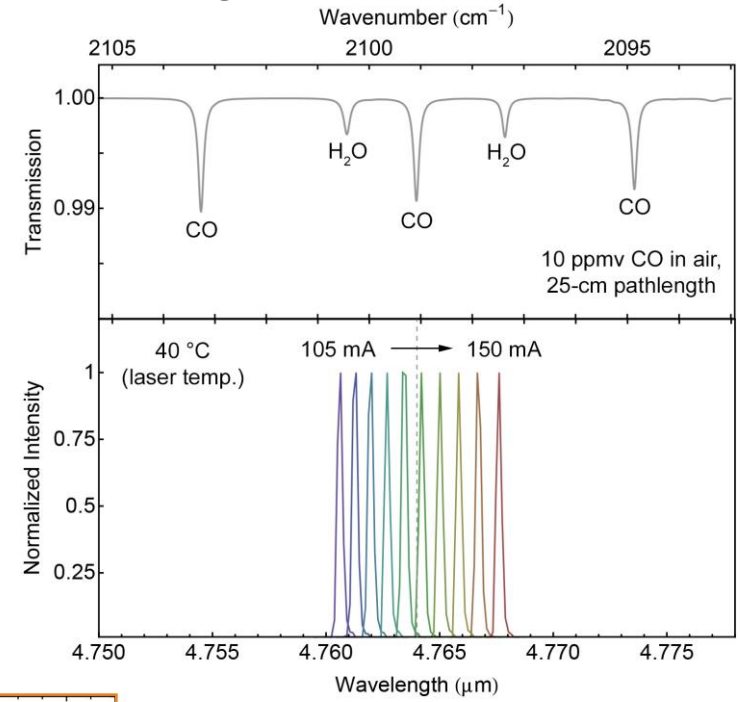
Laser wavelength modulation spectroscopy

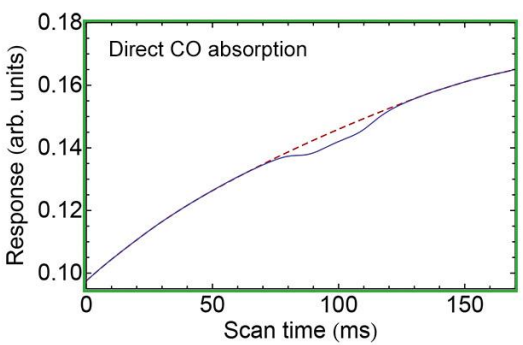
Laser light-current-voltage characteristics

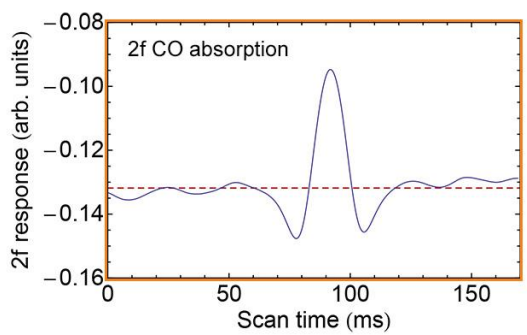


By sweeping current sourced to a single-mode laser, relative absorption is measured over a known pathlength

Current tuning of laser emission wavelength



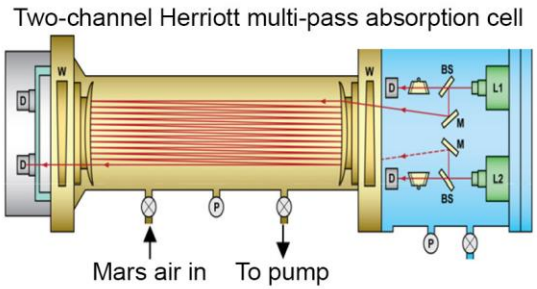


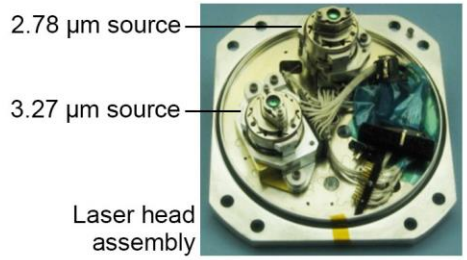


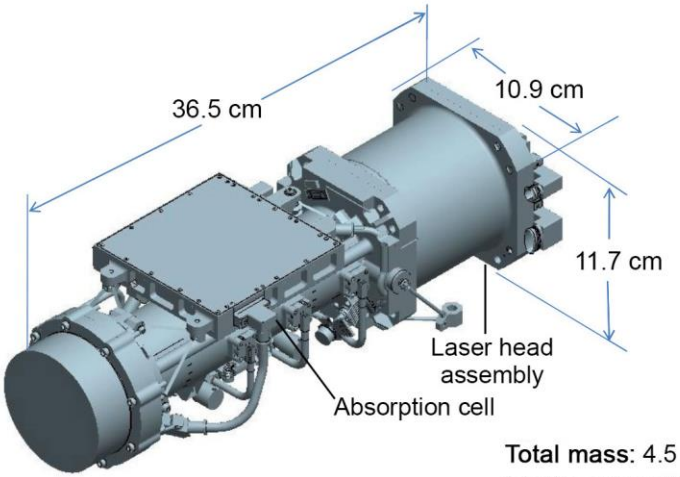
With additional small-amplitude modulation of the current, the demodulated spectral response can be measured with reduced noise

Tunable Laser Spectrometer (TLS) on the Mars Curiosity rover

TLS instrument layout for CH_4 and CO_2/H_2O detection

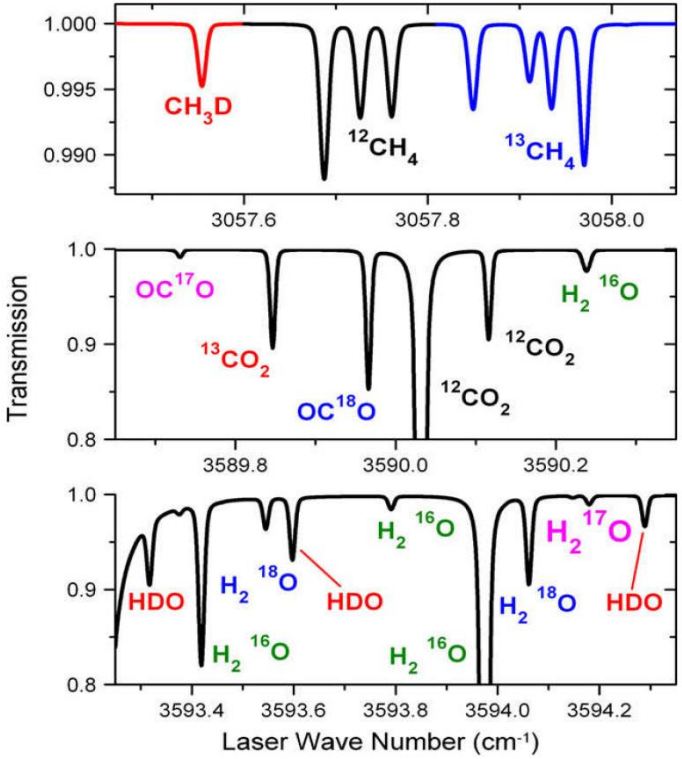






Total mass: 4.5 kg
Input power: 25 W (16.7 W avg.) @ 28 V
Operating temperature: -20 to +40 °C
Survival temperature: -40 to +100 °C

Target absorption lines



Webster, *et al.*, *Science* **341**, 260 (2013)
Webster, *et al.*, *Science* **347**, 415 (2015)

Tunable Laser Spectrometer (TLS) on the Mars Curiosity rover

C, O, and H isotope ratios in Martian atmosphere

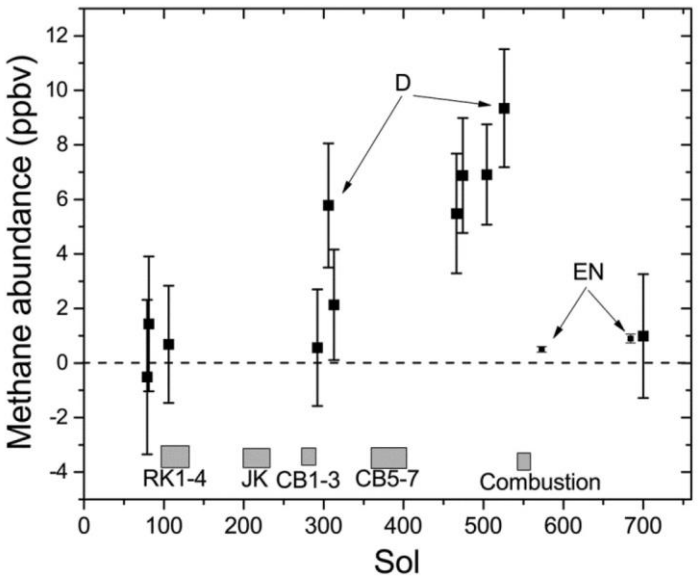
Table 1. Carbon dioxide isotope ratios ‰ ± 2 SEM (standard error of the mean). *, not measured.

