National Aeronautics and Space Administration

Compact, Low Power, Visible Band Frequency Combs for Extreme Precision Radial Velocity Measurements

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Program: FY22 R&TD Strategic Initiative

Strategic Focus Area: Precision Radial Velocity - **Strategic Initiative Leader:** Charles Lawrence

Objective

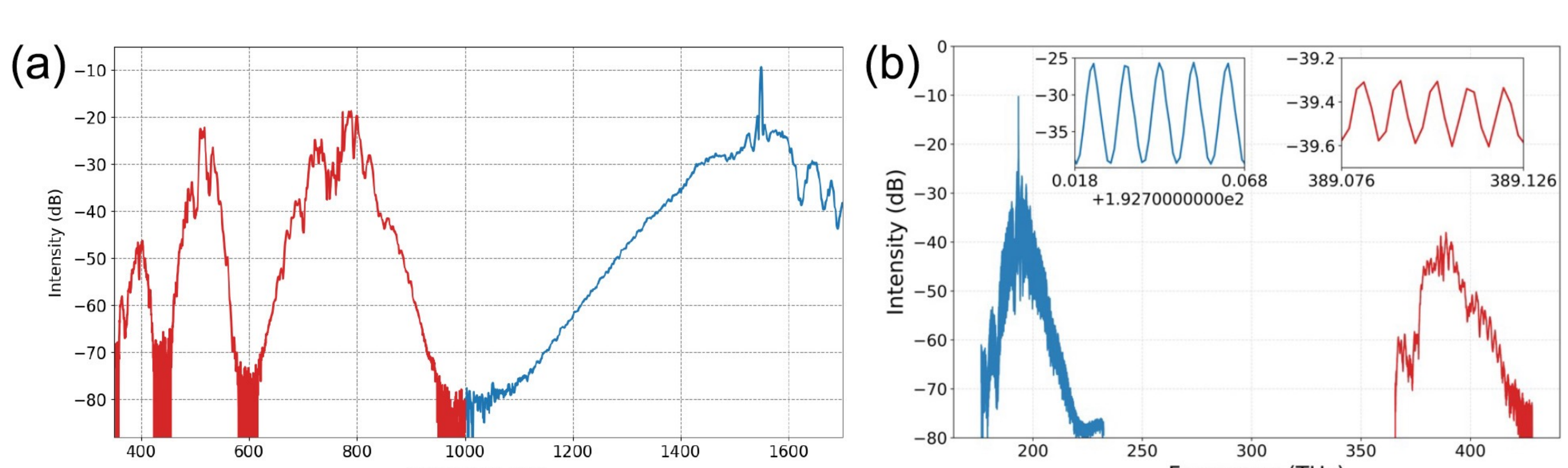
The objective of this task was to create a visible-band (400-800 nm), high repetition rate (10-20 GHz) frequency comb for precision radial velocity (PRV) spectrograph calibration. We achieved this goal through sum frequency generation and nonlinear spectral broadening of frequency combs in the near-infrared (NIR) by integrating them with waveguides exhibiting high second- and third-order nonlinearities. We developed waveguides based on thin-film lithium niobate-on-insulator (LNOI) with chirped periodic poling to achieve broad spectral coverage. Our approach enables a dramatic reduction in pulse power over that needed in state-of-the art NIR comb broadening technology based on silicon nitride, silicon oxide, and other materials that lack second-order nonlinearity. Ultimately, we achieved supercontinuum emission from 350 nm to more than 1 µm wavelength, with repetition rates from 100 MHz to 10 GHz. Combining our frequency-broadening waveguide with the robust, portable NIR electro-optic (EO) comb source used for 10-GHz pumping, we have a complete calibration system that can be deployed for future observatory operations.

Background

The NASA /NSF Extreme Precision Radial Velocity (EPRV) working group identified the development of robust, long-lived visible band spectrograph calibration sources as a critical technology in the search for habitable worlds. This Strategic R&TD effort combines expertise in the area of high-precision, high-accuracy frequency standards at JPL and among collaborators at University of Colorado and Caltech to create a visible-band laser frequency comb for EPRV spectrograph calibration starting in the NIR and progressing into visible wavelengths where most spectral content for solar-type stars is concentrated.

