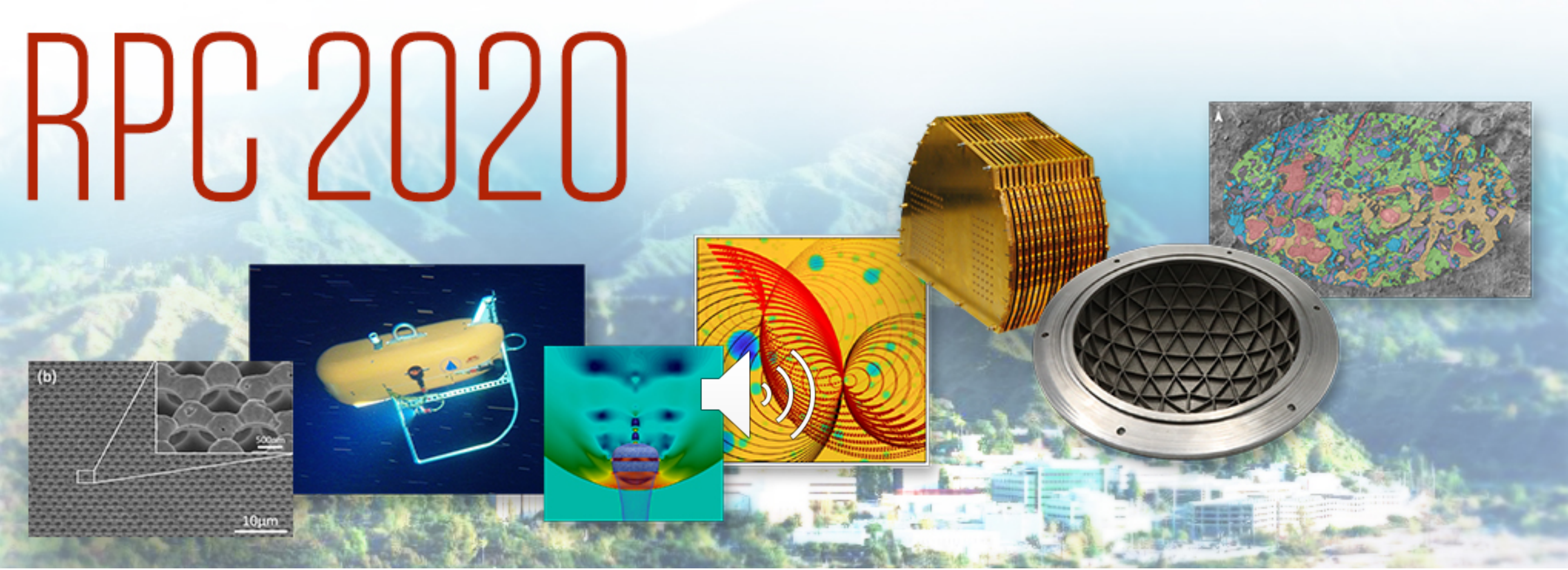

Virtual Research Presentation Conference

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

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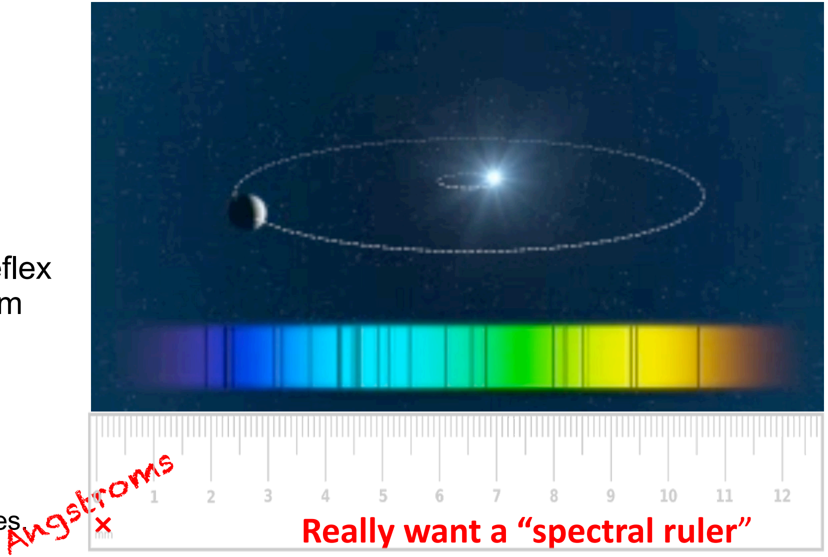
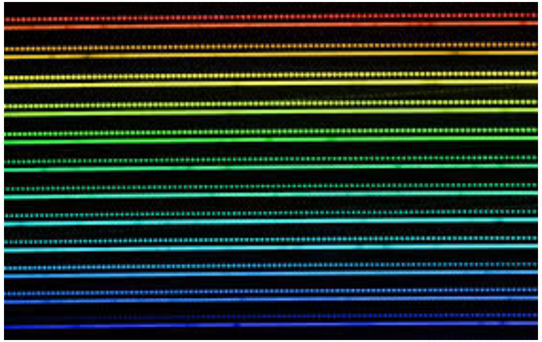
Jet Propulsion Laboratory
California Institute of Technology