Measurement	$\delta^{13}C$	$\delta^{18}O$	$\delta^{17}O$	$\delta^{13}C^{18}O$
SAM-TLS	46 ± 4	48 ± 5	24 ± 5	109 ± 31
SAM-QMS (*3*)	45 ± 12	*	*	*
Phoenix lander (*12*)	−2.5 ± 4.3	31.0 ± 5.7	*	*
Viking Neutral Mass Spectrometer (*11*)	23 ± 43	7 ± 44	*	*
SNC meteorites (*8*, *12*, *32*)	36 ± 10	3.9–5.4 ± 0.1	~0.53* $\delta^{18}O$	~ $\delta^{13}C$+ $\delta^{18}O$
ALH84001 meteoritic carbonate range (*30*, *31*)	27 to 64	−9 to 26	~0.53* $\delta^{18}O$	~ $\delta^{13}C$+ $\delta^{18}O$
ALH84001 meteoritic carbonate mean value (*31*)	46 ± 8	4.6 ± 1.2	*	*
Earth telescopes (*9*)	−22 ± 21	18 ± 18	*	*

Table 2. Water isotope ratios ‰ ± 2 SEM. *, not measured.

Measurement	δD	$\delta^{18}O$
SAM-TLS atmosphere	4950 ± 1,080	*
SAM-TLS evolved water: Rocknest fines 230° to 430°C (*23*)	5880 ± 60	84 ± 10
Meteoritic crustal reservoirs (*26*)	~5000	*
Earth telescopes (*24*)	1700–8900	*
ALH 84001 (*17*)	3000	*
Shergotty USNM 321-1 (*17*)	4600	*

Methane abundance on Mars



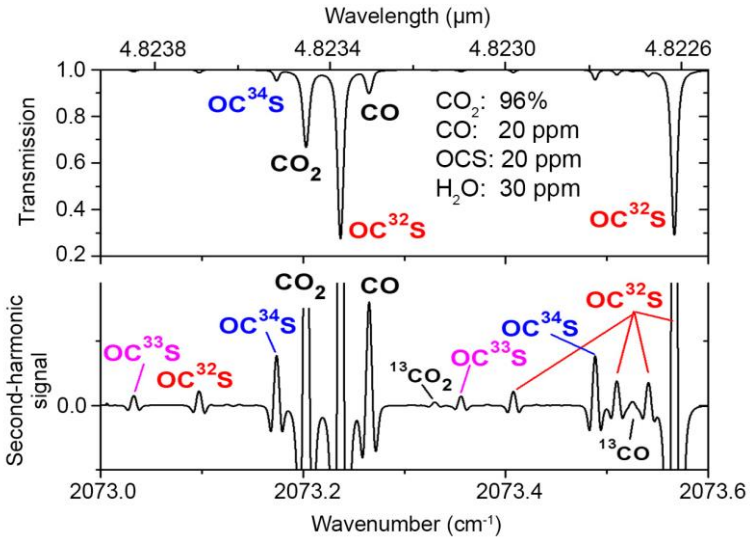
Webster, *et al.*, *Science* **341**, 260 (2013)
Webster, *et al.*, *Science* **347**, 415 (2015)

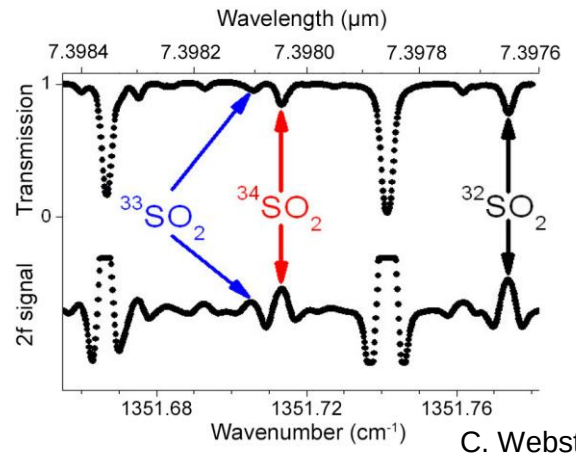
Future planetary science instruments: Venus In Situ Explorer

Venus In Situ Explorer
atmospheric probe concept

NASA

Target molecules: OCS and SO_2

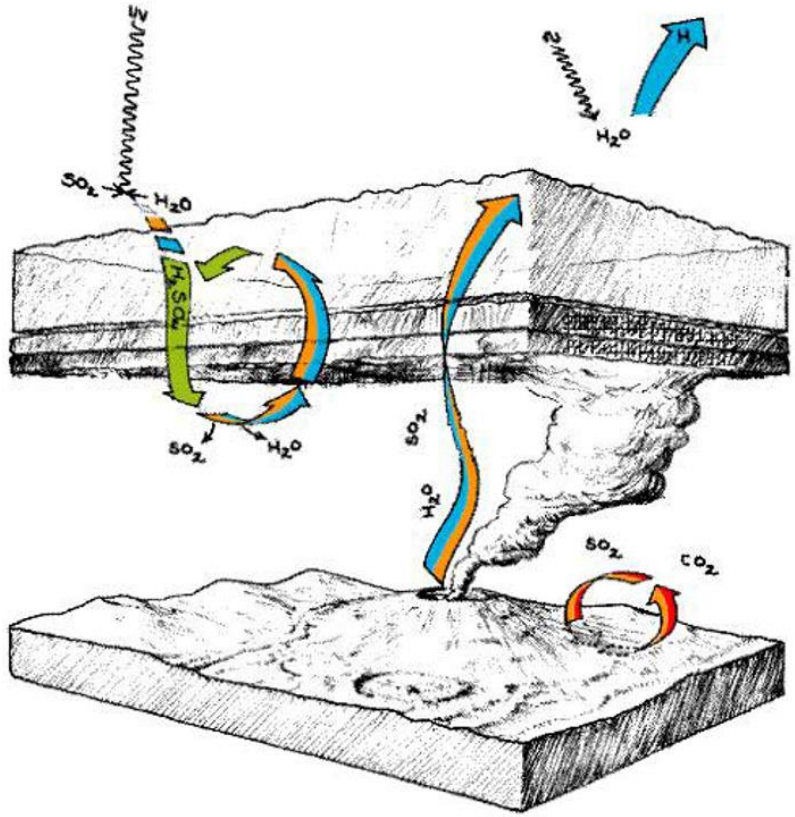




C. Webster, JPL

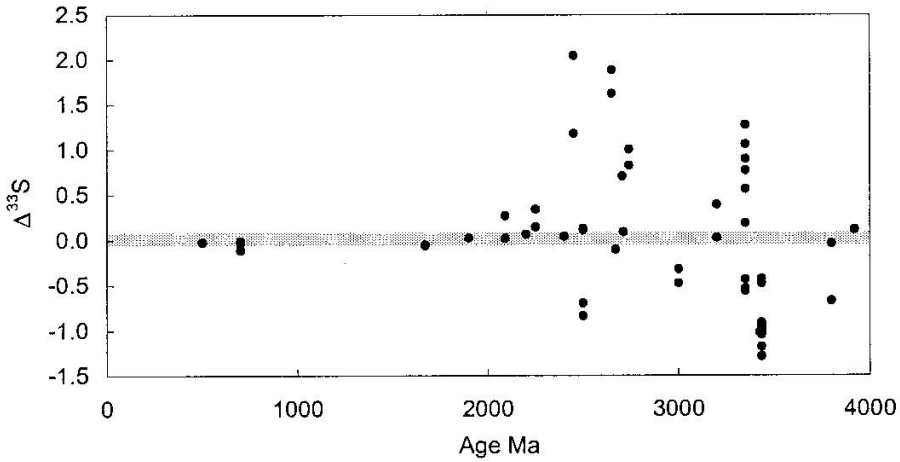
Future planetary science instruments: Venus In Situ Explorer

