Dynamic Laser Frequency Combs for Astronomical Spectrograph Characterization and Calibration

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Abstract: We demonstrate a dynamic frequency comb, which is tunable in both frequency and intensity, to characterize and calibrate an astronomical spectrograph. These capabilities are critical for achieving cm/s level radial velocity precision to detect Earth-analogs.

The search for Earth-like exoplanets using the radial velocity (RV) technique is a challenging spectroscopy problem, requiring RV precision at the cm/s level. Optical frequency combs are critical to such measurements, but to date they have operated as fixed frequency calibrators. We break the "picket fence" modality of a frequency comb and introduce dynamic frequency and intensity tunability that increases the utility of the comb for the most demanding astronomical applications. Specifically, we have developed a frequency-scannable 30 GHz electro-optic comb spanning 700-1300 nm as well as dynamic amplitude shaping to provide tailored frequency and intensity distribution across all the comb lines. These advances will allow us to map the point spread function (PSF) at any wavelength across the entire spectrograph bandwidth, as well as to characterize detector defects such as sub-pixel quantum efficiency variation, brighter-fatter effect, and nonlinear response that present significant barriers to realizing the RV precision needed to find exoplanets like our own [1, 2].

Fig. 1(a) illustrates the schematic of our technique for generating a tunable frequency comb. The 30 GHz frequency comb spanning 700-1300 nm is based on fiber-integrated electro-optic (EO) modulation techniques and efficient supercontinuum generation in nanophotonic silicon nitride (SiN) waveguides. Details of the experimental setup can be found in [3, 4]. A Fabry-Pérot cavity with an FSR matching the comb repetition rate follows the base EO comb to suppress the broadband noise between the comb lines. As the laser frequency is tuned, the cavity length adjusts so that the center comb teeth resonates within the cavity. However, this leads to a comb-cavity mode walk-off since the cavity FSR does not match the comb repetition rate. To prevent this walk-off, the repetition rate must be simultaneously tuned along with the laser frequency. The resultant tunable supercontinuum (SC) spanning 700-1300 nm generated in SiN waveguide is shown in Fig. 1(b) for two instances when the CW laser frequency is scanned by 10.8 GHz. The linear frequency shift of the comb modes at 1064 nm and 1290 nm across the 30 GHz tuning range is illustrated in Fig. 1(c) and (d). The broadband coherent SC remains unchanged across the entire 30 GHz tuning range, with the measured short-term fractional intensity fluctuations outside the pump wavelength in the range of 10 - 20%.

The intensity profile of the supercontinuum generated after nonlinear spectral broadening is not flat (see Fig. 1(b)) and exhibits variations of over several orders of magnitude. This results in detector saturation at certain frequencies, while comb lines with lower intensity levels are buried beneath the detector's noise floor. Temporal intensity fluctuations of comb lines along with flux-dependent detector defects change the shape of the instrumental point spread function, leading to wavelength calibration errors. Additionally, astronomical spectrographs exhibit a characteristic blazing pattern over the different echelle orders as illustrated in the top plot of Fig. 1(g). A comb with dynamic spectral tailoring can mitigate these effects and compensate for the spectrograph response in order to maintain constant flux of all comb lines at the detector (Fig. 1(e)). Our approach to dynamic spectral control is based on Fourier-transform pulse shaping using a spatial light modulator (SLM) [5, 6]. The frequency comb used in this experiment is a 10 GHz resonant electro-optic comb pumped at 1550 nm, with a spectral coverage of 700–1700 nm after spectral broadening in a SiN waveguide [7]. Pumping at 1550 nm reduces the required dynamic range of attenuation across the desired wavelength range of 800-1300 nm. The SC output is launched onto the spectral tailoring setup as illustrated in Fig. 1(f). The SLM acts as a variable waveplate on adjusting the voltage applied to its pixels. Cross-polarizers at the input and output of the SLM convert this polarization rotation into wavelength-dependent attenuation. Using this setup, we achieved a dynamic range of attenuation of approximately 25 dB. The LFC output is continuously measured and feedback is sent to the SLM to adjust the comb line intensity levels to match the applied SLM mask. We analyzed the LFC output from the spectral flattener on an optical spectrum analyzer (OSA) in two ways: in-loop and out-of-loop. In-loop refers to cases where both feedback and measurement are performed using the same instrument (OSA), while out-of-loop refers to using two separate instruments (OSA and spectrometer). The corresponding LFC outputs on applying this inverse echelle response mask on the SLM are shown in the bottom plot of Fig. 1(g). Both in-loop and out-of-loop measurements show good agreement with the applied SLM mask (depicted as black dashed line). The real-time feedback to the SLM reduces spectral intensity variations over time, improving the spectral stability by nearly a factor of two. The spectral bandwidth after the flattener is limited by the efficiency of the grating employed. In future, we plan to replace it with a grating that provides high efficiency over a broader bandwidth. Although spectral tailoring has been demonstrated with a 10 GHz comb, this technique can be directly applied to the 30 GHz comb setup.

