ANDES, the high-resolution spectrograph for the ELT: a 30 GHz UB-band astrocomb from 390–470 nm

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ABSTRACT

Next generation extreme precision radial velocity (EPRV) instruments such as the ANDES spectrograph of the Extremely Large Telescope will require an unprecedentedly high-precision calibration approach, particularly in the UB band region in which the most dense stellar absorption lines are present. For this purpose, astrocombs delivering thousands of atomically referenced, evenly-spaced calibration lines across a broad spectrum have the potential to be ideal calibration sources. Here, we report a novel and effective approach to generating a laser frequency comb with a multi-GHz mode spacing covering a broad wavelength range in the UB band. The approach is based on nonlinear mixing between near-infrared ultrafast laser pulses in a MgO:PPLN waveguide. The generated 1-GHz comb, spanning 390–520 nm, was filtered to a 30 GHz sub-comb using a low-dispersion Fabry-Perot etalon. The resultant UB-band astrocomb was then captured on a lab-built cross-dispersion echelle-prism spectrograph, demonstrating well resolved comb lines across the etalon bandwidth of 392–472 nm.

Keywords: Astrocomb, Ti:sapphire laser, MgO:PPLN waveguide, sum-frequency-mixing.

1. INTRODUCTION

The UB band of stellar spectra holds the key to many exciting new scientific ventures with its rich and high-quality absorption lines. Some of the main scientific drivers of the ANDES spectrograph include testing potential variations in fundamental physical constants, such as the fine structure constant, as well as redshift drift measurements like the Sandage–Loeb test [1]. These involve exploiting the dominant absorption lines in the UV/visible spectra of quasi-stellar objects (QSOs) [2], imposing demanding requirements on the spectrograph calibration source not only in wavelength coverage but also in stability and precision, which the classic ThAr lamp approach can no longer accommodate. A laser frequency comb, providing thousands of ultra-stable, atomically referenced, and evenly spaced calibration lines resolvable by the astronomical spectrograph, also known as an astrocomb, has the potential to act as the ideal calibrator for high-resolution spectrographs [3].

Although astrocombs have been successfully demonstrated in labs and on telescopes across the world, providing a continuous, gap-free astrocomb in UB band has remained challenging. Early approaches [4,5,6,7,8] often involved second-harmonic generation (SHG) of a NIR mode-locked lasers or supercontinuum generation (SC) in photonic-crystal (PCF) fiber which enabled blue-green coverage as wide as 435–600 nm [8]. However, the spectrally suppressive nature of the $\chi^{(2)}$ process as well as the material limitations imposed by a PCF hindered the bluer coverage of the bandwidth. With advances in waveguide manufacture, results in recent years have migrated to an on-chip approach, utilizing a primary comb derived from either a fiber-based modelocked laser or an electro-optical comb [9,10,11]. While exploiting

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second-order $\chi^{(2)}$ and third-order $\chi^{(3)}$ nonlinear processes allowed multi-harmonic generation down to 350 nm, gaps remained in the spectral coverage. The relatively low starting repetition rate of source comb along with the high energy requirement of the $\chi^{(3)}$ process also meant that multiple stages of amplification/broadening/compression/filtering were required to achieve the desired comb bandwidth and mode spacing, which could potentially imprint noise in the system onto the final calibration linewidth.

Here, we introduce a new approach generating a continuous spectrum across a large portion of the UB band by utilizing both SHG and sum-frequency-mixing (SFM) nonlinear processes in an aperiodically-poled MgO:PPLN waveguide. While SHG inherently suppresses weaker spectral features in the fundamental light due to its $\chi^{(2)}$ quadratic nature, using a strong auxiliary pulse allows SFM to linearly convert the weak yet broad infrared components into the visible. Using a 1 GHz Ti:sapphire laser as the primary comb, we experimentally demonstrate gap-free coverage from 390 nm to 520 nm, requiring only ≈100 pJ pulses. The wide mode spacing of the source comb indicates that only one stage of Fabry-Pérot filtering would be needed to extract a wider mode-spacing of sub-comb while maintaining significant (approaching 30 dB) suppression of neighboring 1 GHz comb modes. The 30-GHz UB-band astrocomb was visualized on our lab-built proxy spectrograph, demonstrating the effectiveness of our approach.

