Quantum Well Laser Diode Frequency Comb in the 2 μm Region

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Abstract: We present the first semiconductor laser frequency comb in the 2 μm region. The source relies of an inherent gain nonlinearity in a quantum well laser diode, which promotes frequency-modulated operation with sub-THz spectral coverage.

1. Introduction

The growing demand for data capacity drives the research effort to open new spectral windows beyond the well-established 1.55 μm for telecommunications. Progress in the development of rare-earth-doped fibers using thulium [1] and holmium [2] ions accompanied by improvements in modulator [3] and photodetector [4] technology suggests that the 2 μm region slowly reaches technological maturity to address this need. For wavelength-division-multiplexing (WDM) widely used in telecommunications, greatly desired is a miniaturized solid state source of equidistantly spaced optical lines. Here, we present such a broadband coherent frequency comb source operating around 2.06 μm of wavelength based on chip-scale Fabry-Pérot quantum well laser diodes.

2. Frequency comb characterization

The lasers with a 2.06 μm center wavelength were grown on an *n*-GaSb substrate following the design and growth procedures in Ref. [5]. After cleaving to 2 mm of length, the front and rear facets of Fabry-Pérot devices were coated with an anti-reflective (AR) and highly-reflective (HR) coating, respectively. Fig. 1a shows the light-current-voltage (*L-I-V*) characterization of a representative device, where 35 mW of optical power is collected from the AR coated facet at less than a watt of electrical pumping. Stable self-starting frequency comb generation with kilohertz intermode beat note linewidth occurs over a range of temperatures (10°C–25°C) and currents typically exceeding 250 mA. At higher injection currents, the optical spectrum takes a relatively uniform shape with a total spectral coverage of 20 nm (Fig. 1b) with most of the optical power concentrated within 10 nm. Despite the broad comb spectrum, the optically detected intermode beat note located at 19.37 GHz has an extremely narrow linewidth (1.5 kHz) even within 140 ms of acquisition time (Fig. 1c), which suggests a high level of phase coherence. However, the observation of a narrow intermode beat note only is not sufficient to claim frequency comb operation. This is because even two optical lines are sufficient to produce a strong microwave beat signal while the rest may be incoherent. To fully assess the degree of line-to-line coherence, we employed a linear phase-sensitive autocorrelation technique known as Shifted Wave Fourier Transform Spectroscopy (SWIFTS) [6]. Using a high-bandwidth lock-in amplifier and a Fourier transform spectrometer (FTIR), we recorded a normal (DC) interferogram along with quadrature components (X/Y) of the interferometrically-modulated intermode beat note at 19.37 GHz.

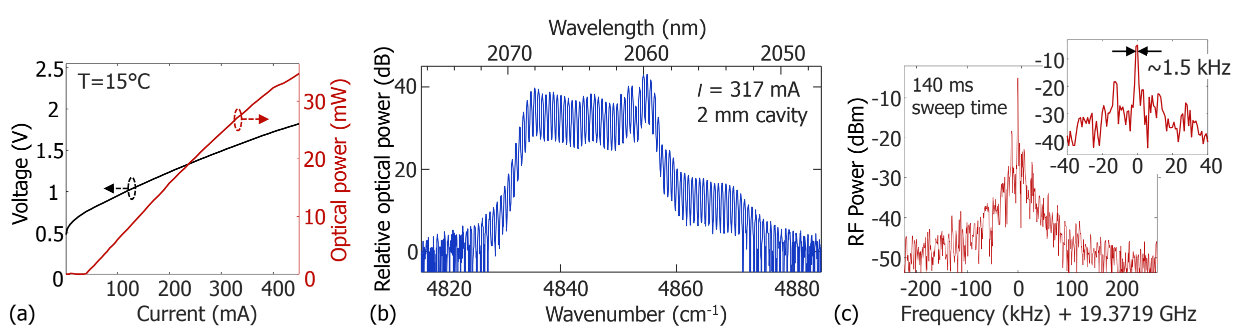

Fig. 1. Device characterization. (a) Light-current-voltage characteristics. Frequency comb generation occurs between 250 mA and the maximum current (450 mA) with more than 35 mW of optical power. (b) Example optical spectrum in a frequency comb regime. (c) The corresponding microwave internode beat note 3 dB linewidth is ~1.5 kHz.

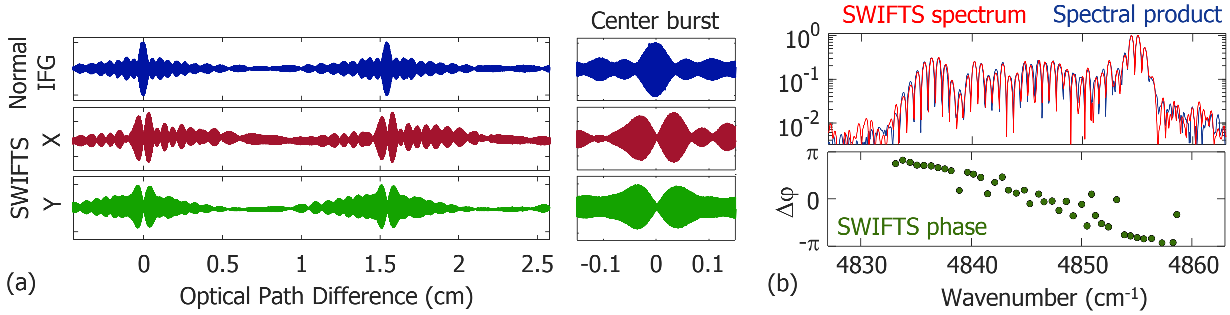

Fig. 2. Shifted Wave Fourier Transform Spectroscopy (SWIFTS) analysis. (a) Normal (DC) interferogram (IFG) recorded along with the in-phase (X) and in-quadrature (Y) components of the interferometrically modulated intermode beat note signal at 19.37 GHz. The minimum of the SWIFTS traces indicates a strongly frequency modulated (FM) continuous wave output. (b) Spectral analysis of data in (a). The comb spectrum covers ~25 cm^{-1} (750 GHz/10.6 nm) and exhibits a linear phase difference ($\Delta\varphi$) between neighboring comb teeth. The SWIFTS phases cover a range of -π to π, as expected for chirped FM combs suppressing amplitude modulation (AM).

The results of the SWIFTS analysis are plotted in Fig. 2. Around the zero path difference (ZPD) point where the normal interferogram has a maximum, the microwave interferograms (X and Y) exhibit a minimum. This feature is characteristic of frequency-modulated (FM) combs [7], and indicates that amplitude modulation is heavily suppressed thus favoring continuous wave (CW) operation. This additionally finds confirmation in the intermodal phase difference analysis (Fig. 2b), where the mode-to-mode phase difference $\Delta\varphi$ is approximately linear. Therefore, we expect that the emitted waveform is strongly chirped and no pulses are generated. Good agreement between the SWIFTS spectrum and the spectral product calculated from the normal interferogram [6] proves that all lines contribute to the narrow intermode beat note.

3. Conclusion

In conclusion, we have demonstrated the first semiconductor laser frequency comb operating in the important 2 μm region with excellent suitability for telecom, and spectroscopic sensing applications. The source requires ~500 mW of electrical power to develop a sub-THz-wide spectrum with 19.37 GHz repetition rate and kilohertz intermode beat note linewidths. The optical power in bias conditions favoring a moderately flat comb generation exceeds 25 mW, which yields more than 0.5 mW of power per one of the dominant 40 comb lines. Compatibility of the source's wavelengths with thulium and holmium doped fibers enables further power amplification and enhancement of the optical coverage through nonlinear spectral broadening.

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