Introduction

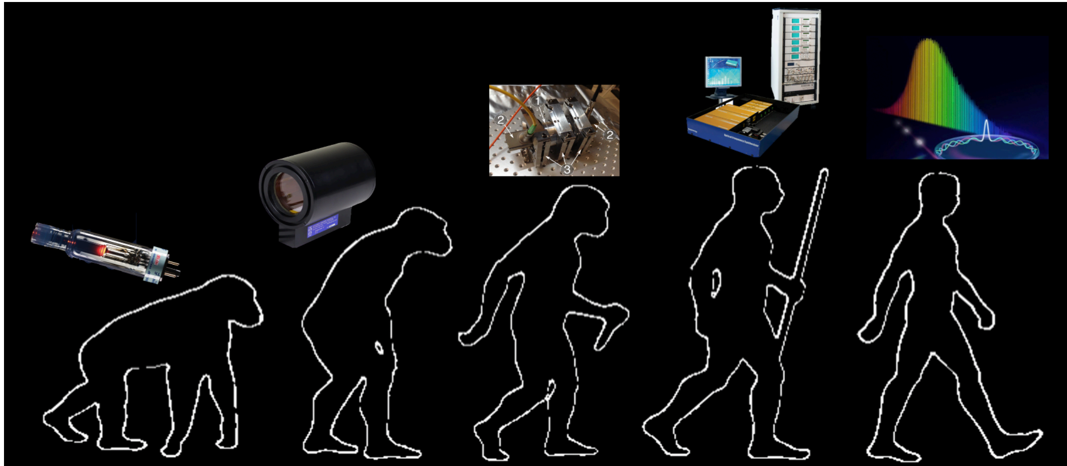
- The detection and characterization of exoplanets is one of the most exciting fields of modern astrophysics!
- One of the two methods that can determine exoplanet mass is the Precision Radial Velocity (PRV) method that measures the Doppler reflex motion of exoplanets by examining the motion of spectral features from exoplanet-hosting stars on a cross-dispersed echelle spectrograph.
- But how do we measure that motion? Relative to what? We need a reference against which to measure it – a spectral ruler if you will
  - one that measures on an angstrom scale
  - and it must be at least an order of magnitude more stable than the stellar lines
- The challenges, in addition to assuring that level of stability, are getting the grid of lines you want at the right line spacing across the full instrument bandpass.
- The best tool for calibration of PRV spectrographs is the Optical Frequency Comb
- Combs allow us to achieve calibration precision at levels below a cm/s – appropriate for detecting Earth-like planets orbiting solar-type stars. This is the realm of ***Extreme*** Precision Radial Velocity (EPRV)





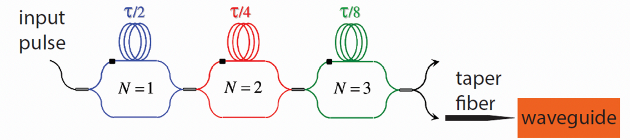
Finding Exo-Earths is Challenging!

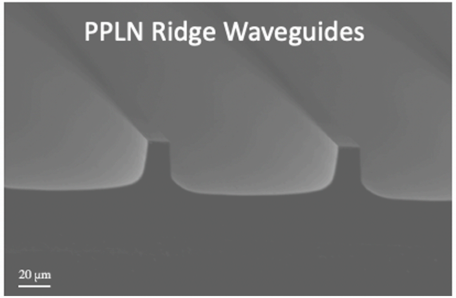
- Finding an Earth-like planet orbiting in the Habitable Zone of a solar type star requires that we look in the part of the spectrum where most of the spectral features are to be found – the visible band with wavelengths between roughly 400 nm and 800 nm.
- Prior methods of PRV spectrograph calibration have used arc lamps, gas cells, and Fabry-Perot etalons, but each of the methods fails to meet either the stability or line density requirement for EPRV.
- Visible band frequency combs are commercially available, but they've proven to be large, complex, expensive, and unreliable at bluer wavelengths, necessitating frequent repair.
- Our goal is to develop visible band frequency combs that are smaller, less expensive, lower power, and more reliable.
- This will help NASA and JPL meet the challenge of developing observational capabilities for a major EPRV initiative called for by the National Academy of Sciences [1].