Photolysis and the sulfur cycle on Venus



D. Grinspoon and C. Emmart, NASA

Geological sulfur isotope record on Earth

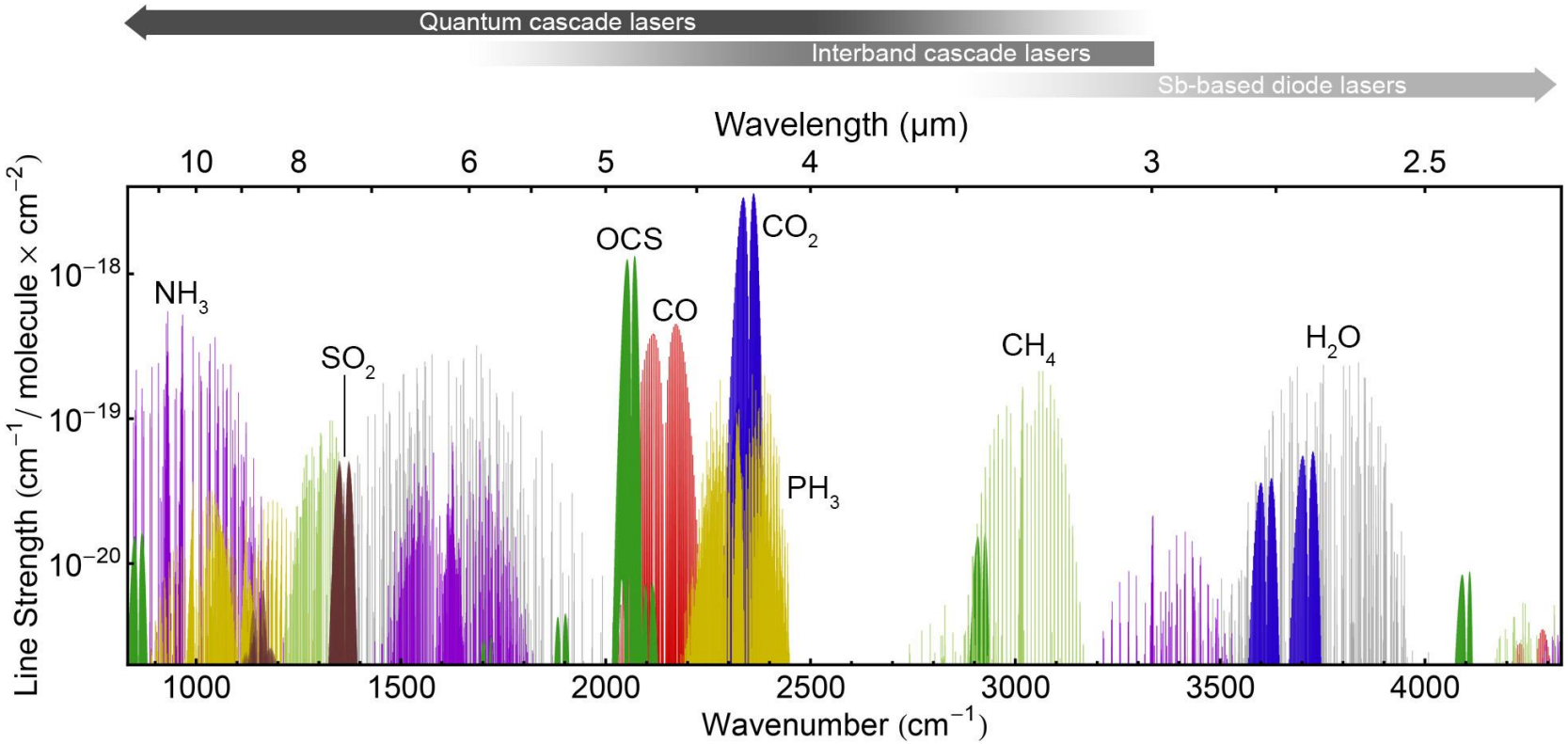


Farquhar, *et al.*, Science **289**, 756 (2000)

S isotope measurements are a primary objective for proposed missions to Venus

Isotope ratios are key to understanding climate cycles on Venus and can verify theories of the evolution of Earth's atmosphere

Semiconductor laser technologies for TLS instruments

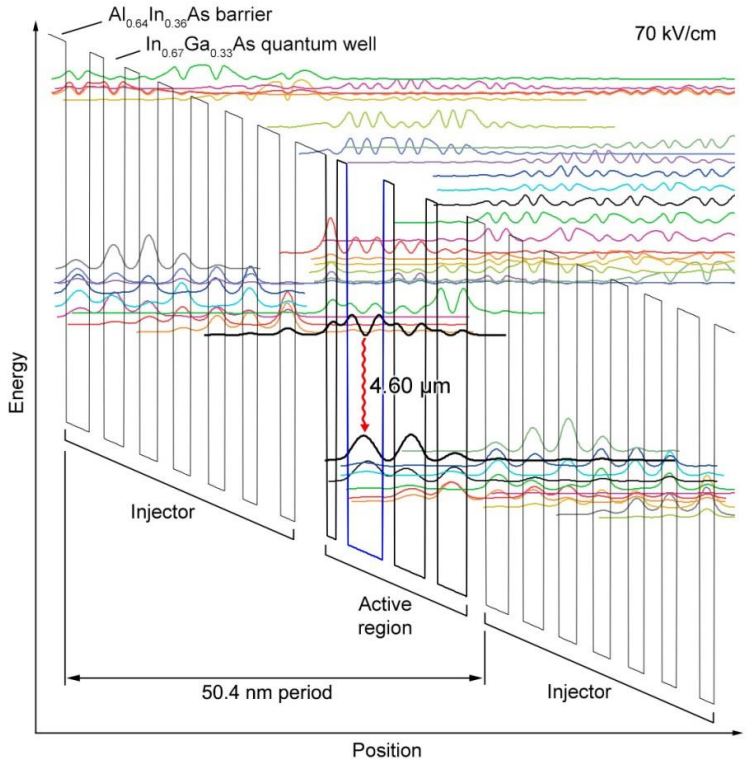


Future laser spectrometers will target longer-wavelength lines, which will require QC lasers

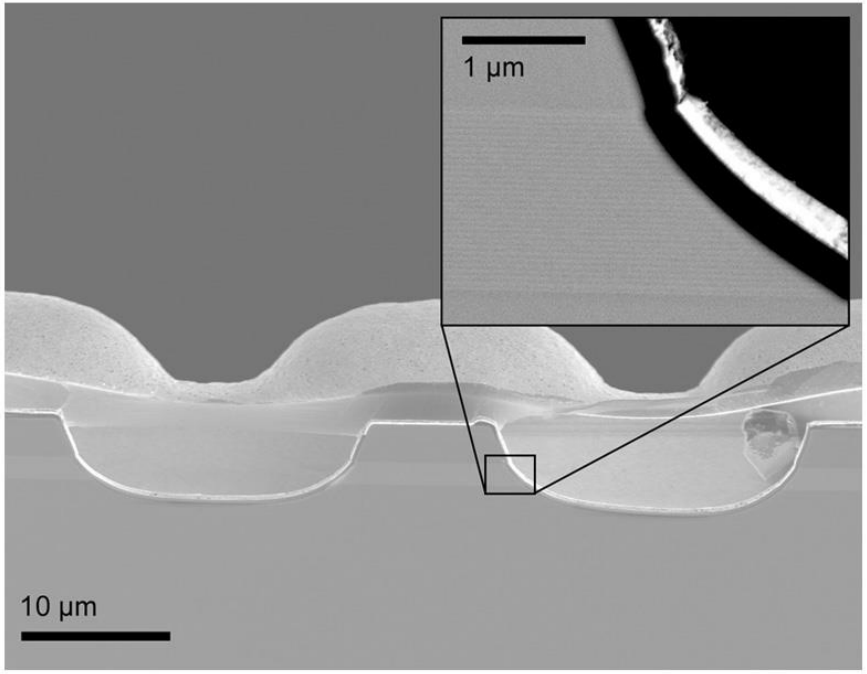
Power consumption is a limiting factor in component selection

Mid-infrared quantum cascade active region design

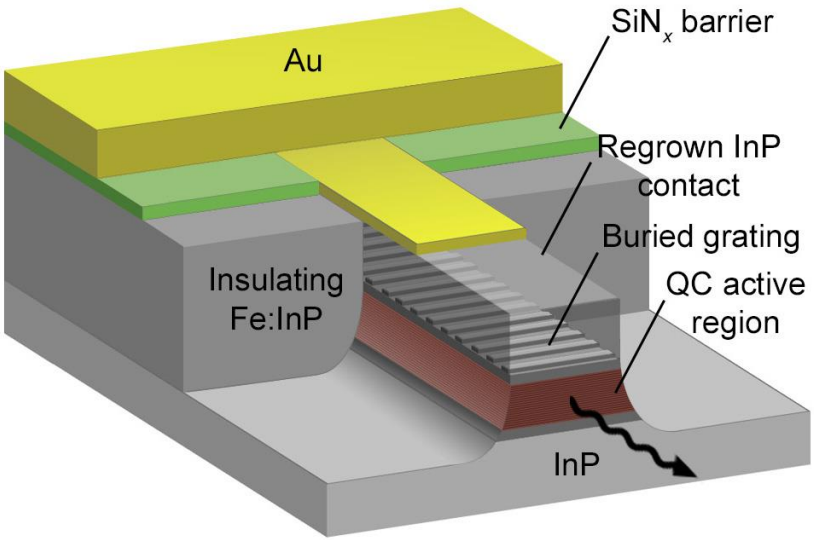
Strain-balanced two-phonon resonance design for emission near 4.6 µm