2. UB-BAND ASTROCOMB GENERATION

2.1 Supercontinuum Generation in the UB band

Our approach started by mixing a NIR mode-locked laser and its supercontinuum in a quasi-phase-matched MgO:PPLN waveguide (Covesion). Without any temporal overlap between the two pulses, a spectral gap is expected between the SHG of the two fields, as lower-intensity features at the edges of the pulse spectra are suppressed by the quadratic nature of the $\chi^{(2)}$ process. Fig. 1 shows that this limitation can be overcome by using the sum-frequency mixing process between the two pulses after first overlapping them temporally in the waveguide. Since the supercontinuum light has the same carrier-envelope offset frequency (f_{ceo}) as the pump, the SHG and SFM components share identical comb offsets ($2f_{ceo}$) and are indistinguishable within the comb.

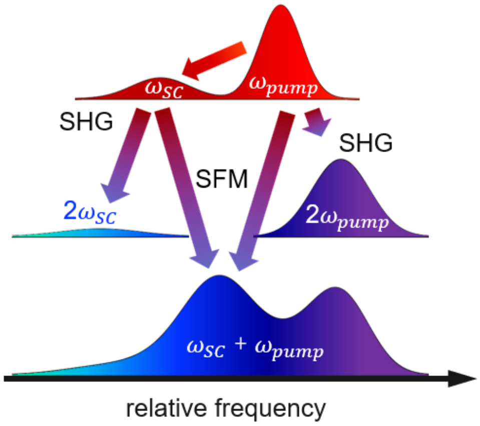

Figure 1. Broadband UV to blue-green generation using sum-frequency mixing.

To ensure efficient nonlinear conversion across a broad bandwidth, performance based on typical laboratory parameters was simulated (Figs. 2(c-e)). A nonlinear envelope model was used to compute the 650–1050 nm SC field from a few-centimeter nonlinear fiber with zero-dispersion at 775 nm and 950 nm, which was then used as the input for a further nonlinear envelope model describing the SHG and SFM generation (Figs. 2(c-e)). The model was iterated to identify the optimum pump-SC delay and waveguide aperiodicity (Fig. 2(a)) needed to provide the broadest UV–green spectrum. The aperiodic grating reduces progressively from 6.3 µm to 2.2 µm along the waveguide, with initial sections phase-matched for transferring the longer-wavelength supercontinuum to >445 nm and the intermediate sections phase-matched for SFM between the intense 800 nm pump pulse and supercontinuum components from 890–1140 nm. The shorter end of the coverage is produced by SHG of pump light from 760–840 nm in gratings with periods of Λ = 2.2–3.2 µm.

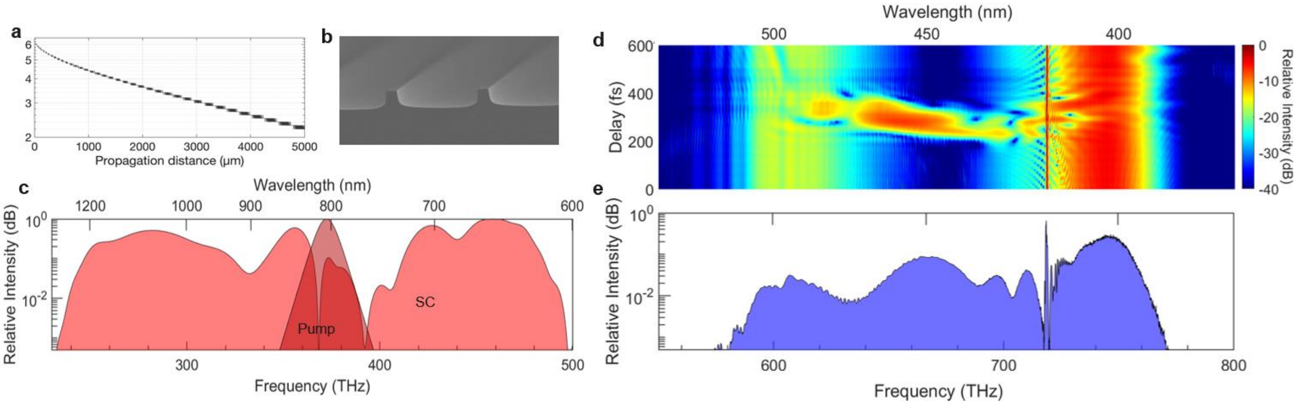

Figure 2. (a) MgO:PPLN periods and (b) waveguide SEM micrograph. (c) Simulated input showing pump and supercontinuum (SC) spectra. (d) Simulated delay-resolved spectrum and (e) line-cut of this at optimum delay.