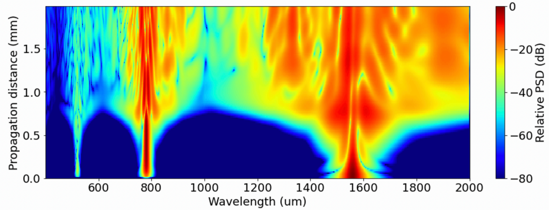


Methodology for creating low power, visible band, high repetition rate frequency comb for EPRV

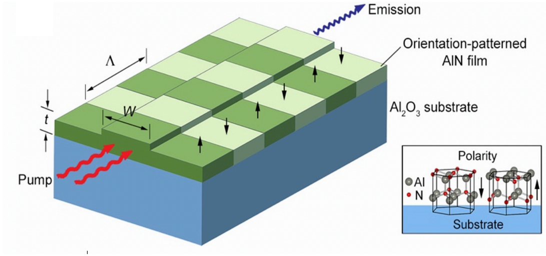
- Start with generating combs in the less-challenging near-infrared (NIR)
- Use sum frequency generation and nonlinear spectral broadening of frequency combs by integrating them with high second- and third-order nonlinear coefficient ($\chi(2)$ and/or $\chi(3)$)) waveguides.
- Target waveguide materials that will enable a dramatic reduction in pulse power over that needed in current NIR comb broadening technology
    - lithium niobate (LN) [2] and lithium tantalate (LT) waveguides
    - developing the capabilities for fabrication of dispersion-engineered LN waveguides and their characterization,
    - exploring periodically-poled AlN waveguides,
    - study resonator-based spectral broadening mechanisms in LN to reduce the power requirement.
- Novel approach for chip-platform pulse rate multiplication [3] of low repetition rate frequency combs to reduce the power demands for all of the material sets under study.





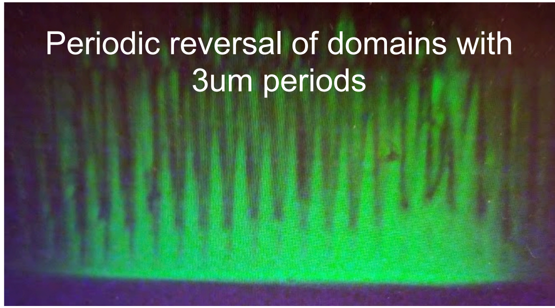


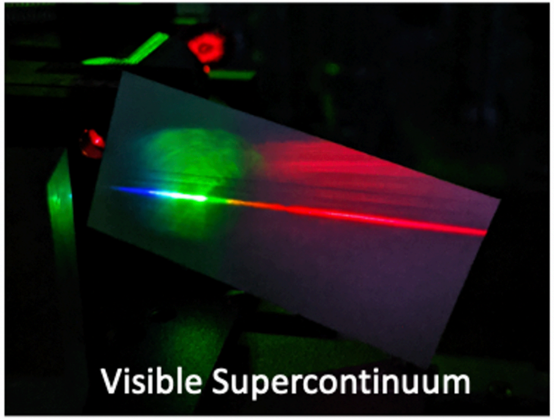
Above: Simulation of spectral broadening and second harmonic generation in quasi-phased matched thin-film LN waveguide
Below: Orientation-patterned aluminum nitride (AlN) waveguide



Results and Path Forward

- Introduced, modeled and implemented broad bandwidth Sum Frequency Generation in LN photonic waveguides
- If the 200+ THz predicted by our modeling is quantitatively verified, this would represent the broadest bandwidth SFG up-conversion that we are aware of. Potentially high efficiency up-conversion will allow generation of broad bandwidth high-repetition rate frequency combs as needed for astronomical spectrograph calibration.
- Our exploration of spectral broadening in resonators has shown that the inherent pulse compression in nonlinear processes can be an additional advantage. This can reduce the requirements on the pump (for instance from femtosecond pulses to picosecond pulses) which can reduce a great deal of complexity of the entire system. Resonant enhancement is also expected to provide another reduction factor in the pulse energy requirement.
- If successful, the pulse repetition rate multiplier will enable the use of readily available, lower repetition rate NIR compact fiber laser frequency combs as the seed for the higher repetition rate visible band astrocombs we seek. These devices have potential commercial applications as well.





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[1] "Exoplanet Science Strategy", National Academies of Sciences, Engineering, and Medicine 2018. Washington, DC: *The National Academies Press*.

[2] M. Jankowski *et al.*, "Ultrabroadband nonlinear optics in nanophotonic periodically poled lithium niobate waveguides," *OPTICA*, vol. 7, no. 1, pp. 40–46, Jan. 2020.

[3] Haboucha, A., Zhang, W., Li, T., et al, "Optical-fiber pulse rate multiplier for ultralow phase-noise signal generation," *OPTICS LETTERS*, Vol. 36, No. 18, September 15, 2011.