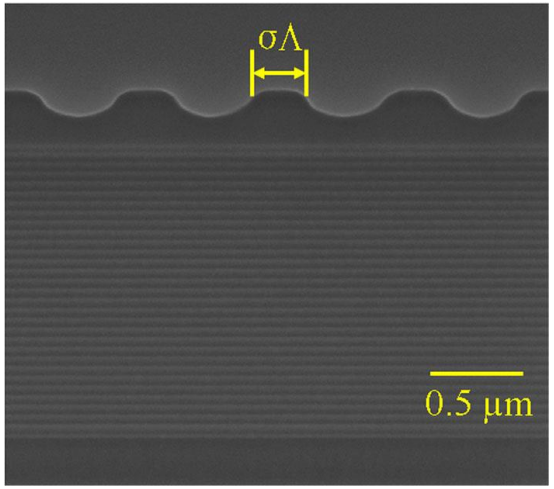


Wet-etched QC laser ridge with metallization



Buried-heterostructure DFB QC lasers

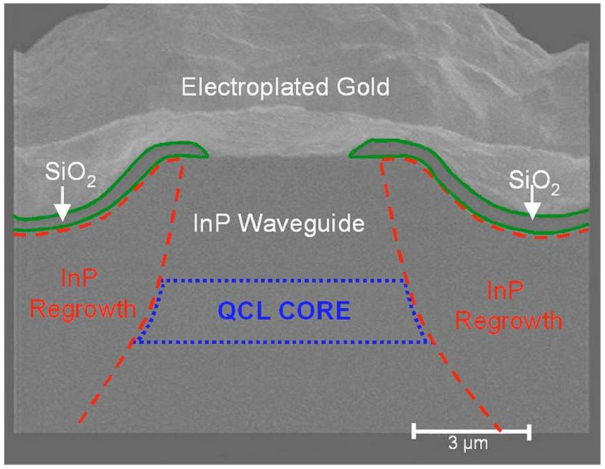




Zhang, *et al.*, *Appl. Phys. Lett.* **100**, 112105 (2012)

Provides low optical loss, excellent heat dissipation, and reliability, but requires two epitaxial regrowth processes

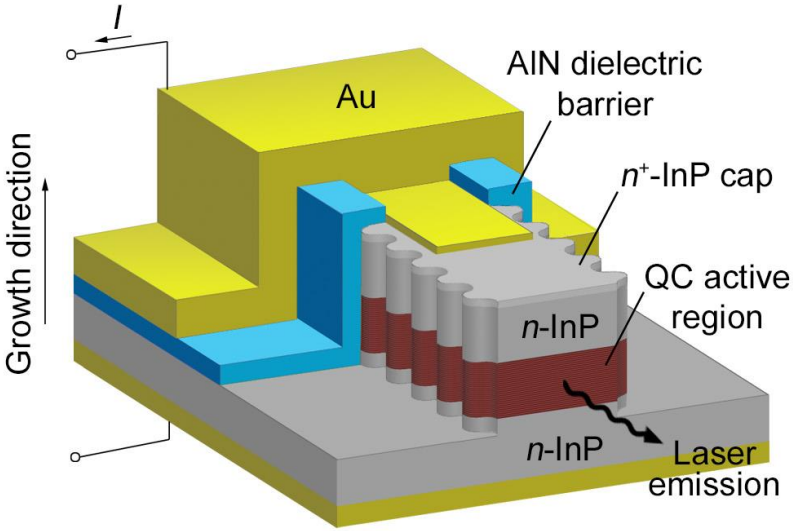
Mid-infrared emission with sub-watt power consumption recently demonstrated by ETH Zürich and Alpes Lasers



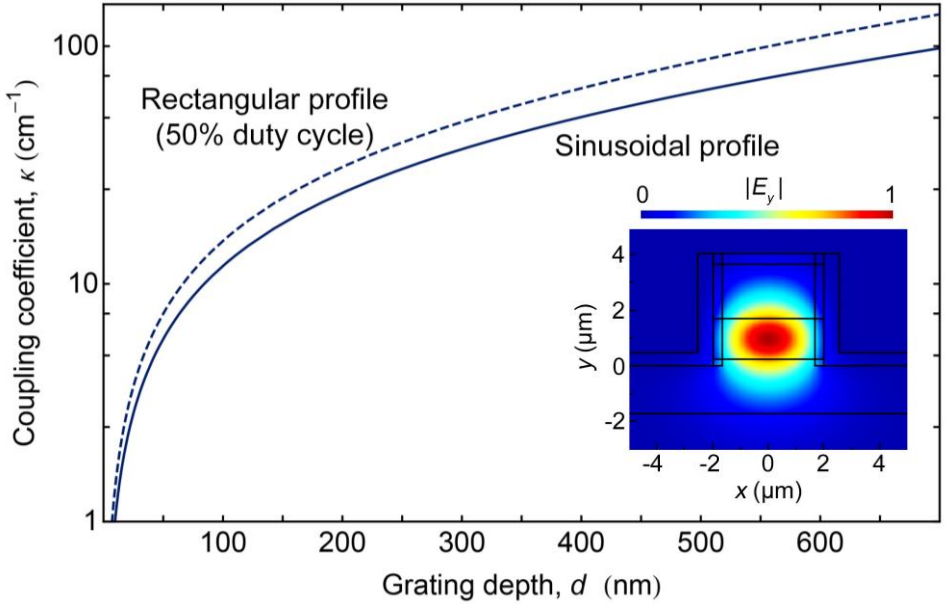
Evans, *et al.*, *Appl. Phys. Lett.* **91**, 071101 (2007)

Hinkov, *et al.*, *Electron. Lett.* **646**, 071101 (2012)
Bismuto, *et al.*, *Opt. Express* **23**, 5477 (2015)

Regrowth-free DFB QC laser design



Calculated grating coupling coefficient:
4.8 µm wavelength, 775 nm pitch

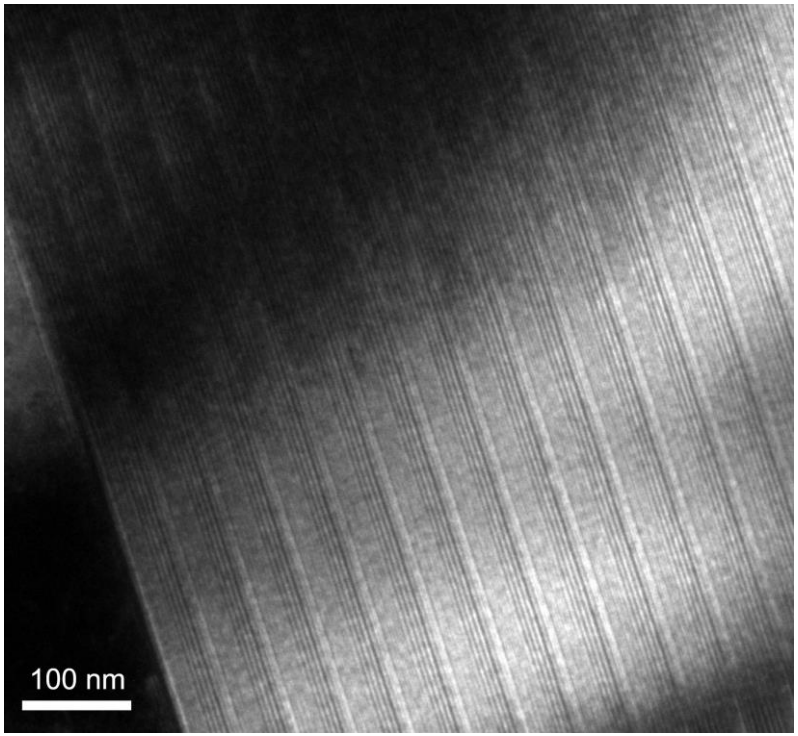


Sidewall gratings with low-index dielectric cladding provide high optical confinement

Narrow, vertically etched ridges enable low-current operation

Ridge etching for QC laser fabrication

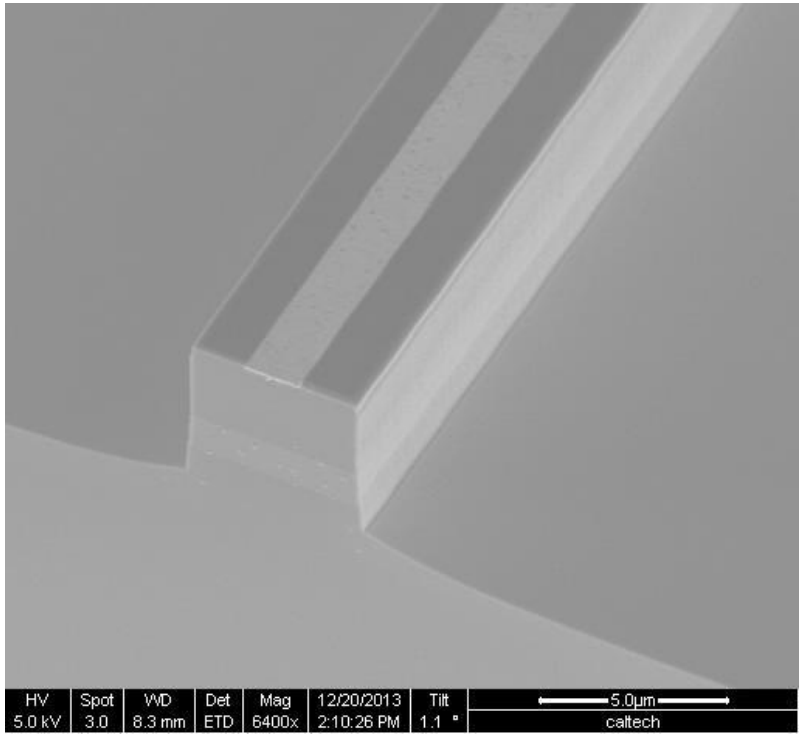
MBE-grown QC active region on InP



Transmission electron microscopy by M. Sullivan (Caltech)

