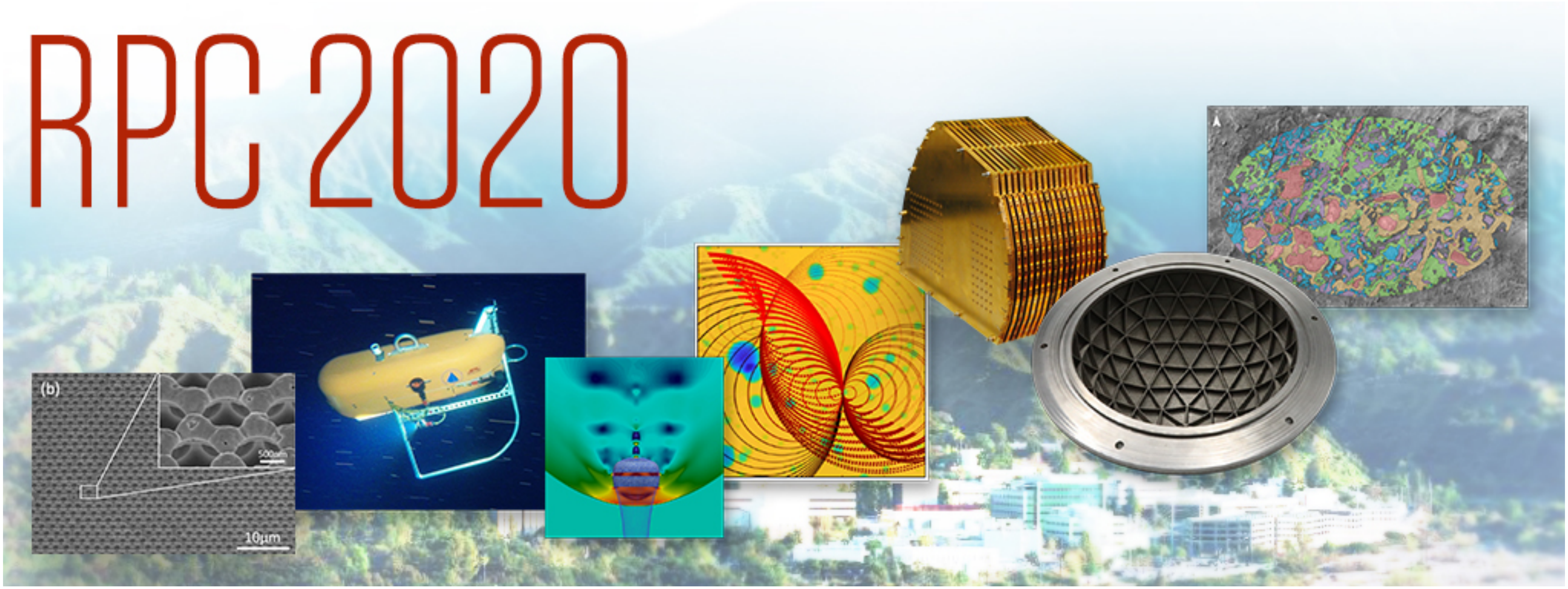

Virtual Research Presentation Conference

Optical pulses from 2 µm quantum well laser diodes

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Program: Spontaneous Concept

Assigned Presentation RPC-203

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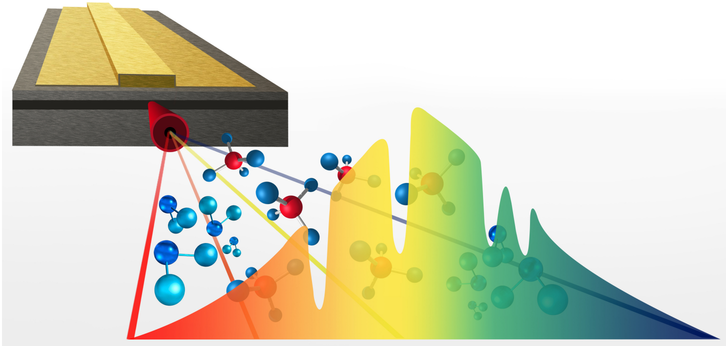
Tutorial Introduction

Optical frequency combs (OFCs) have revolutionized the field of metrology by enabling measurement of optical frequencies with unprecedented precision [1]. An OFC consists of a set of equidistant mutually coherent modes, and has predominantly been generated by mode-locked lasers.