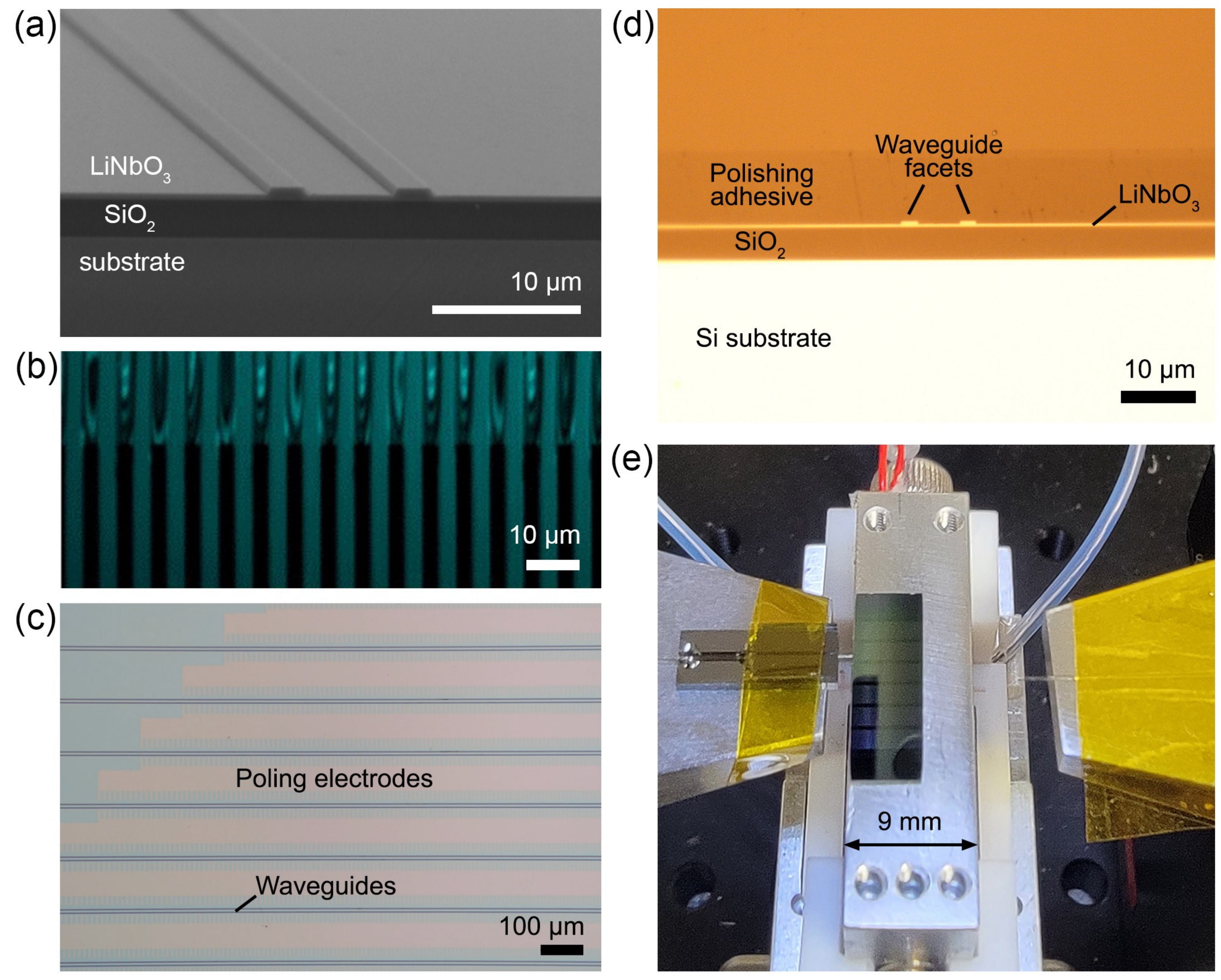
Significance and Benefits to NASA and JPL

- Detecting the 9 cm/s signature of an Earth-like planet orbiting a solar-analog requires precision and stability of ~1 cm/s over years
- Current solutions at visible wavelengths, are problematic in terms of output power, reliability, and resolution
- The technology demonstrated here is ready for implementation with visible EPRV spectrographs, such as NEID at Kitt Peak Observatory or the Keck Planet Finder at Keck Observatory in Hawaii
- This platform also has potential as a low-mass, low-power space-based solution for studying stellar activity through observations of the sun above Earth's atmosphere

