Interband Cascade Laser Frequency Combs

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ABSTRACT

We discuss progress in improving electrically-pumped mid-infrared frequency combs based on interband cascade lasers (ICLs) for enhanced spectral coverage and tunability. We exploit the ICL's intracavity second order nonlinearity to upconvert the fundamental mid-infrared comb from ~3.6 μm to the near-infrared region around 1.8 μm with a nonlinear conversion efficiency exceeding 3 μW/W^2. To further extend the wavelength portfolio of ICL combs, we develop devices operating in the 3.25 μm region targeting important volatile organic compounds. Through injection locking, we obtain full free-spectral-range current tuning with minimal changes in the modal structure for gapless frequency comb spectroscopy.

INTRODUCTION

Greatly desired for many applications is a compact source of mid-infrared coherent light with a frequency comb spectral structure. An obvious response to this demand relies on semiconductor chip-scale semiconductor lasers with the most widespread example of the quantum cascade laser (QCL) (Hugi et al., 2012), albeit in recent years two novel platforms have emerged, namely the interband cascade laser (ICL) (Bagheri et al., 2018), and type-I quantum well cascade diode laser (Feng et al., 2018). Their key advantage is self-starting electrically-pumped mid-infrared comb generation without relying on externally provided pump lasers. While above 4.5 μm of wavelength QCL combs dominate, in the shorter wavelength region ICL combs offer sufficiently low intracavity dispersion accompanied by an order of magnitude decrease in electrical power consumption to operate as broadband comb sources with sub-kilohertz electrical repetition rate beat notes at room temperature. The excellent modal phase coherence makes them a perfect source for high-sensitivity free-running dual-comb spectroscopy in the 3-4 μm band, as demonstrated on selected molecular targets: methane, and hydrogen chloride (Sterczewski et al., 2019). Nevertheless, the full potential of these highly miniaturized sources (see Fig. 1a) has not been exploited to date. In particular, improvements of the tuning range in a frequency comb regime, spectral coverage, and modal structure stability are of paramount importance for their use in future terrestrial and space applications.

RESULTS

In order to improve the spectral coverage, we exploit intracavity nonlinearities in the ICL (Sterczewski et al., 2019). Fig. 1b,c plots the simultaneously measured emission in the mid-IR around 3.6 μm, and in the near-IR around 1.8 μm obtained due to an intracavity $\chi^{(2)}$ process resulting in sum-frequency and second-harmonic generation.

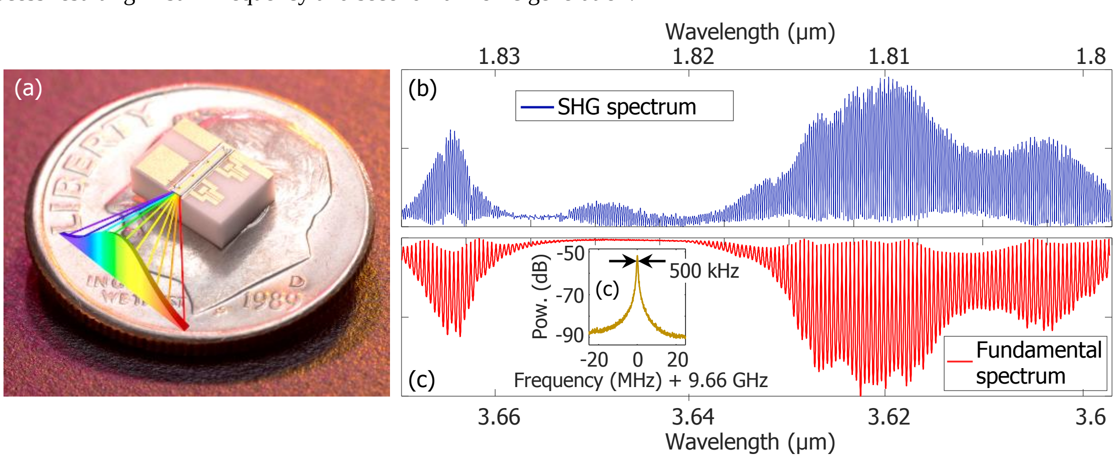

Fig. 1. (a) Photography of an ICL comb mounted on a beryllium oxide submount. The laser cavity is 4 mm long. (b),(c) Dual-band frequency comb operation enabled by the device's second order nonlinearity. The appearance of new spectral features around 1.82 μm, which cannot be created solely by SHG, is an indication of sum-frequency generation between the two dominant spectral lobes in the mid-infrared separated by ~40 nm. Inset shows the intermode (repetition rate) beat note with a sub-MHz linewidth.