Chip-scale electrically pumped OFCs are expected to play a fundamental role in applications ranging from telecommunications to optical sensing. To date, however, the availability of such sources around 2 μm has been scarce. In this work, a frequency modulated (FM) OFC operating around 2060 nm of wavelength exploiting the inherent gain nonlinearity of single-section GaSb-based quantum well diode lasers is presented. A 2 mm long device operating as a self starting comb outputs 50 mW of optical power over more than 20 nm of bandwidth while consuming <1 W of electrical power. Using the Shifted Wave Interference Fourier Transform Spectroscopy (SWIFTS) technique [2], the generated frequency-modulated waveform is analyzed, a linearly chirped intermodal phase relationship among the entire emission optical bandwidth is demonstrated. Furthermore, by compensating for the linear chirp, 6 ps-long optical pulses are generated. The frequency stability of the devices with 19.3 GHz repetition rates allows us to perform mode-resolved free-running dual-comb spectroscopy.

Problem Description

a) The 2 µm region is of large interest for the next-generation telecommunication systems, eye-safe light detection, and molecular spectroscopy, in particular for monitoring global emissions of carbon dioxide.

2 µm combs can enable spectrally-efficient orthogonal-frequency division multiplexing (OFDM) in optical interconnects to be implemented in a new spectral window.

In sensing applications they would allow measurement of broadband and high-resolution spectra on extremely short time scales using the dual-comb technique.

b) State-of-the-art

Our frequency modulated (FM) combs generate more than 10 times more power than state-of-the-art passively mode-locked counterparts at the same spectral window

Our FM combs has narrower 10-100 times narrower linewidth than the passively-mode-locked counterparts which suits them better for free-running spectroscopy applications

c) Relevance to NASA and JPL (Impact on current or future programs)

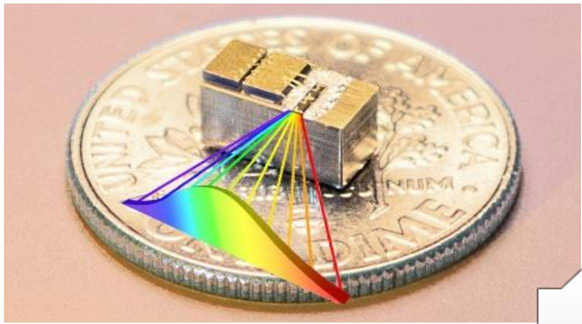
a) This makes QWDLs promising candidates for low-drive-power sensors of environmentally important molecular species like carbon dioxide or ammonia in the 2 um region.

b) The high power per tooth yields a high average spectroscopic signal-to-noise. This permits measurement over much shorter time scales (even microseconds), which is well suited for studying reaction kinetics.

Methodology

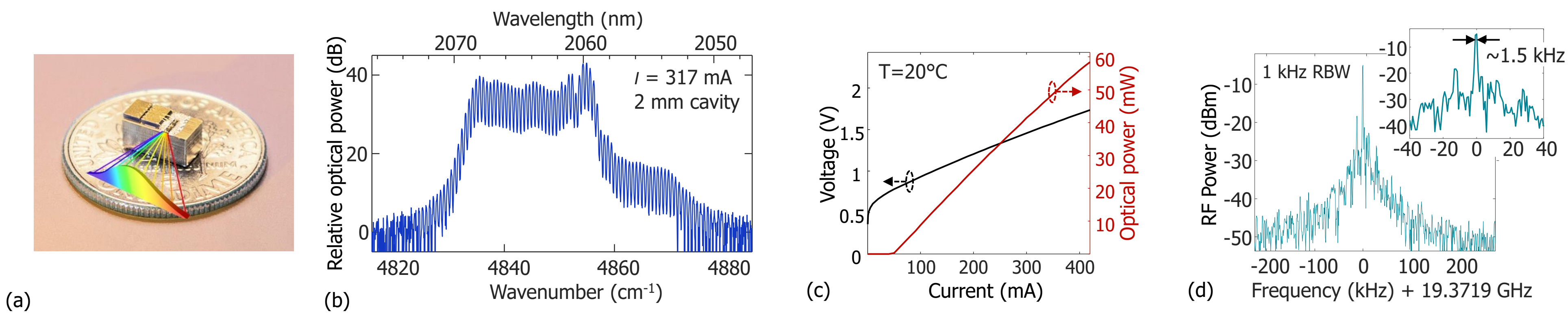
a) QWDL devices based on a monolithic single-section Fabry-Pérot cavity design

a) emitting a frequency-modulated THz-spanning OFC
b) 50 mW of optical power centered around 2060 nm
c) less than 1 W of electrical power consumption at room temperature.
d) 10 times more average optical power than the previously demonstrated mode-locked 2 μm QWDL devices [3]