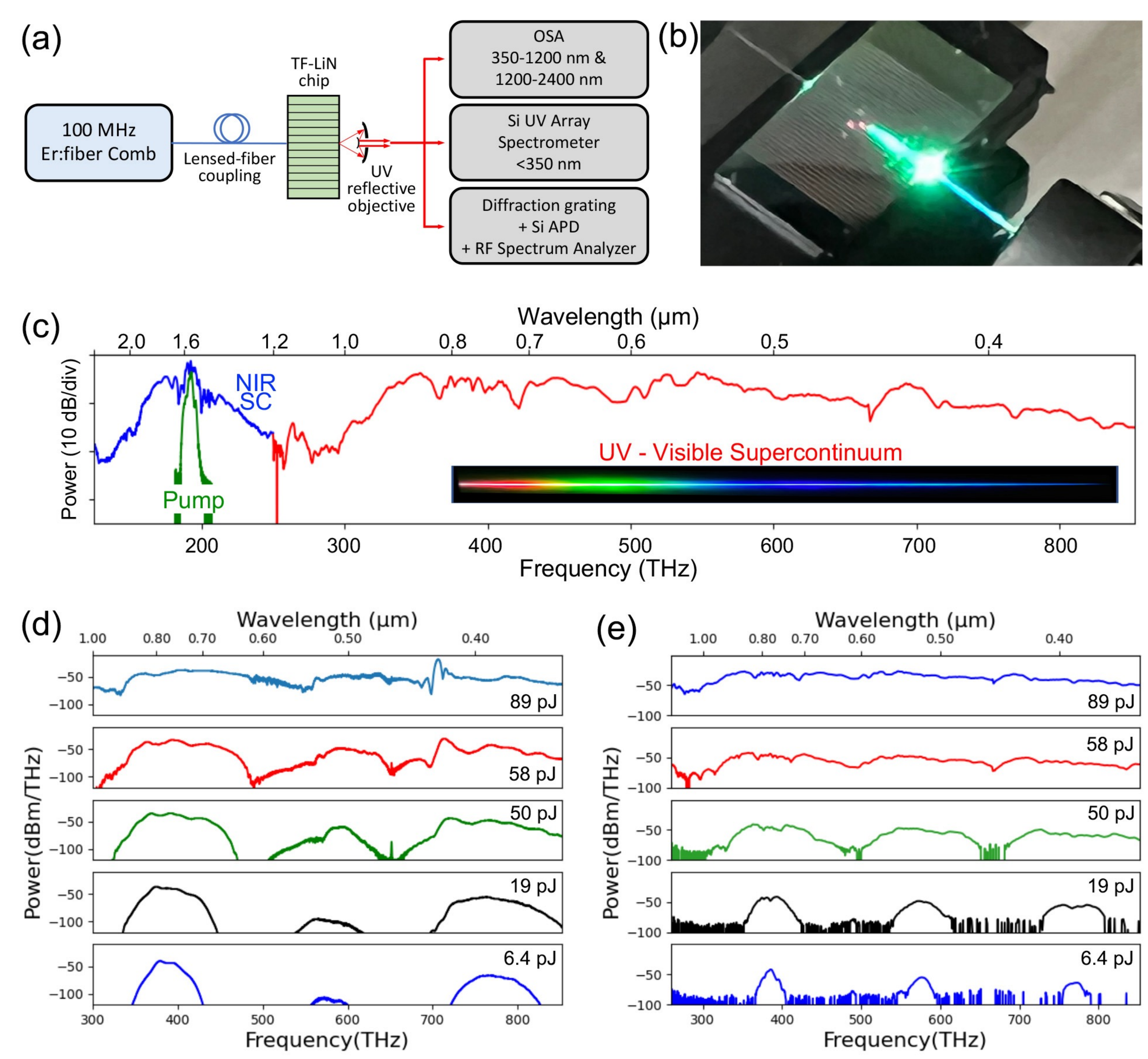


(a) Measured emission spectrum for the same chip shown in Fig. 2 when pumped with 2.9 W of pump power at 10-GHz repetition rate. (b) Pump (blue) and waveguide-generated (red) spectra measured with NIR and visible optical spectrum analyzers, respectively, showing individual comb lines separated by 10 GHz.

Approach and Results



(a) Scanning electron micrograph of etched thin-film lithium niobate waveguides fabricated at Caltech. (b) Second-harmonic microscope image of a periodically poled lithium niobate thin film. (c) Top-down view of the final thin-film lithium niobate waveguide chip fabricated for this task, including electrodes for chirped poling. (d) Edge-view microscope image of the same chip after facet polishing. (e) The same chip undergoing transmission measurements using optical fiber couplers.



(a) Schematic of the 100-MHz mode-locked laser comb used to pump the lithium niobate waveguides fabricated under this task. (b) Photograph of a waveguide chip during testing, showing visible emission. (c) Supercontinuum spectrum emitted from a waveguide with chirped poling and image of grating dispersed visible emission (inset). (d) Calculated and (e) measured spectra from a waveguide with chirped poling as a function of pump pulse energy.

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Publications:

T.-H. Wu, L. Ledezma, C. Fredrick, P. Sekhar, R. Sekine, Q. Guo, R. Briggs, A. Marandi, S. A. Diddams, "Ultraviolet to Near-infrared Frequency Comb Generation in Lithium Niobate Nanophotonic Waveguides with Chirped Poling," *CLEO: QELS Fundamental Science*, FW4J.2, May 2022.

L. Ledezma, R. Sekine, Q. Guo, R. Nehra, S. Jahani, and A. Marandi, "Intense optical parametric amplification in dispersion engineered nanophotonic lithium niobate waveguides," *Optica* **9**(3), 303-308 (2022).

A. Marandi, L. Ledezma, Y. Xu, and R. M. Briggs, "Thin-film parametric oscillators," US Patent 11,226,538 (2022).

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