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# Field-enhancing tapered planarized waveguides for THz quantum cascade laser frequency combs

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**Abstract.** We present a new planarized waveguide geometry for THz quantum cascade laser frequency combs with improved waveguide losses, RF and thermal dissipation properties. Ridge devices display broadband free-running comb states, and the THz emission can be further broadened by RF injection. Tapered waveguide devices feature a strong field-enhancement effect, which results in an improved comb performance. This includes free-running comb states with strong single beatnotes up to nearly -30 dBm at 90 K, almost three orders of magnitude stronger than for ridge devices. Improved comb operation is maintained also for high operating temperatures, up to 115 K.

## 1 Introduction

Terahertz (THz) quantum cascade lasers (QCLs) [1] are compact sources of broadband THz radiation, appealing for spectroscopy and sensing applications due to their operation as frequency combs [2] and dual combs [3]. The double metal waveguide is one of the most commonly used cavities for THz QCLs, as it features low losses and near-unity overlap of the fundamental mode with the active material, which is sandwiched between two metallic plates. It also acts as a microwave waveguide in the radio-frequency (RF) range, a property crucial for frequency combs, where an efficient guiding, readout and injection of RF signals is required.

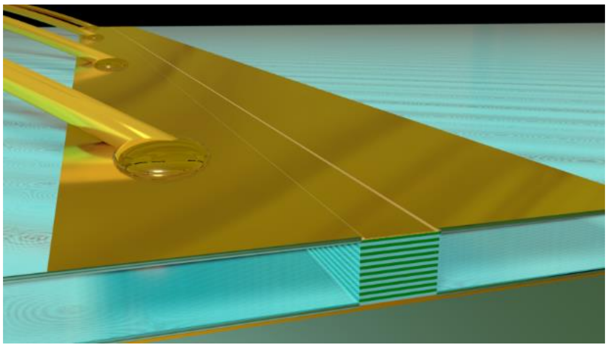

**Fig. 1.** Illustration of the planarized double metal waveguide geometry, where the active region waveguide (ridge with stripes) is embedded in a low-loss BCB polymer (on the sides). The bonding wires are placed on the extended top contact over the BCB-covered area, which improves the waveguide properties.

## 2 Results

### 2.1. Fabricated devices

We present an improved waveguide geometry: the planarized waveguide. After a standard double metal waveguide process with dry-etched active waveguides, the surrounding region is planarized with BCB, a low-loss polymer [4, 5]. This enables the fabrication of a wider top metallization, extending beyond the width of the active waveguide, and placing wire bonds above the BCB-covered area, as shown in Fig. 1. The latter prevents the formation of any defects or hotspots forming on top of the waveguide, which would degrade the device performance. Additionally, the active waveguide can now be narrower than the wire bond, which improves the heat dissipation properties and enhances high-temperature performance in continuous wave (CW).

The narrow waveguide dimensions can act also as a selection mechanism for lasing in the fundamental transversal mode for a stable comb operation. The extended top contact enhances the RF properties, as it forms an enclosed metallic cavity with the ground plane. Besides ridge waveguides, we also fabricated waveguides with a tapered profile, similar as demonstrated previously for mid-IR QCLs [6]. While the narrow waveguide sections act as a transversal mode filter, the wider sections have lower losses and provide more gain. Another crucial aspect is a strong field-enhancement effect in the narrower sections, which is roughly proportional to the width ratio. Consequently, four wave mixing, which is the fundamental frequency comb formation mechanism in QCLs, is greatly enhanced as it is a third order nonlinear

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process, proportional to the cube of the field intensity inside the active material.

### 2.2 Measurement results

We first present results on simple ridge devices with a cleaved facet, as shown in Fig. 2.(a). The waveguide is 40 µm wide, which is a good balance between low waveguide losses and fundamental transversal lasing mode selection. Due to the use of low-loss Cu-Cu planarized waveguides and a low-dissipation broadband active region [7], the LIV measurements in Fig. 2.(b) display a low threshold current density of 140 A/cm^2. The peak ouput power is around 3 mW in pulsed and CW operation at a heatsink temperature of 40 K. When measuring the output spectrum, free-running comb states with bandwidths above 600 GHz and single beatnotes up to nearly -60 dBm are found, as shown in Fig. 2.(c). With a strong RF injection (+35 dBm at the source), the emission can be broadened to over 1.4 THz, as shown in Fig. 2.(d) (these are typically not frequency comb states).