Results

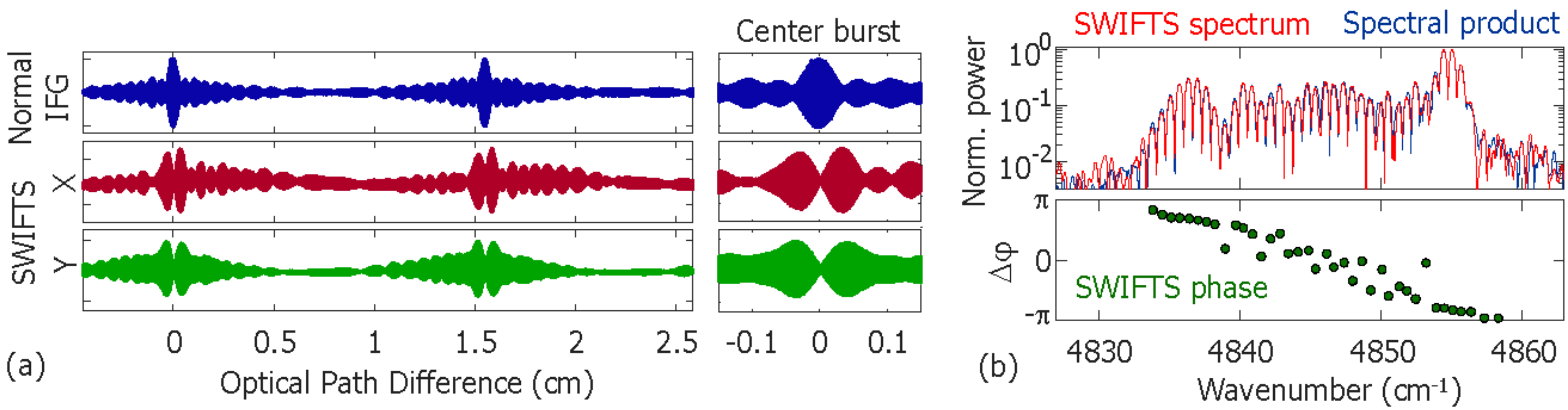
(a) Photo of a QWDL comb on (b) Optical spectrum (c) P-I-V characterization of the device at room temperature (d) Electrical intermode beat note spectrum



Combs demonstrate broad optical spectrum (> 20nm) with low intermode beat node phase noise

Results

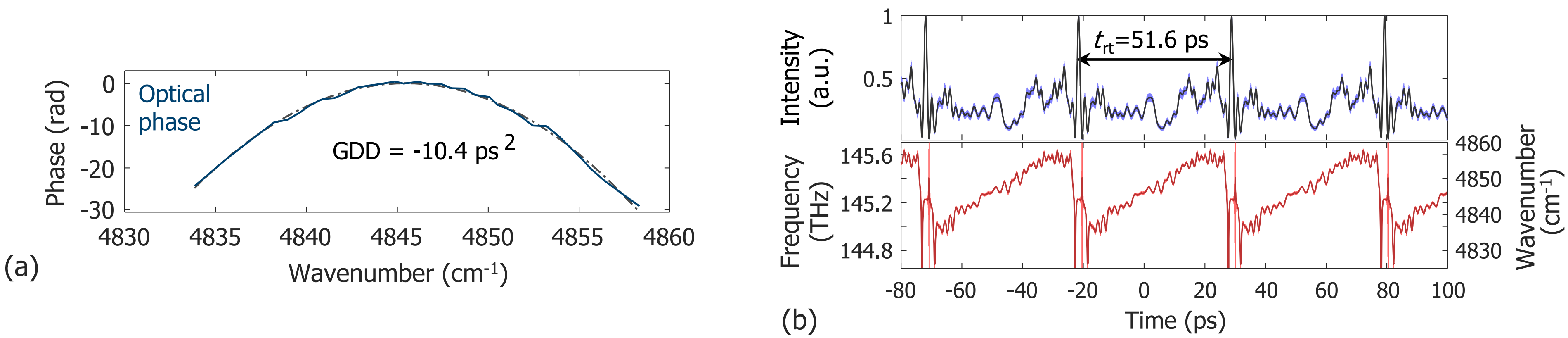
SWIFTS interferograms (a) along with the corresponding amplitude and phase spectra.



