optica

Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph

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Received 22 September 2014; revised 11 February 2015; accepted 12 February 2015 (Doc. ID 214735); published 11 March 2015

Searches for Earth-like exoplanets using the periodic Doppler shift of stellar absorption lines require 10 cm/s precision in the measurement of stellar radial velocity (RV) over timescales of years. Current techniques have led to the discovery of short-period exoplanets that induce RV wobbles as small as ≈1 m/s on their parent stars. It has been suggested that order-of-magnitude improved RV precision may be achievable using an astro-comb, a laser frequency comb optimized for astrophysical spectrograph wavelength calibration. Here we report the development of a broadband visible-wavelength astro-comb and its operation with the HARPS-N spectrograph at the Telescopio Nazionale Galileo in the Canary Islands. This green astro-comb has >7000 narrow (<1 MHz) spectral lines spaced by 16 GHz with relatively uniform line power from 500 to 620 nm. The line frequencies are locked to GPS, enabling us to realize HARPS-N wavelength calibration with RV measurement precision and stability <10 cm/s.

OCIS codes: (140.3490) Lasers, distributed-feedback; (060.2420) Fibers, polarization-maintaining; (060.3735) Fiber Bragg gratings; (060.2370) Fiber optics sensors.

http://dx.doi.org/10.1364/OPTICA.2.000250

1. INTRODUCTION

A critical challenge for high-precision stellar radial velocity (RV) measurements is the approximately five orders of magnitude difference between a typical stellar linewidth and the RV precision necessary to detect Earth-like exoplanets orbiting in the habitable zone of solar-type stars, a gap that must be bridged by making measurements with a correspondingly high signal-to-noise ratio (SNR). Astrophysical spectrographs such as HARPS-N have been optimized to meet this challenge [1], with a bandwidth of several hundred nanometers to allow measurement of thousands of stellar lines simultaneously, and a spectral resolution of twice the typical stellar linewidth of a solar-type star to maximize optical throughput for a given instrument size, and hence the measurement SNR per unit time. Additionally, to reduce spectrograph-induced systematic errors in the RV measurement, the stellar spectrum and a wavelength calibration source are measured simultaneously by the spectrograph through the same optics and with the same detector. Thus, an ideal wavelength calibrator for RV measurements

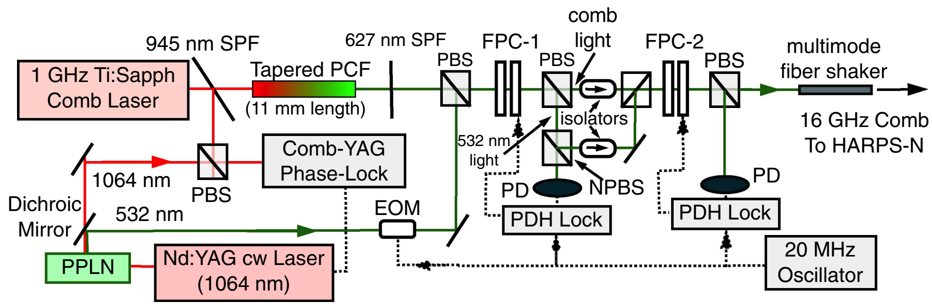

Fig. 1. Schematic of key components of the green astro-comb. Comb lines spanning an octave in the near infrared with 1 GHz spacing are generated by a titanium:sapphire (Ti:sapphire) laser, and stabilized to an atomic clock referenced to GPS. A tapered photonic crystal fiber (PCF) coherently shifts the comb lines to visible wavelengths. Two broadband Fabry–Perot cavities (FPC-1; FPC-2) then filter the comb light, passing every 16th spectral line. A Nd:YAG laser (1064 nm) is locked to the source comb and doubled to 532 nm, after which it is used to lock to the FPCs via a Pound–Drever–Hall (PDH) type scheme. (EOM, electro-optic modulator; NPBS, 50:50 nonpolarizing beam splitter; PBS, polarizing beam splitter; PD, photodetector; SPF, short-pass filter.)

must have many thousands of calibration lines over >100 nm bandwidth with line spacing greater than the spectrograph resolution, relatively uniform line power, and accurately determined wavelength values. An astro-comb [2–11] is such an ideal calibrator, and is typically composed of (i) a high-repetition-rate laser frequency comb [12] stabilized to an atomic clock (the "source comb"), (ii) a nonlinear element to shift the spectrum of the comb to the desired calibration band, and (iii) filter cavities to match the line spacing to the spectrograph resolution (Fig. 1). The green astro-comb we developed provides equally spaced optical emission lines over about 120 nm in the central part of the visible spectrum, with line power homogeneity of better than 6 dB for most of the spectrum [Fig. 2(a)]. The green astro-comb's line spacing of 16 GHz [Figs. 2(b) and 2(c)] is approximately 2.5 times larger than the resolution of the HARPS-N spectrograph in this spectral range, which is the optimal line spacing for spectral calibration [2]. With the source comb referenced to the Global Positioning System (GPS) and the validation of filter cavity performance as described below and in Supplement 1, the wavelength of each astro-comb line as measured on the HARPS-N spectrograph provides a calibration accurate to <10 cm/s, and the full astro-comb spectrum provides sufficient SNR to realize a calibration precision of <10 cm/s with a single exposure of the spectrograph.