Two-phonon-resonance design used <5 µm, non-resonant extraction designs used >5 µm

Ridge isolation etch: $Cl_2/H_2/CH_4$ plasma

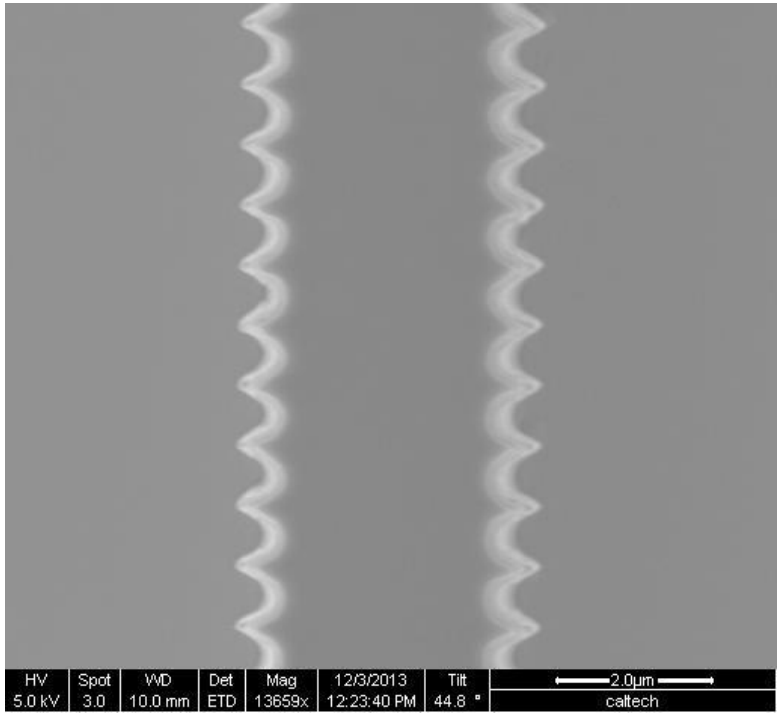


Anisotropic without undercutting of ternary alloys

Etch rate is ~2x slower through active region compared with InP cladding

QC laser ridges with DFB sidewall gratings

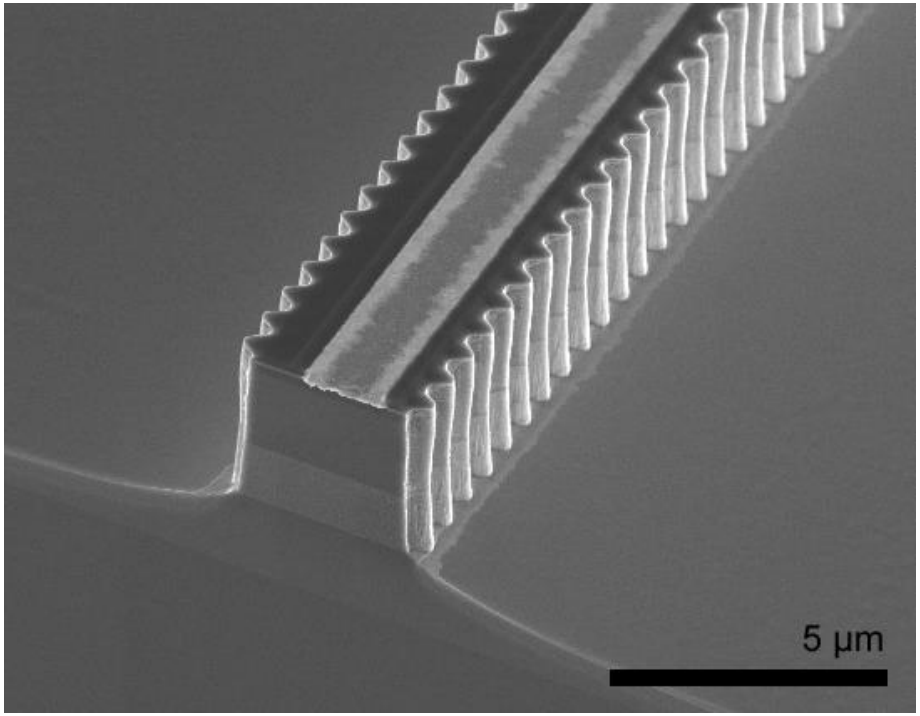
Low-stress SiN_x hard mask



Patterned by electron-beam lithography

Pattern transfer into hard mask using anisotropic SF_6/C_4F_8 "pseudo-Bosch" etch

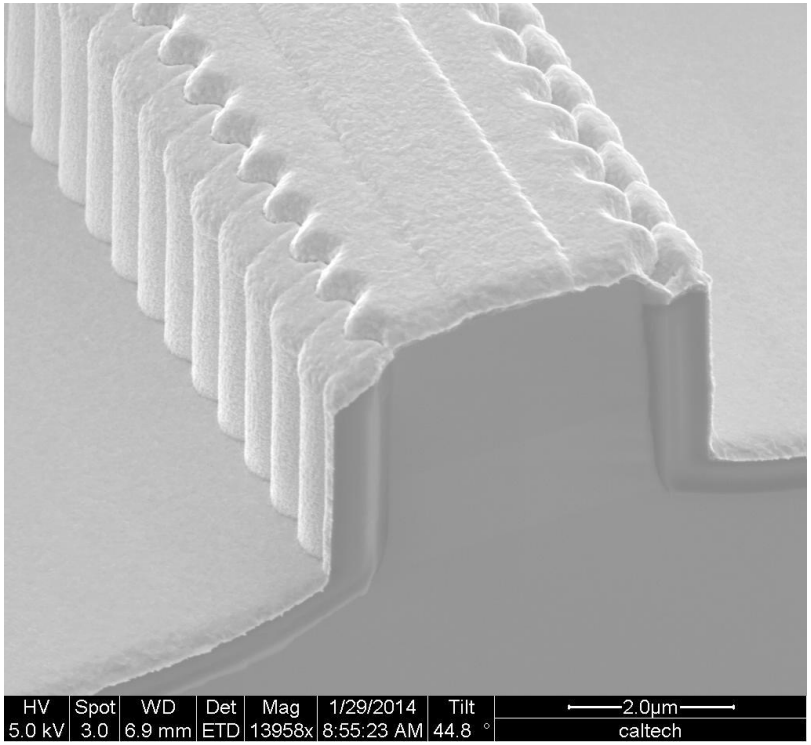
Ridge isolation etch: $Cl_2/H_2/CH_4$ plasma



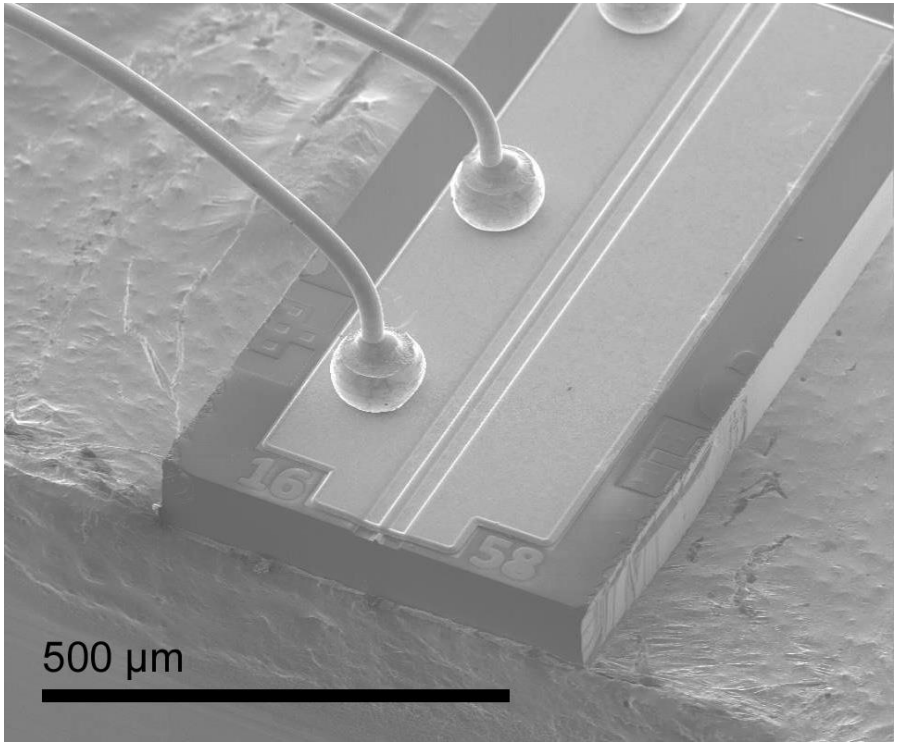
$Cl_2/H_2/CH_4$ etch has enabled excellent pattern fidelity with sub-micron features to depths up to 10 µm

