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Broadband Frequency Comb for Calibration of Astronomical Spectrographs

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Abstract

We present our state-of-the-art version of a frequency comb for calibration of astronomical spectrographs. The mode spacing of the frequency comb can be designed to match the resolution of a spectrograph. Combined with its excellent accuracy and stability, the spectral coverage of more than 70% of the whole visible spectrum range makes the frequency comb an ideal calibration source. In addition, the new version introduces the automatic start-up function that brings convenience to the astronomers.

Keywords

Frequency Combs, Astronomical Spectrograph Calibration

1. Introduction

Precise calibration sources are required for astronomical spectrographs when applying the radial velocity (RV) method. Based on the Doppler effect, the RV method is used to search of Earth-like extrasolar planets, which typically needs to measure the RV modulation of 9 cm/s in a term of one year. The commonly used calibration source is not offering sufficiently high accuracy and long-term stability. For example, the thorium-argon lamps, their lines differ in intensity and spacing, and positions of the lines are not turnable. These make the thorium-argon lamps have the short-term repeatability of some 10 cm/s. At the same time, the thorium-argon lamps are suffering from their agings, their calibration lines are moving with time. Therefore, the thorium-argon lamps only offer long-term calibration repeatability of several m/s. The appearance of astronomical frequency combs (astro-combs) in contrast should enable exo-Earth detection. Beyond this, astro-combs should allow meeting the even greater scientific challenge of direct detection of cosmic acceleration [1] [2].

For a more intuitive comparison, as shown in **Figure 1**, an astro-comb and a thorium-argon lamp are imaged on the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph (run by ESO). It is obvious that the modes of the astro-comb are precisely equidistant, with little intensity modulation.

Several astro-combs have been permanently installed on astronomical spectrographs by now. The one for Solar Vacuum Tower Telescope (VTT) is working since 2011 [3] with a mode spacing of 5.445 GHz and a bandwidth

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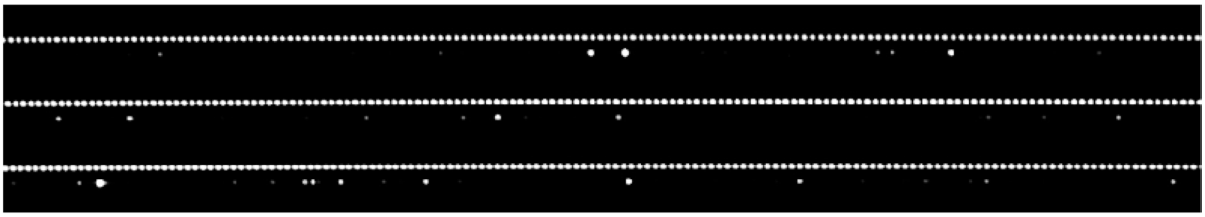

Figure 1. Comparison between an astro-comb (upper channel) and a thorium-argon lamp (lower channel) on the HARPS spectrograph.

of 460 - 680 nm. On HARPS-N, the astro-comb features a mode spacing of 16 GHz, and a spectral coverage from 500 nm to 620 nm. It allows an RV measurement accuracy and stability <10 cm/s [4]. The former approach of the astro-comb for HARPS is to frequency-double an infrared high repetition rate comb, and then broadens the green pulses. The mode spacing is 18 GHz, and a spectral coverage from 440 nm to 600 nm is reached. It enables an accuracy in the sub-cm/s range [5]. In this paper, our new approach of the astro-comb is presented, which gives an even wider bandwidth.

2. The Astro-Comb System

As shown in **Figure 2**, the astro-comb is based on an ytterbium fiber femtosecond laser, which has a mode spacing of 250 MHz. Three Fabry-Pérot cavities (FPCs) are used to filter out the unwanted modes. Each FPC's free spectral range (FSR) is set to an integer multiple of the mode spacing of the source comb. There by desired mode spacing can be reached. All the three cavities are locked to a continuous-wave fiber laser (cw laser), which itself is locked to one comb mode. A wavemeter monitors the frequency of the cw laser, which helps to select the subset comb modes at the designed mode spacing. For the 25 GHz astro-comb, 1 out of each 100 comb modes passes through the cavities. The optical power is greatly reduced and the pulses are strongly chirped after the mode-filtering. Therefore, a fiber-based power amplifier and a combined grating and prism compressor are applied. After them, the infrared comb spectrum is centered at 1040 nm with pulse duration of about 140 fs. The optical power can be adjusted, with an upper limit of around 15 W. Without frequency doubling, the high power infrared light is coupled into a tapered photonic crystal fiber (PCF) for broadening of its spectrum. The taper is specially designed to broaden the spectrum from infrared range to visible range. A TEM FiberLock controls a piezo-driven mirror before the tapered PCF. Without any need for manual realignment, the FiberLock offers automatic two-dimension coupling efficiency optimization. Therefore, the maximum of the coupled power is kept and the spectral bandwidth is thus maintained. The broadened spectrum is typically fairly structured. Therefore, in the last step, a spectral flattening unit reshapes the spectrum to a flat-top. Based on a spatial light modulator (SLM), the flattening unit has a dynamic flattening range up to 27 dB. A look-up table is introduced in the software of the flattening unit, which can reshape the flat-top to fit the wavelength-related sensitivity of an astronomical spectrograph. For the output of the system, a single mode fiber is used to offer the best beam quality. The fibers for the light transmission in the broadening unit and the flattening unit are all single mode fibers in visible light range, as most of the spectrographs work for detecting visible light. Thus, the broadband super continuum created by the tapered PCF, which can cover a wide infrared range as well as the visible range, is blocked in the long wavelength range. The fibers can the changed if an astro-comb is designed for infrared calibration. Even, the whole super continuum range can be covered by using the endless single mode photonic crystal fibers for transmission.

