Lateral far-field characteristics of interband cascade laser frequency combs

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Abstract – The far-field characteristics of mid-infrared interband cascade laser frequency combs with different ridge widths are studied. We find that narrow-ridge devices that suffer from pronounced modal leakage exhibit anomalous deterioration of the vertical far-field profile, with periodically-occurring fringes.

I. Introduction

Interband cascade lasers (ICLs) have emerged as unique chip-scale mid-infrared sources for optical frequency combs (OFCs) that emit in the 3–4 µm wavelength region with sub-watt room-temperature power consumption [1]–[3]. They have already shown excellent suitability for broadband and high-resolution molecular spectroscopy. Moreover, the same ICL structure can serve as a fast, room-temperature photodetector with GHz bandwidth, which provides all-room-temperature dual-comb spectroscopy [4] and paves the way for fully-integrated on-chip sensors with source and detector defined photolithographically on the same chip [5]. However, current ICL OFCs operate with limited optical bandwidths accompanied by uneven spectral envelopes. Furthermore, at higher injection currents they often suffer from quasiperiodic mode grouping, which is potentially attributable to a mode leakage phenomenon that plagues a variety of semiconductor laser platforms [6], [7]. Because the ICL's modal index is lower than the refractive index of the GaSb substrate, the lasing mode can leak through an insufficiently-thick clad layer into the high-index substrate, and reflect from the bottom contact. This leads to multiple interference effects, such as modulation of the gain spectrum and rapid oscillation of the group velocity dispersion. Here we show that mode leakage can also severely degrade the far-field characteristics of an ICL comb.

II. Results

Figure 1 shows the far-field intensity profiles and emission spectra for a typical 4.6-µm-wide Fabry-Pérot ICL ridge biased below (top) and above (bottom) threshold. The far-field characteristics were measured using a custom 2-axis rotation stage assembly with a nitrogen-cooled MCT photodetector mounted on a 20-cm-long arm.

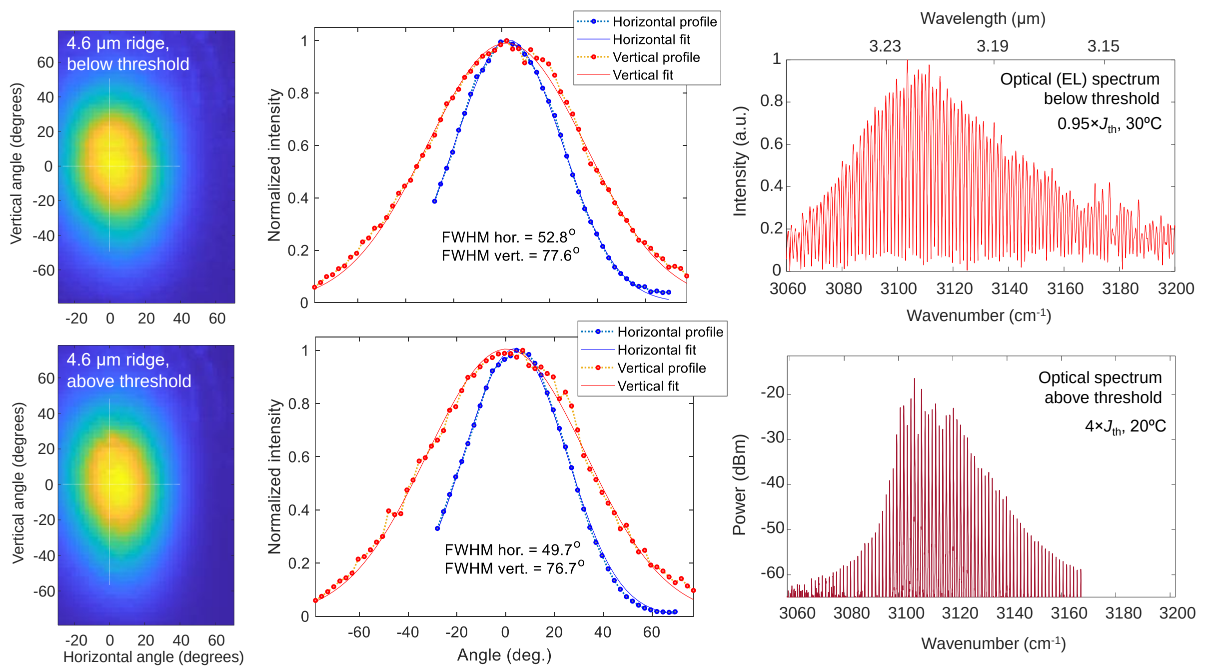

Fig. 1. Full far-field profiles (left), horizontal and vertical beam cross-sections (center), and emission spectra (right), for a 4.6- µm-wide ridge measured below (top row), and above (bottom row) threshold. The optical spectra were measured by a Fourier transform spectrometer (FTIR), and the horizontal angle is limited on the negative side due to mechanical constraints of the stage assembly.

