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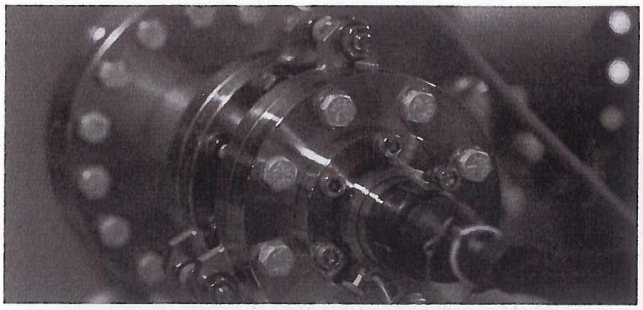

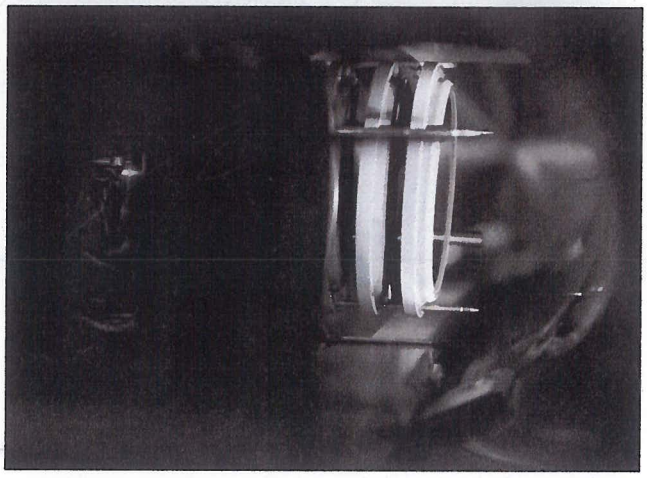

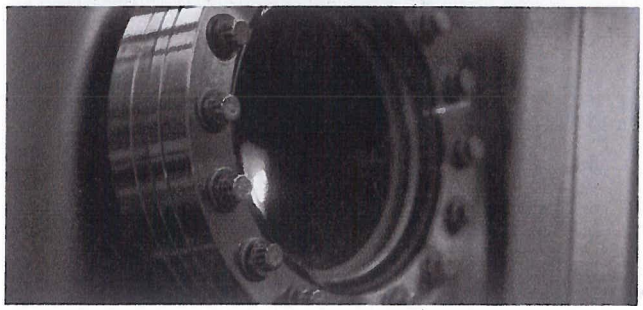

Ring Quantum Cascade Lasers: Versatile Light Emission and Applications in Spectroscopic Sensing

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Quantum cascade lasers (QCLs) are compact and versatile light sources emitting in the mid-infrared and terahertz spectral range. Therefore, QCLs are popular light sources for spectroscopy and chemical fingerprinting.

Ring QCLs [1] consist of a ring-shaped waveguide with a second order distributed feedback (DFB) grating on top. The latter selects the lasing mode and provides vertical light emission. Due to the relatively large emitting area, these lasers provide a strongly collimated emission beam.

We present several techniques for efficient light extraction from these ring QCLs including integrated phase shifts [2] and metamaterial-induced manipulation of the substrate-emitted light [3] as shown in Fig. 1 and 2, respectively.

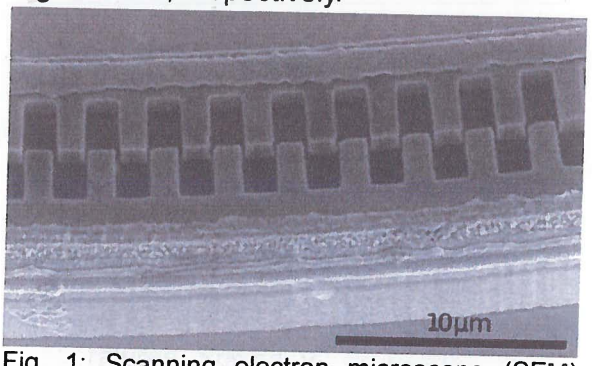

Fig. 1: Scanning electron microscope (SEM) image of a ring QCL with a dual grating forming a continuous π-phase shift grating. [2]

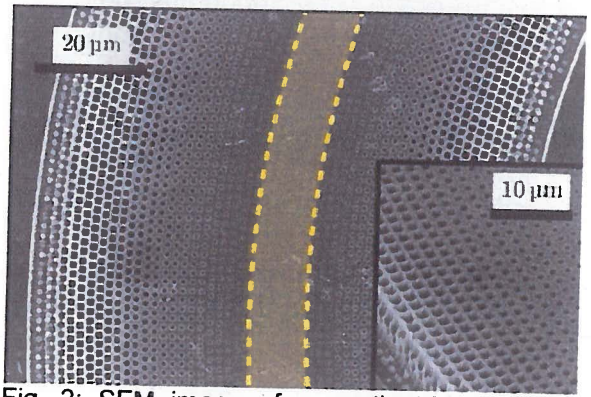

Fig. 2: SEM image of a gradient-index meta-material fabricated on the substrate side of a ring QCL for on-chip light collimation. [3]

In the last years, these lasers have proven to be mature and reliable light sources, suitable for spectroscopic applications. In combination with bi-functional quantum cascade hetero-structures [4], ring QCLDs are utilized for compact on-chip gas sensor systems [5,6] as shown in Fig. 3.

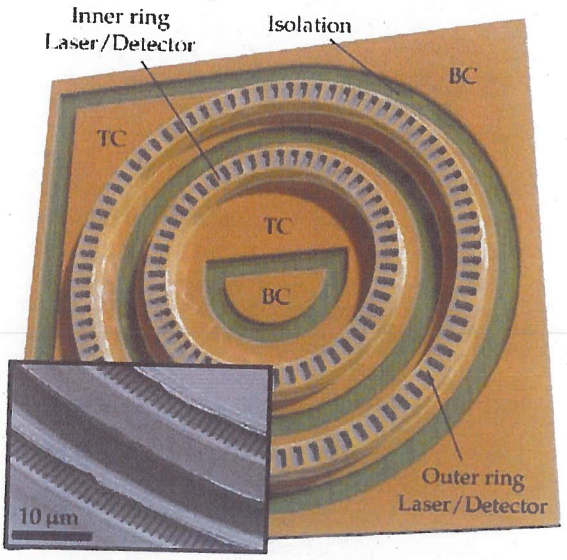

Fig. 3: Sketch and SEM image (inset) of an on-chip ring QCLD gas sensing system. [6]

This sensor concept combines surface-emitting and –detecting elements on a single-chip and paves the way for compact hand-held quantum cascade gas sensors.

[1] E. Mujagic et al., Appl. Phys. Lett. **93**, 011108 (2008).
[2] R. Szedlak et al., Sci. Rep. **5**, 16668 (2015).
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[5] A. Harrer et al., Sci. Rep. **6**, 21795 (2016).
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