A characteristic minimum around the zero-path-difference (ZPD) point visible in the SWIFTs traces confirms the FM character. Additionally, the phase difference between neighboring lines varies almost linearly from π to - π as expected for a maximally chirped comb state

Results

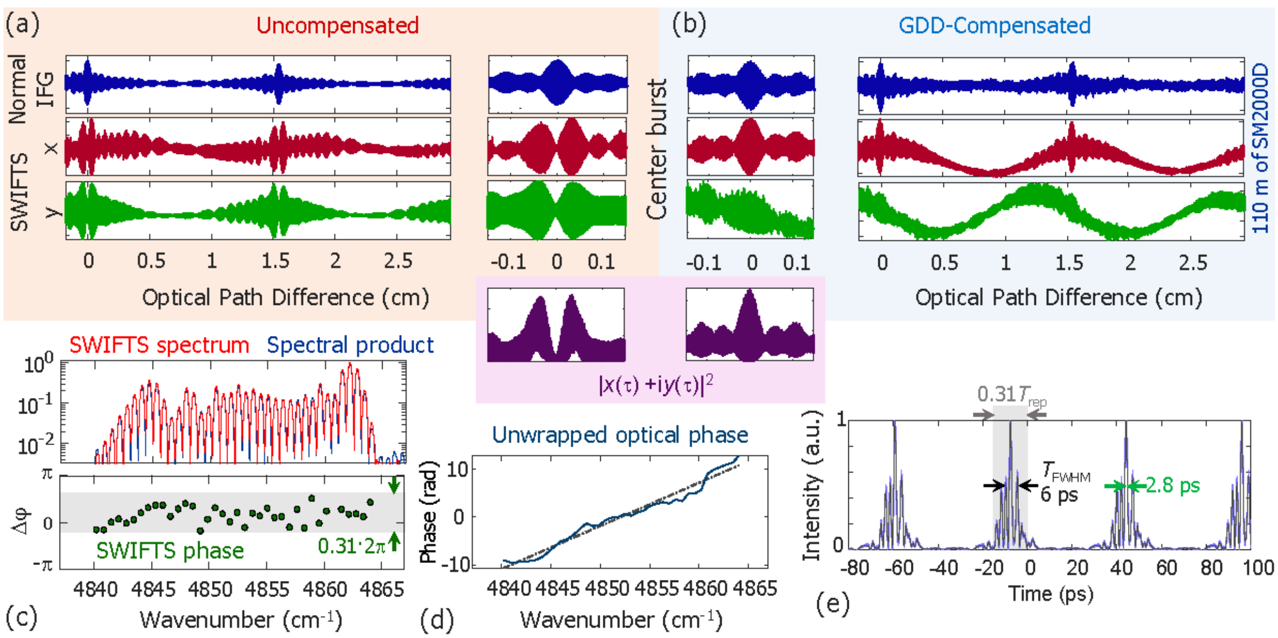
Optical phase with an arbitrary global offset obtained. (b) Calculated instantaneous intensity and frequency based on the modal intensities and phases.



- A linear modal phase difference corresponds to a second order dispersion. A least-squares fit to the parabolic phase yields a field GDD of –10.4 ps^2
- A quasi-continuous wave output periodic with the repetition frequency has a strong amplitude modulation component with pronounced spikes of intensity when the laser changes the direction of its frequency sweep.