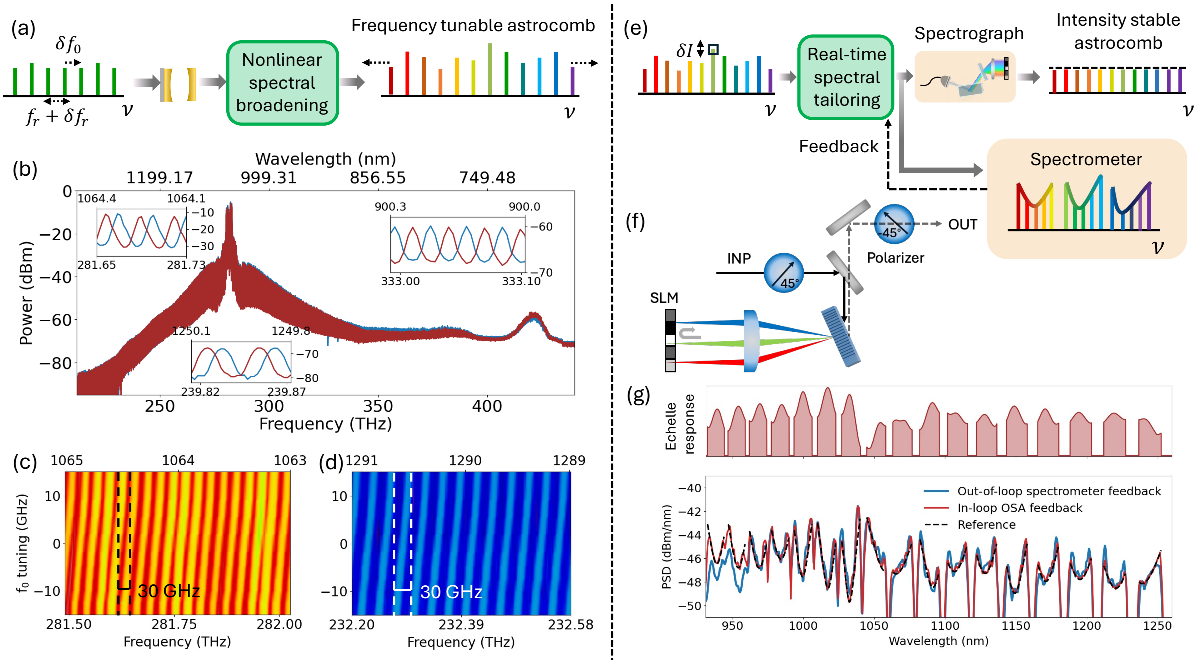

Fig. 1. Astrocombs with frequency and intensity tunability. (a) Schematic for generating a frequency tunable broadband electro-optic comb. (b) Comb-resolved 30 GHz supercontinuum (SC) spanning 700 - 1300 nm in SiN waveguide obtained by tuning the CW laser frequency through 10.8 GHz. Zoomed-in version of SC across the entire 30 GHz tuning range for comb lines centered at (c) 1064 nm, and (d) 1290 nm. (e) Schematic for real-time spectral tailoring of astrocombs achieving constant flux. (f) Experimental setup of spectral flattener using a spatial light modulator (SLM). (g) The top plot shows the echelle response from the spectrograph and the bottom plot shows the LFC output after applying the SLM mask to compensate for this spectrograph response.

We intend to implement the dynamic frequency and intensity tunability on the 30 GHz comb deployed at the Habitable-zone planet finder (HPF) spectrograph. This work will turn a static frequency comb into a dynamic metrological tool for precise characterization of large format detector arrays as a critical step towards cm/s RV precision in the near-infrared and visible.

References

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