Completed QC lasers

QC laser ridge with dielectric barrier and metallization

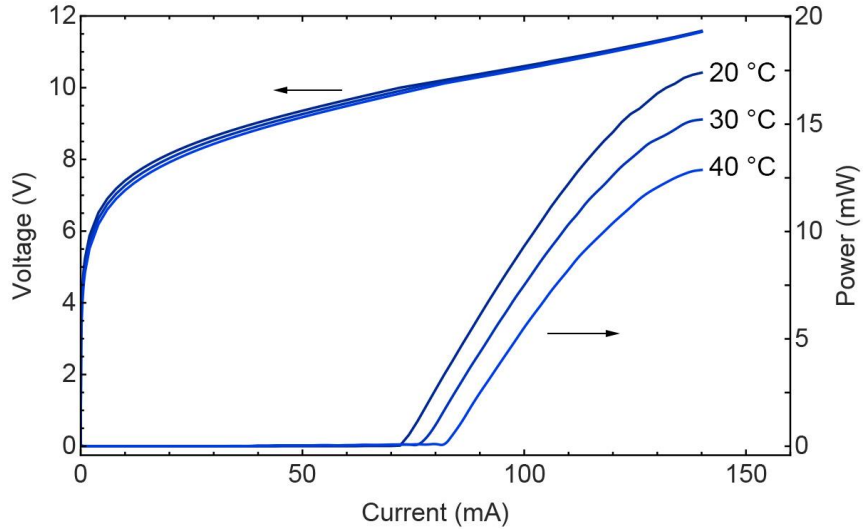


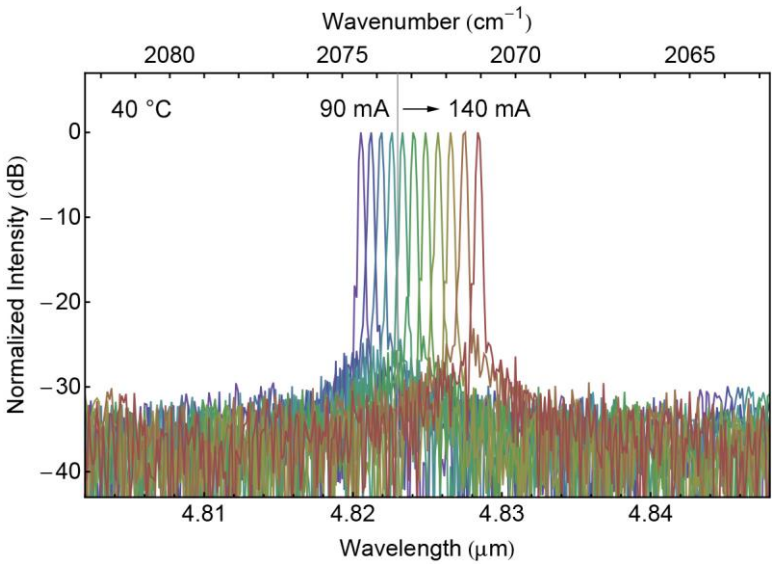
QC laser chip soldered to submount and wire-bonded

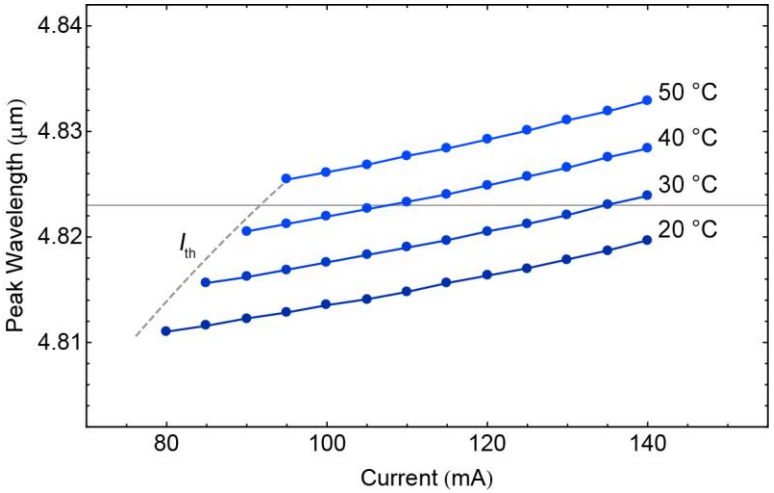


DFB QC laser performance: 4.8 µm wavelength for OCS detection

CW performance: 1 mm cavity, HR-coated back facet







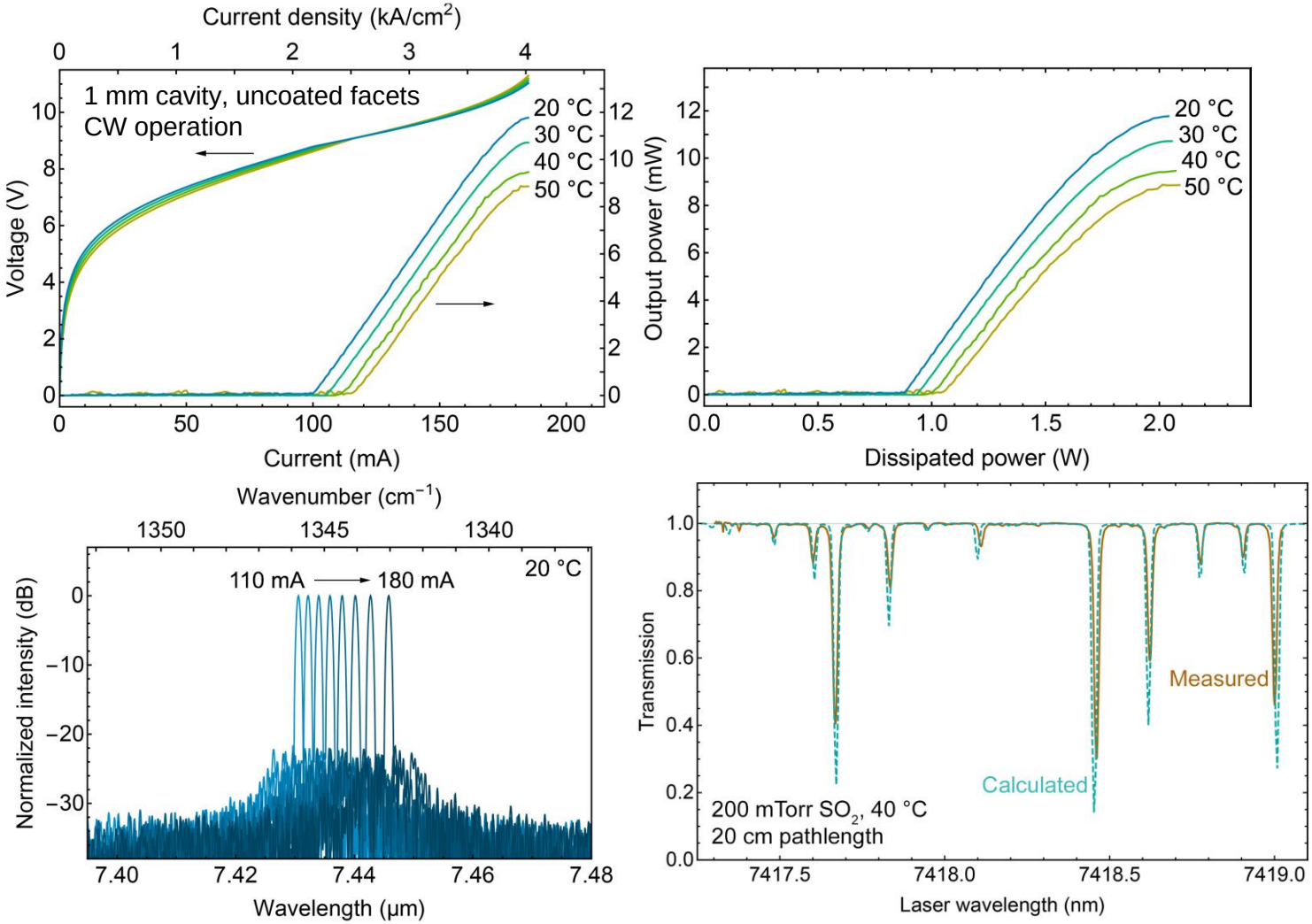
Stable, single-mode emission with 750 mW CW threshold power consumption at 20 ° C