Results

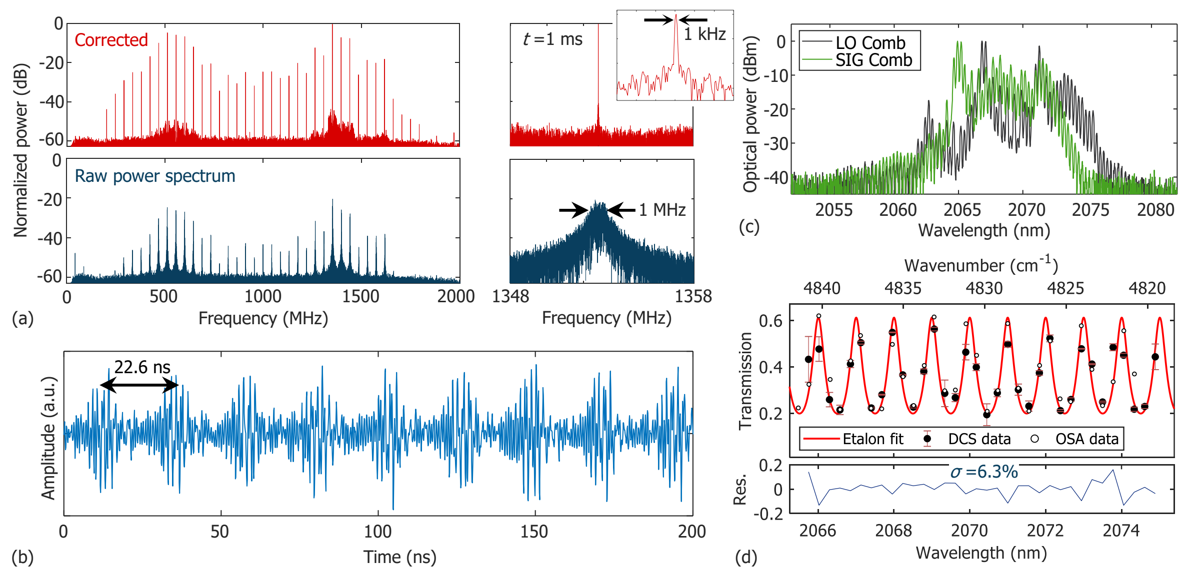
Chirp compensation using a dispersion-tailored single mode fiber. (a) Normal and SWIFTS IFGs of the device operating. (b) Device in the same comb state measured GVD compensation



Around ZPD, the rf beat note IFG has a sharp peak indicating strong amplitude modulation.

Results

Free-running Dual Comb Spectroscopy using a pair of QWDLs.



Retrieved DCS transmission spectrum along with a low-finesse GaSb etalon fit. An independent transmission measurement using an optical spectrum analyzer (OSA) is plotted for comparison.

Results

a) Quantum well diode laser optical frequency combs operating in the 2 μm region with more than 1 mW per comb tooth.

  a) Optical frequency comb generation is using self-starting frequency modulation (FM).

  b) The stability of the 19.37 GHz repetition rate is excellent lies in the near-kilohertz range over 40 ms,

  c) The stability was be further improved down to a sub-hertz level using a fast optical phase locked loop (OPLL).

  d) Interferometric characterization of the devices revealed a strongly-chirped waveform with a GDD on the order of -10 ps^2

  e) GDD was compensated externally to generate 6 ps long optical pulses limited by the high order dispersion

  f) A pair of devices was used to demonstrate proof-of-concept free-running dual-comb spectroscopy of a low finesse Fabry-Pérot etalon.

b) Significance

  a) We have demonstrated the feasibility of a dual frequency comb spectroscopy experiment by multiheterodyning two QWLD combs on a fast InGaAs detector.

  b) This makes QWDLs promising candidates for low-drive-power sensors of environmentally important molecular species like carbon dioxide or ammonia in the 2 um region.

  c) The high power per tooth yields a high average spectroscopic signal-to-noise. This permits measurement over much shorter time scales (even microseconds), which is well suited for studying reaction kinetics.

c) Next steps

  a) Passive mode-locking of these dev ices was envisioned but were not demonstrated

Publications and References

PUBLICATIONS

[A] Lukasz A. Sterczewski , Clifford Frez, Siamak Forouhar, David Burghoff , and Mahmood Bagheri , “Frequency-modulated diode laser frequency combs at 2 m wavelength,” APL Photonics 5, 076111 (2020); https://doi.org/10.1063/5.0009761.

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[2] D. Burghoff, Y. Yang, D. J. Hayton, J.-R. Gao, J. L. Reno, and Q. Hu, “Evaluating the coherence and time-domain profile of quantum cascade laser frequency combs,” Optics Express 23, 1190–1202 (2015)

[3] S. Becker, J. Scheuermann, R. Weih, K. Rößner, C. Kistner, J. Koeth, J. Hillbrand, B. Schwarz, and M. Kamp, “Picosecond pulses from a monolithic GaSb-based passive mode-locked laser,” Applied Physics Letters 116, 022102 (2020).