2.2 Laboratory Realization of Blue-Green Supercontinuum

To demonstrate the concept, we started with a 1 GHz, 33 fs Ti:sapphire master laser (Novanta). Its 2W of power was shared between an f-to-2f interferometer for comb-offset locking, a short PCF and a pump beam path containing an adjustable optical delay (Fig. 3(a)). At only 35 mm long, the PCF generated SC pulses with a smooth 650–1050 nm spectrum (Fig. 4(a)) which were then co-launched into the MgO:PPLN waveguide along with replica pump pulses. The temporal overlap between the two pulses was then optimized using a delay stage in the replica pump beam path. As the pulse delay was adjusted, additional bandwidth was generated through the sum-frequency mixing process and combined with the SHG light achieved a broadband coverage from 390–520nm (Fig. 3(b)).

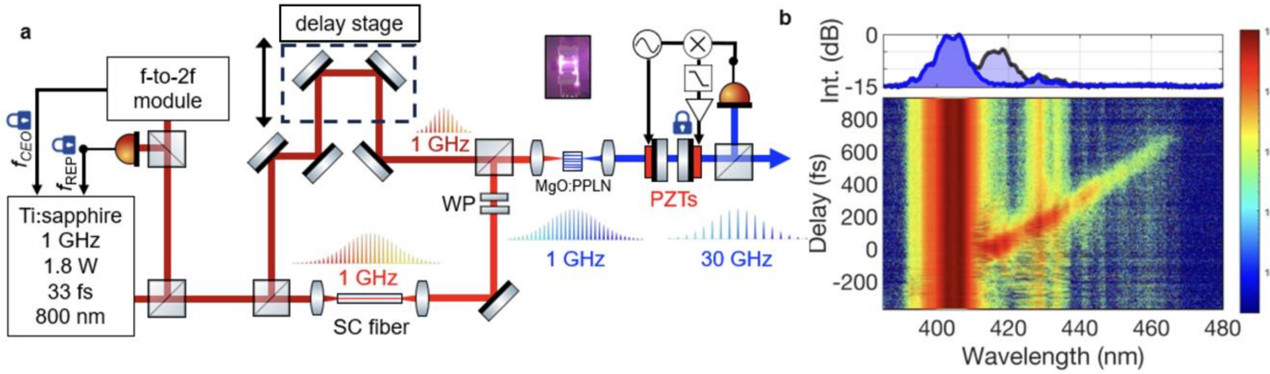

Figure 3. (a) Configuration to experimentally generate the 30 GHz astrocomb from a 1 GHz Ti:sapphire comb at 800 nm. (b) Delay-resolved spectra as the delay between the SC pulse and the replica pump pulse was adjusted.

2.3 Mode Filtering to Create a 30 GHz Astrocomb

To prepare the 1-GHz UB-band comb for spectrograph visualization, the beam was aligned into a plane-plane Fabry–Pérot etalon cavity for filtering. The wide 1 GHz mode spacing of the primary frequency comb lessened the requirements on the etalon finesse (≈300) and therefore a design of mirror coatings that exhibited a low GDD across a wide bandwidth (390–470 nm) was possible. As one mirror was dithered at ≈10 kHz, the other one was swept across a few μm to allow the maximum transmission to be found. Part of the Ti:sapphire SHG at ≈400 nm, which is also the strongest, was selected through a bandpass filter and used for etalon locking. With a mirror separation of ≈5 mm, the etalon was locked to select a sub-comb of $m \times f_{\rm rep} = 30$ GHz. The etalon was dither-locked for several hours, producing a 30 GHz astro comb covering from 390–470 nm (Fig. 4(b)).

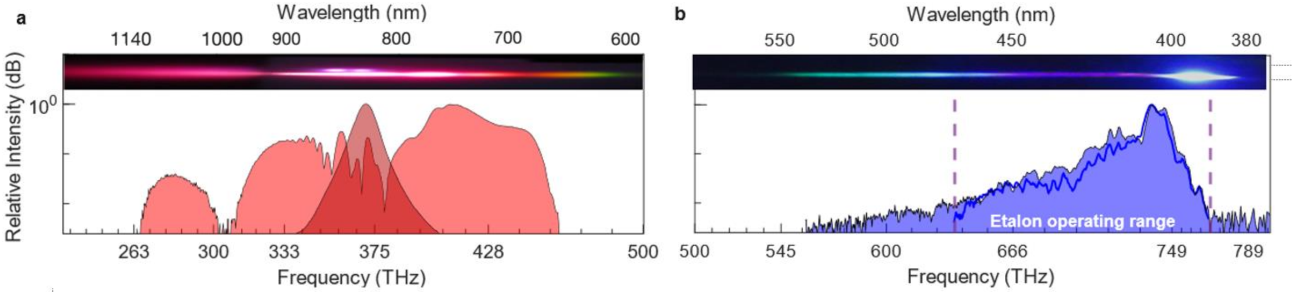

Figure 4. (a) Experimentally measured spectra of the fundamental pulses and their image. (b) Resultant SHG/SFM field from the MgO:PPLN waveguide and image of the UV-green comb spectrum at the optimum delay position. The shape and bandwidth of the SHG/SFM spectrum after the Fabry-Pérot etalon filtering (solid blue line) is preserved.