Mode-hop-free tuning across target wavelength above room temperature

Devices have been run for as long at 2000 hours without degradation

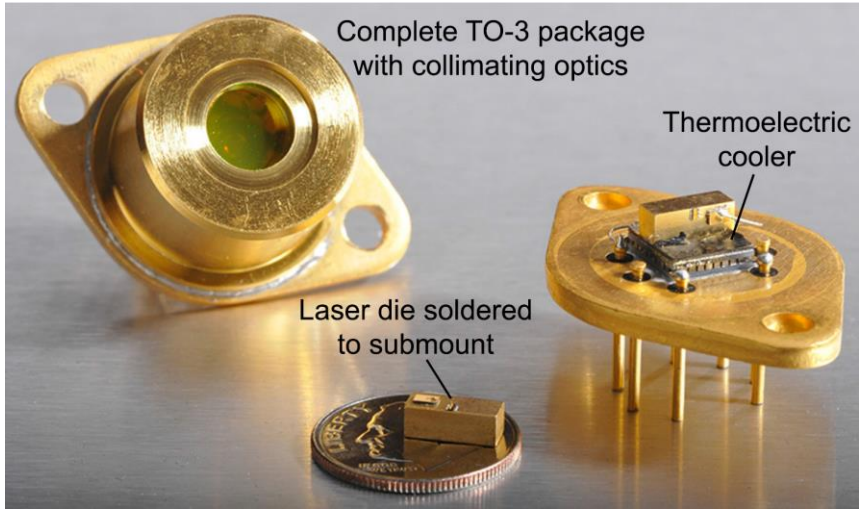
Briggs, *et al.*, *Appl. Phys. Lett.* **105**, 141117 (2014)

DFB QC laser performance: 7.4 µm wavelength for SO_2 detection

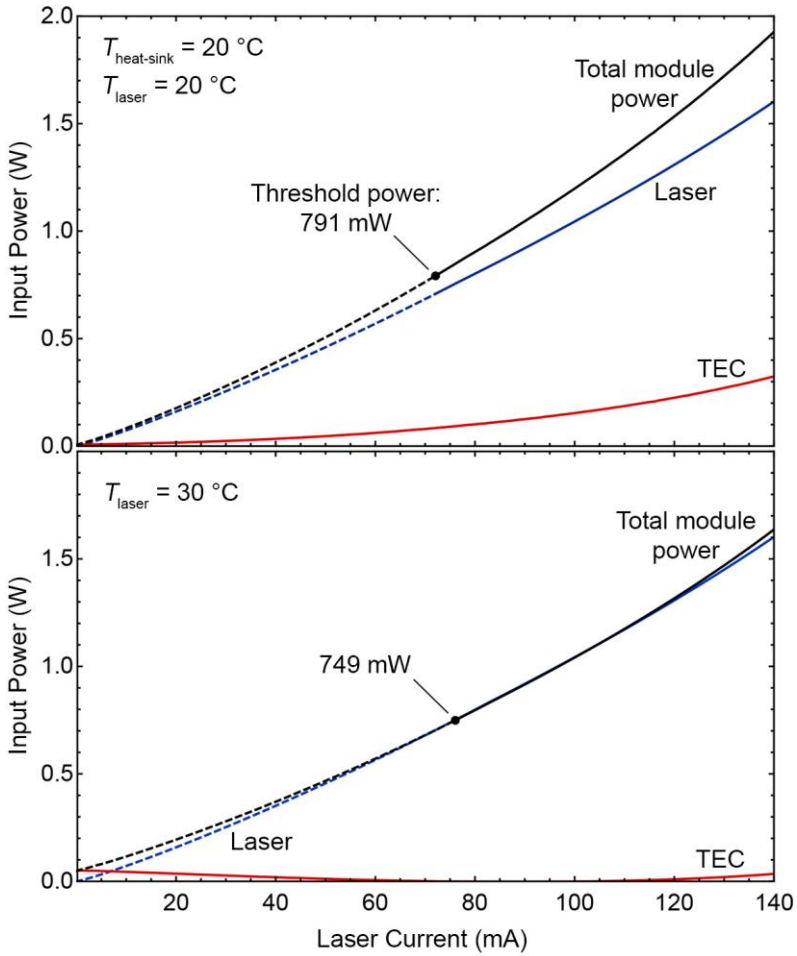


Briggs, *et al.*, *Opt. Express* **24**, 14589 (2016)

QC laser packaging



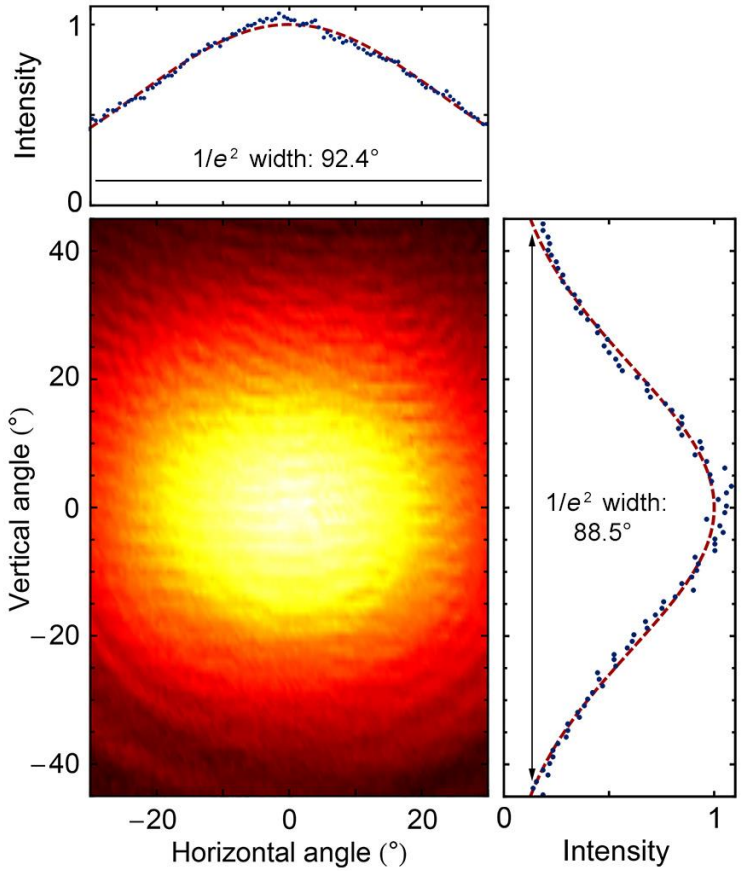
Packaged 4.8 µm QC laser CW power consumption



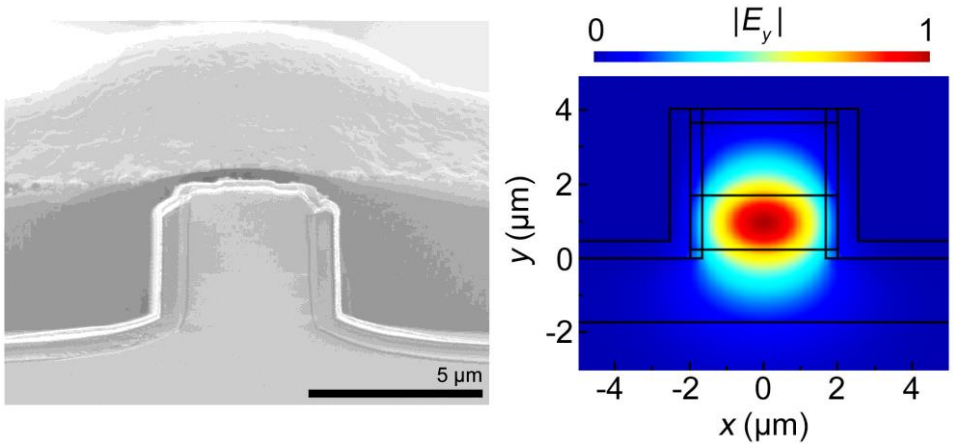
Low dissipation and high operating temperatures enable use of small form factor packages

Demonstrated modules with power consumption <1 W at threshold and <2 W at maximum output