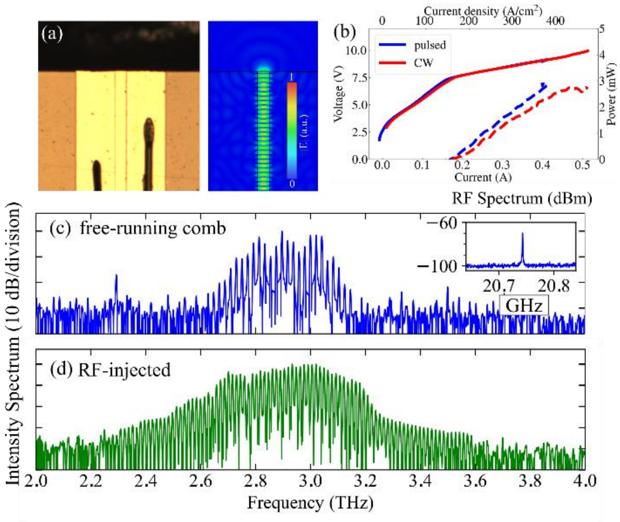


**Fig. 2.** (a) Microscope image of a ridge waveguide device. The cleaved facets act as mirrors, and standing waves form in the cavity, as shown on the right image with the E-field profile from a 3D numerical simulation of the propagating fundamental waveguide mode. (b) LIV curves of a 40 µm wide and 2.7 mm long device with a low threshold current density of around 140 A/cm$^2$ and peak powers around 3 mW at a heatsink temperature of 40 K. (c) Spectral measurement of a free-running device in a frequency comb state with a bandwidth over 600 GHz and a single RF beatnote (inset). (d) Injecting with a strong external RF signal (+35 dBm at source) close to the natural roundtrip freqeuncy broadens the THz emission to span over 1.4 THz.

Next, we present results on the tapered waveguides. Free-running devices produce very strong single beatnotes, measured up to nearly -30 dBm, as can be seen in Fig. 3.(a). This nearly three orders of magnitude stronger RF signal comes from the significant field enhancement in the narrow waveguide sections. The improved comb properties are observed also for high operating temperatures (Fig.3.(b)). While ridge devices are typically in a single mode regime close to the maximum operating temperature, for tapered devices we observe comb operation up to a heatsink temperature of 115 K, very close to the maximum CW lasing temperature of 118 K.

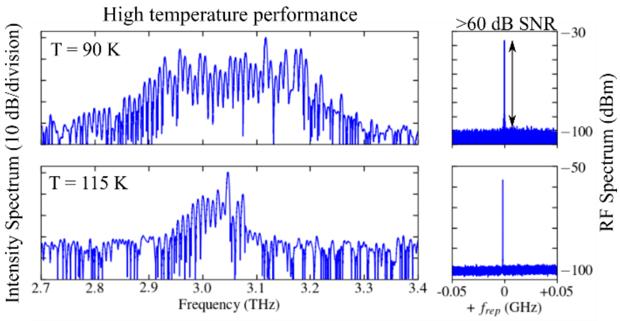


**Fig. 3.** (a) Free-running tapered waveguide devices produce very strong beatnotes, measured up to nearly -30 dBm at 90 K. (b) The improved frequency comb performance is maintained also for high temperatures, with a bandwidth of 200 GHz and a single beatnote measured above -60 dBm at a heatsink temperature of 115 K.

## 3 Conclusion

We have presented an improved planarized waveguide geometry for THz QCL frequency combs. The planarization with a low-loss BCB polymer and the extended top metallization result in improved waveguide losses, RF and heat dissipation properties. Ridge devices display broadband free-running comb states, with the THz emission broadened further with an external RF signal.

Tapered devices show three orders of magnitude stronger RF beatnotes and high temperature comb operation due to a strong field enhancement effect. The planarized waveguide platform will also enable a relatively straightforward co-integration of active and passive waveguide elements on the same chip.

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