The characterized 4 mm long device with a 3.5 μm wide ridge waveguide emits ~10 mW of mid-IR optical power at at 13°C, which is upconverted to 320 pW of near-IR power. Dips in the second harmonic (SHG) spectrum are caused by water vapor absorption, which prove the real nature of the measured signal. Future optimization of the device for improvement in phase matching and intracavity absorption should increase the nonlinear conversion efficiency and hence the obtainable near-IR power.

From an application standpoint, of particular interest is the 3.2 μm spectral region, where methane and many other hydrocarbons have their strongest absorption features. To address this need, we have developed an ICL comb with a repetition rate of ~9.6 GHz emitting ~5 mW of optical power at ~0.6 W of electrical power consumption. Through injection locking of a short absorber section of the cavity, we enable tuning over a full free spectral range without significant changes in the modal structure, as visible in Fig. 2(a) and (b). The amount of microwave power used for repetition rate stabilization was only 0 dBm (1 mW), yet it was sufficient to lock the intermode beat note down to a hertz level, as detected optically (inset of Fig. 2a).

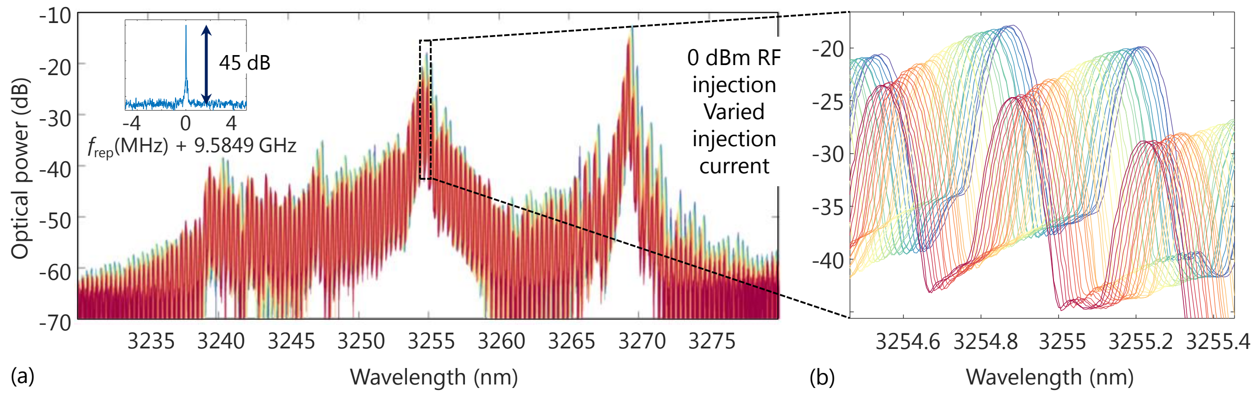

Fig. 2. (a) Optical spectra of an ICL comb operating around 3.25 μm targeting the C-H stretch spectral band. Inset shows an optically detected intermode (repetition rate) beat note with a hertz linewidth under radio frequency injection locking conditions (0 dBm of power). This level of power enables injection current tuning over a full free spectral range without changes in the mode structure. (b) Zoom around 3.255 μm showing only slight changes in the modal amplitudes.

CONCLUSIONS

In summary, we have demonstrated a second order nonlinear process in an interband cascade laser frequency comb leading to simultaneous light emission in two spectral bands: the mid- and near-infrared. We also show that active injection locking with moderate levels of microwave power is sufficient to enable gapless current tuning of novel ICL comb devices operating at ~3.25 μm. This ability plays a key role for measuring species like methane with atmospheric pressure absorption lines typically narrower than the current comb tooth spacing.

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