3. ASTROCOMB VISUALIZATION

To provide an instantaneous understanding and characterization of our astrocomb, a cross-dispersion Echelle-prism spectrograph (Fig. 5) was set up as a proxy astronomical spectrograph. The beam was first coupled onto a 31.6 lines mm^{-1} Echelle grating (63° blaze angle). The diffracted light was then cross-dispersed by an F2-glass prism and imaged onto a 20.2-megapixel monochrome camera after a 200 mm curved mirror (Fig. 4).

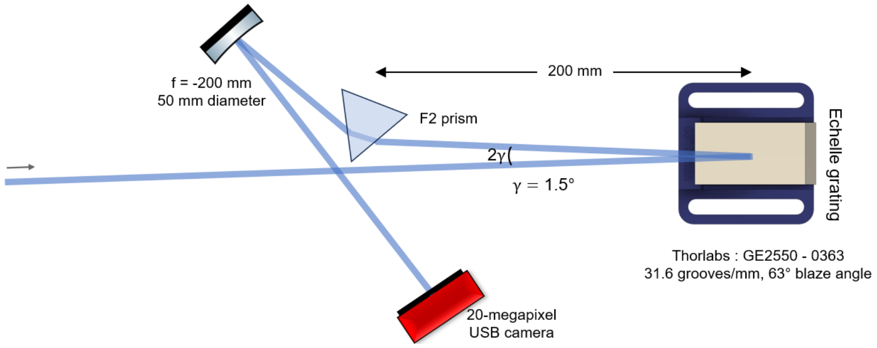

Figure 5. The cross-dispersion Echelle-prism spectrograph used for astrocomb visualization.

With a spectrograph resolving power of ≈46,000, the result of the mode-filtering is illustrated in Fig. 6. Individually resolved comb modes can be seen across a bandwidth from 392–470 nm. To compensate for the 8-bit dynamic range limitations from the camera, different sections of the UB band were recorded under different gain values. The color map on the left of Fig. 6 corresponds to the intensity of the comb modes on a linear scale, while a nonlinear scale has been used for weaker comb modes in the insets. To understand how the weaker region of the comb would be detected by different astronomical spectrographs, an independent camera calibration measurement was performed and showed an approximate power of 100 pW per comb mode (270 million photons / second) at the lower intensity edge of 470 nm, which is sufficient for practical calibration measurements on ANDES.