A photograph of the 18 GHz astro-comb with the new approach for HARPS spectrograph is shown in **Figure 3**. The two enclosures on the left contain the optical system. The two racks on the right contain the electronics, the cw laser, and the pump diode lasers for the power amplifier. The astro-comb was installed permanently in April 2015. The whole system is well controlled by software, which makes the astro-comb a one-button system. From any starting point, with one mouse click, the automation function of the software can start up the complete system. Then a stand-by mode can be used when the calibration campaign is suspended, as the astronomical observation usually stops during the daytime. The one-button system feature meets the needs of astronomers, thus particular training in laser physics is not required.

It is very important to mention that, most of the spectrographs are fed with multimode fibers, as the multimode fibers offer better coupling efficiency for the weak signal detections of the stars or some other celestial

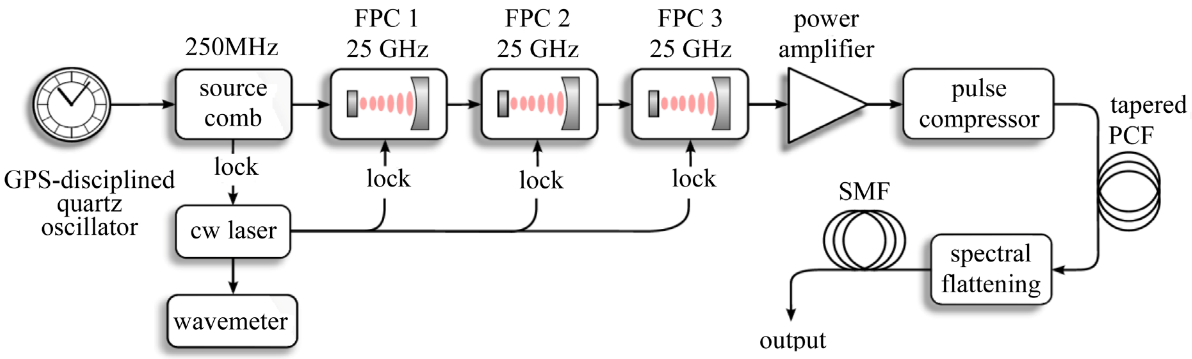

Figure 2. Overview of the astro-comb system. cw laser: continuous-wave fiber laser. FPC: Fabry-Pérot cavity. Tapered PCF: tapered photonic crystal fiber. SMF: single mode fiber.

Figure 3. Photograph of the astro-comb for HARPS spectrograph.

bodies. For a spectrograph with two channels, for example, HARPS, the channel of the star light and the channel of the comb light should pass the same path, which means multimode fiber have to be used for coupling the comb light from the single mode fiber output of the astro-comb to the spectrograph. The multimode fiber introducing the speckle as the comb light is coherent. The speckle can strongly impact the accuracy of the calibration. Therefore, active scrambling of the multimode fiber is critical. The physical shaking of the multimode fiber is commonly used. Some other methods, like using a rotating phase plate to constantly change the phase of the input beam of the multimode fiber, or applying optical fiber with polygonal core, are also effectual.

3. Experimental Results

As shown in **Figure 4**, a remarkably broadband spectrum is obtained with the 25 GHz astro-comb. All the spectra are recorded by a CCD spectrometer in the spectral flattening unit. The blue curve shows the initial spectrum, which is flattened to different levels. Every flattened spectrum shows an excellent smoothness. The −15 dB flattened spectrum exhibits a flat-top shape from 445 nm to 730 nm, which means 75% of the whole visible spectrum range can be covered. Before activing the flattening, the astro-comb can offer an output power of more than 100 mW. For a smaller mode spacing astro-comb, e.g. 18 GHz, the same bandwidth can be reached with

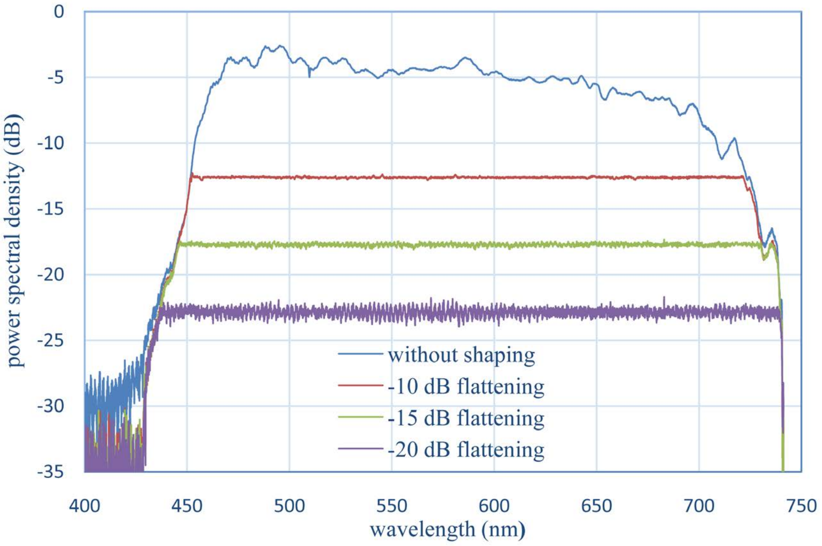

Figure 4. Output spectra of a 25 GHz astro-comb.

even lower pump power.

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