Lock-in power detection ensured a high signal-to-noise ratio for the angle-resolved measurement. Overall, smooth Gaussian-like far-field profiles are observed both below and above threshold, with divergence angles approximately 51° and 77° for the slow and fast axes, respectively. The electroluminescence (EL) spectrum is seen to remain single-lobed, just like the optical spectrum above threshold.

However, the spectra and far-field characteristics change dramatically when a narrower sister device with ridge width 3.6 µm is measured (Fig. 2). First, horizontal ripples appear in the below-threshold far-field image, and become even more pronounced in the above-threshold scan. The inset in the bottom row shows a higher-resolution (sub-degree) scan of the central region. We find that whereas the horizontal profile (parallel to the epitaxial layers) is relatively smooth, the central part of the vertical profile (perpendicular to the epitaxial layers) oscillates rapidly with 2° period. This is most likely an interference effect related to the modal leakage phenomenon, which clearly induces spectral modulation and mode grouping in the EL and lasing spectra. It is unlikely that fringing effects due to Fresnel reflections at optical interfaces of the photodetector are responsible, since more than a dozen devices were tested in the same setup and many had perfectly smooth far-field profiles.

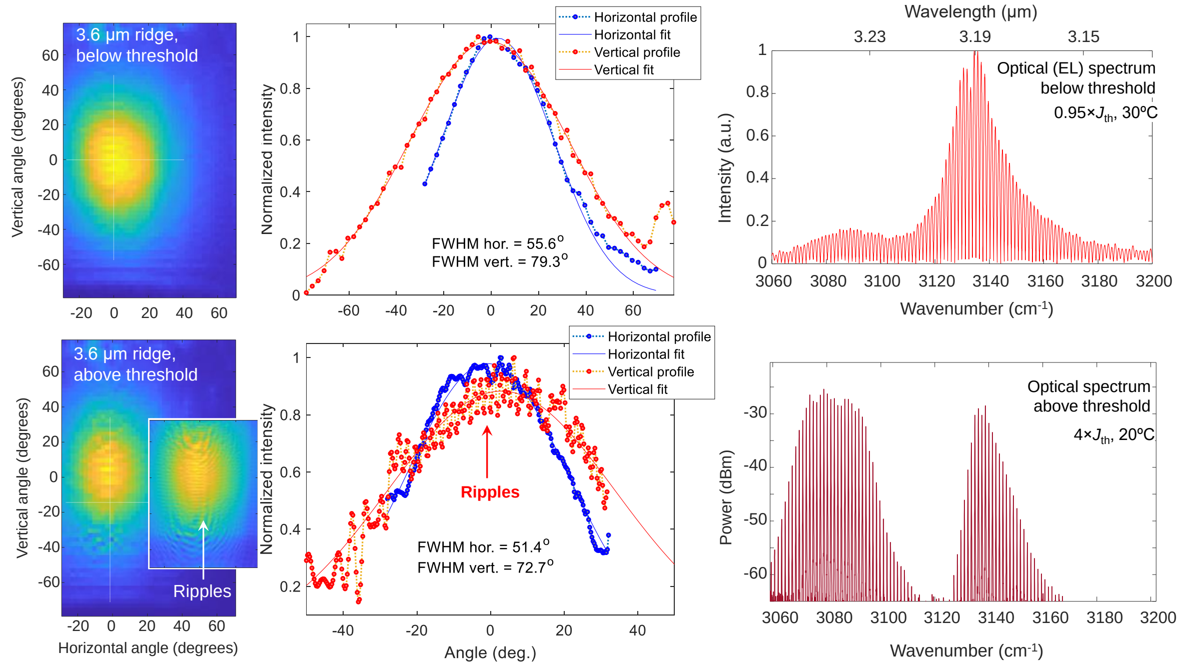

Fig. 2. Full far-field profiles (left), horizontal and vertical beam cross-sections (center), and emission spectra (right) for a 3.6-µm-wide ridge measured below (top row), and above (bottom row) threshold.

It should also be noted that higher-order lateral modes, which could provide a plausible alternative explanation for the poor beam characteristics and spectral splitting in general, become noticeable in the far-field profiles and optical spectra only at ridge widths > 6 µm, and only at extreme injection currents (> 8×J_{th}) [7]. They manifest as nulls around the beam center and additional lines in the optical spectrum, which are not observed for the narrowest-ridge device reported here. On the other hand, a narrow waveguide pushes the optical mode toward the substrate [7], which exacerbates the modal leakage phenomenon and explains the differences between Figs. 1 and 2. Furthermore, an even narrower ridge with width 2.5 µm exhibited even greater distortion of the beam profiles along with anomalies in the *L-I-V* characteristics. While modal leakage effects appear to qualitatively explain the observed far-field profiles and spectra, the origin and period of the regularly-spaced fringes appearing in Fig. 2 should be investigated further.

III. References

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