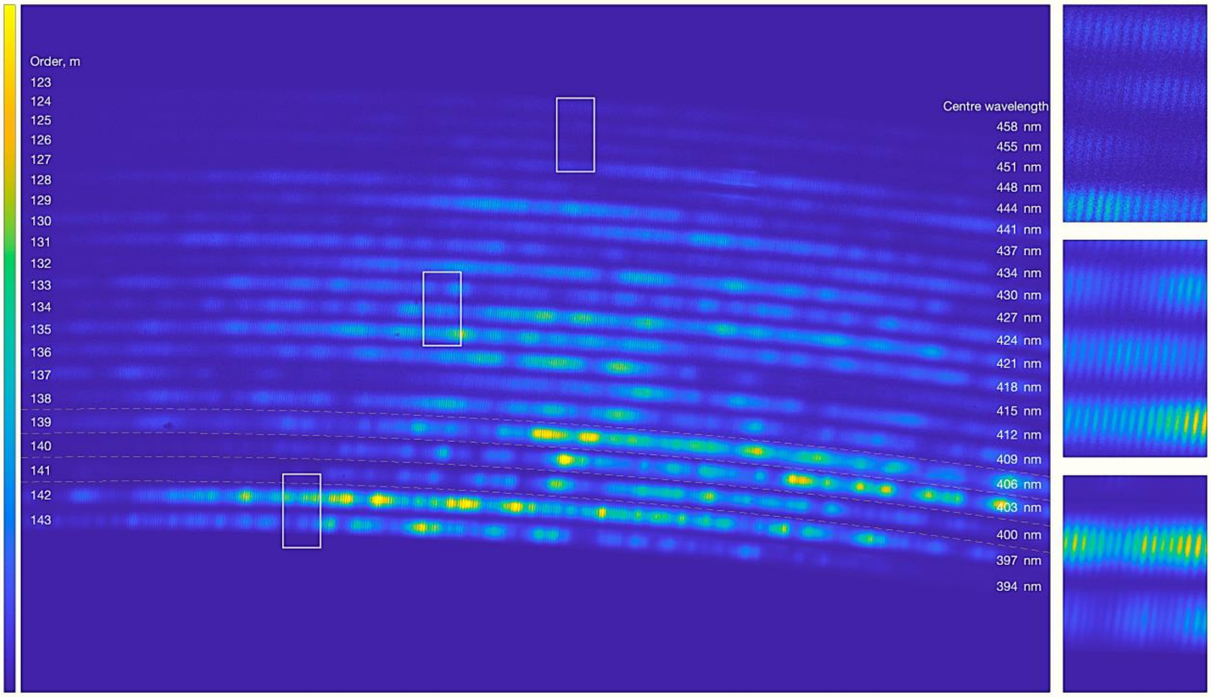

Figure 6. The filtered 30 GHz sub-comb resolved by our lab-built cross-dispersion spectrograph as a proxy to an actual astronomical spectrograph. The insets on the right are zoomed-in regions of the echellogram. The 30 GHz resolved comb modes can been seen across the full range of modes orders 123–143, corresponding to wavelengths from 392–472 nm.

4. CONCLUSION AND OUTLOOK

We have introduced here a new approach for generating continuous UV to blue-green astrocomb. We have demonstrated experimentally a gap-free, broadband UB band astrocomb with a mode format well matched to the calibration requirements of ANDES. Our next steps involve further optimization aligned to the requirements of the ANDES spectrograph. For example, the implementation of spectral flattening using a spatial light modulator (SLM) will be also important as to ensure that even the weakest modes have sufficient intensity to be detected with a high signal-to-noise ratio on the CCD within a reasonable exposure time. Further modelling based on more refined experimental pulse measurements of our fundamental pulses could potentially enable an even broader, more intense, and flatter spectra to be obtained. Moreover, integrating these advancements with our prior work in the visible-NIR spectrum will facilitate the development of a comprehensive astrocomb, and covering the full bandwidth necessary for the precise calibration of the Extremely Large Telescope (ELT) ANDES spectrograph.

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REFERENCES

[1] Marconi, A. et al. "ANDES, the high resolution spectrograph for the ELT: science case, baseline design and path to construction," Proc. SPIE 12184, Ground-based and Airborne Instrumentation for Astronomy IX, 1218424 (2022); https://doi.org/10.1117/12.2628689

[2] Martins, C. J. A. P. et al. "Cosmology and fundamental physics with the ELT-ANDES spectrograph." Experimental Astronomy 57, 5 (2024); https://doi.org/10.1007/s10686-024-09928-w

[3] Steinmetz, T. et al. "Laser frequency combs for astronomical observations," Science 321, 1335–1337 (2008); https://doi.org/10.1126/science.1161030

[4] Benedick, A. et al., “Visible wavelength astro-comb,” Opt. Express 18, 19175 (2010); https://doi.org/10.1364/OE.18.019175

[5] Phillips, D. F. et al., “Calibration of an astrophysical spectrograph below 1 m/s using a laser frequency comb,” Optics Express 20, 13711 (2012); https://doi.org/10.1364/OE.20.013711

[6] Probst, R. A. et al., “A laser frequency comb featuring sub-cm/s precision for routine operation on HARPS,” Proc. SPIE 9147, 91471C (2014); https://doi.org/10.1117/12.2055784

[7] Chae, E. et al., “Compact green Ti:sapphire astro-comb with a 43 GHz repetition frequency,” J. Opt. Soc. Am. B 38, A1 (2021); https://doi.org/10.1364/JOSAB.419078

[8] Glenday, A. G. et al., “Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph,” Optica 2, 250 (2015); https://doi.org/10.1364/OPTICA.2.000250

[9] Obrzud, E. et al., “Visible blue-to-red 10 GHz frequency comb via on-chip triple-sum-frequency generation”, Opt. Lett. 44, 5290 (2019); https://doi.org/10.1364/OL.44.005290

[10] Nakamura, K. et al., "Erbium-doped-fiber-based broad visible range frequency comb with a 30 GHz mode spacing for astronomical applications," Optics Express 31, 20274 (2023); https://doi.org/10.1364/OE.487279

[11] Ludwig, M. et al., “18 GHz Ultraviolet Astrocomb via Chip-Integrated Harmonic Generation”, 2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), 1-1 (2023) http://doi.org/10.1109/CLEO/Europe-EQEC57999.2023.10232253