Symmetric QC laser far-field profile



Measured far-field profile at 4.8 µm



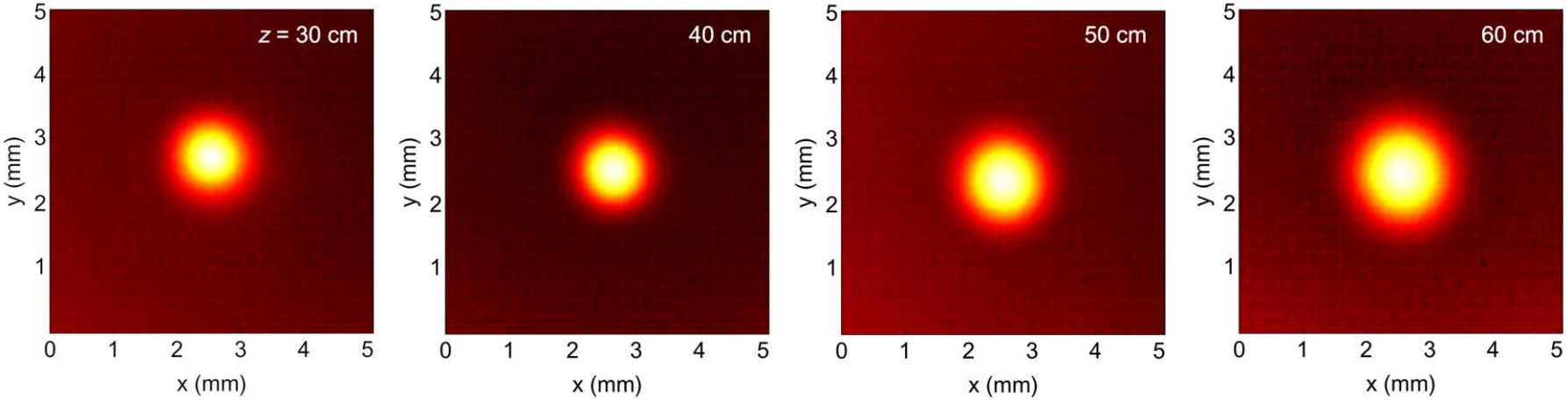
Briggs, *et al.*, *Appl. Phys. Lett.* **105**, 141117 (2014)

Low-index lateral cladding compensates for the asymmetric active region, resulting in a radially symmetric far-field profile

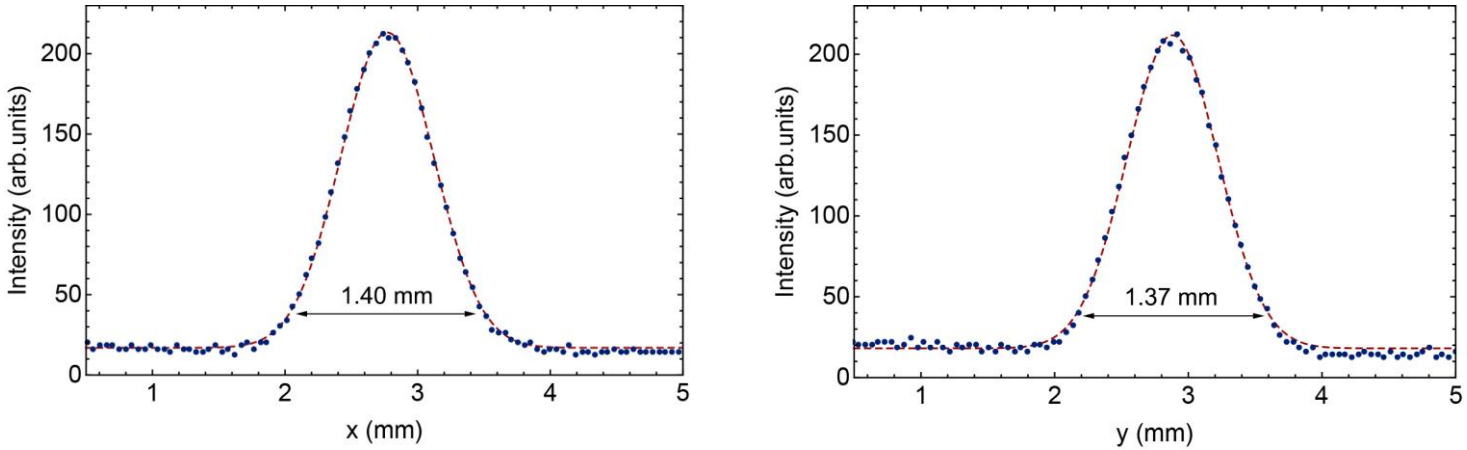
Enables efficient coupling to external optics

Beam profiles for 7.4 µm QC laser: Single aspheric collimating lens

Infrared camera images at varying distance, *z*, from the lens

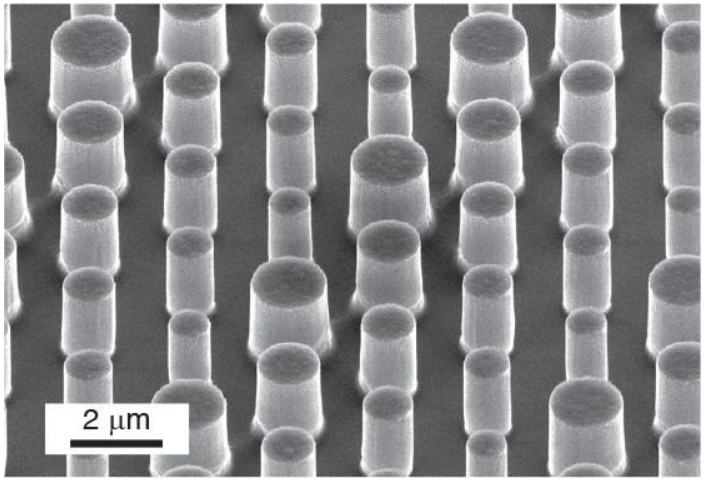


Horizontal and vertical beam profiles at *z* = 40 cm

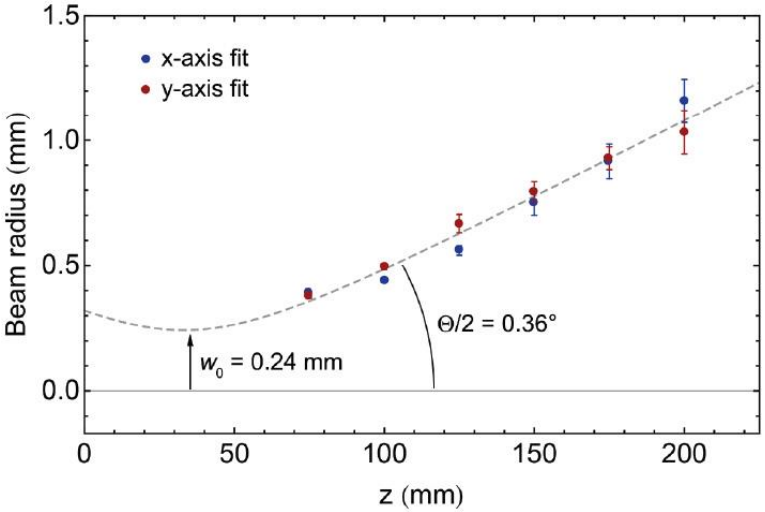


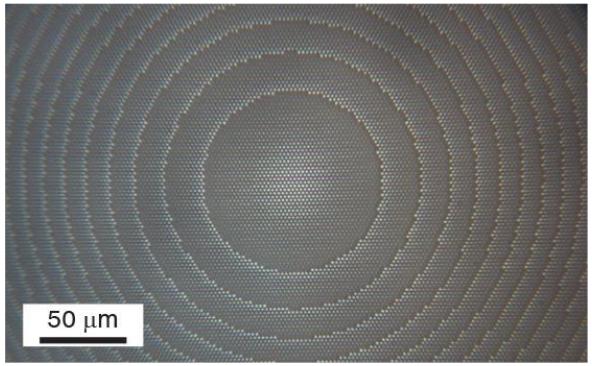
Collimation using flat metasurface lenses

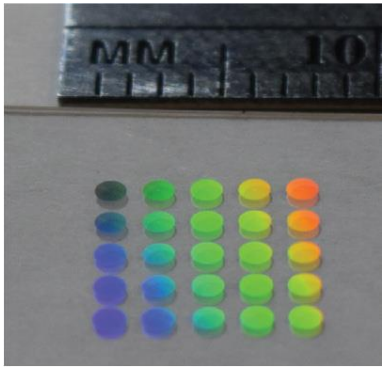
Flat lenses designed for 4.8 µm QC laser collimation

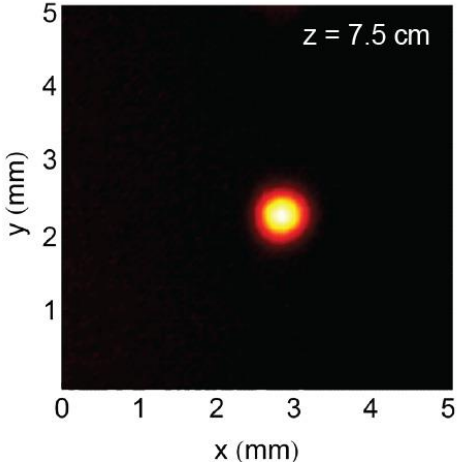


Achieved collimation with $M^2 = 1.02$









Arabi, *et al.*, *Opt. Express* **23**, 33310 (2015)

Acknowledgements

Coworkers:

Clifford Frez, Mathieu Fradet, Mahmood Bagheri, and Siamak Forouhar, *JPL*

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Project support:

NASA Planetary Instrument Concepts and Solar System Observations (PICASSO) Program

NASA New Frontiers Homesteader Program