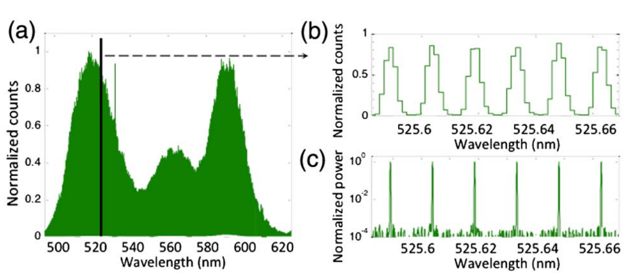

Fig. 2. (a) Broadband spectrum of green astro-comb, as measured by the HARPS-N spectrograph, composed of >7000 spectral lines from 500 to 620 nm. Example segment of green astro-comb spectrum measured by (b) HARPS-N and (c) high-resolution Fourier transform spectrometer (FTS) shows astro-comb lines spaced by 16 GHz (≈0.016 nm at 525 nm). Neither instrument resolves the <1 MHz linewidth.

2. SETUP

The green astro-comb is generated from a 1 GHz repetition rate, titanium-sapphire (Ti:sapphire) octave-spanning laser frequency comb, a custom tapered photonic crystal fiber (PCF) for spectral shifting and broadening, and a 16 GHz longitudinal mode filter, which is composed of two Fabry–Perot cavities (FPCs), as shown in Fig. 1. Comb lines in the green spectral bands, which are the most useful for RV measurements of solar-type stars [13,14], are generated by coupling the near-infrared output of the Ti:sapphire source comb into a solid-core PCF. We optimized the PCF to utilize the nonlinear process known as fiber-optic Cherenkov radiation, which can produce broad spectra of uniform power for lengths of PCF short enough (~few millimeters) to avoid phase mismatch between the original and nonlinearly generated laser fields, and with input laser pulses of only a few optical cycles and sufficient power to have efficient nonlinear conversion over the relatively short interaction length [15,16]. The laser pulsewidth in the fiber is minimized and the green comb output power maximized by careful dispersion management using doubly chirped mirrors to compensate for the positive dispersion of optical elements such as the fiber coupling lens. However, coupling temporally short and thus spectrally broad pulses into a PCF is challenging because of the chromatic aberration of the coupling lens (a singlet asphere to minimize dispersion) and the high numerical aperture (NA) of the fiber ($\mathrm{NA} \approx 0.4$ for $\lambda = 800$ nm). We addressed this technical challenge by reducing the fiber NA by a factor of ~4 using two standard techniques: (i) tapering a larger core, smaller NA fiber to the required size, and (ii) fiber end sealing, which leads to a factor of >2 improvement in the coupling efficiency (see Fig. 3). We performed final optimization of the PCF taper profile using numerical simulation of the nonlinear process that generates the green comb lines in the PCF, as modeled by the nonlinear Schrödinger equation [15,16], to maximize bandwidth coverage, spectral flatness, and conversion efficiency. The resultant optimized green comb spectrum (with 1 GHz line spacing) is shown in Fig 3(c), with >100 nW per comb line and linewidths <1 MHz, as measured with heterodyne detection. We observed no significant change in

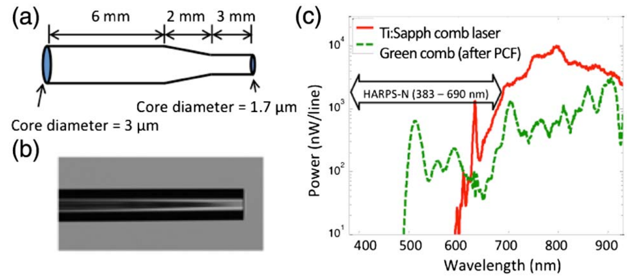

Fig. 3. (a) Dimensions of tapered photonic crystal fiber (PCF, not to scale). A solid-core PCF is tapered to the desired size over a few millimeters, which gives an adiabatic transition between the transverse modes of the large and small fiber cores. (b) Optical micrograph of tapered PCF with a sealed end. End sealing collapses the air holes guiding the light at the beginning and end of the fiber such that there is an adiabatic transition between free propagation in the uniform glass at each fiber end and guided propagation in the solid core of the holey fiber, which approximately halves the numerical aperture. (c) Input near-infrared spectrum to PCF from Ti:sapphire source comb and output green comb spectrum (both with 1 GHz line spacing), as measured on an optical spectrum analyzer. The green comb spectrum covers more than 50% of the bandwidth of the HARPS-N spectrograph (383–690 nm).

the power profile of the green comb spectrum over several months of operation.

To convert the 1 GHz green comb to a 16 GHz green astro-comb, the comb spectral lines generated by the PCF are mode filtered by two FPCs in series. The mode spacing or free spectral range (FSR) of each FPC is tuned such that the FPCs pass every 16th comb line and suppress the intermediate 15 comb lines to a level determined by the cavity finesse (ratio of FSR to the cavity resonance linewidth). The FPCs are composed of plane-parallel, complementary-chirped mirror (CCM) pairs [17–20] with 97.5% reflectivity, and utilize 0.5° wedged mirror substrates to avoid forming unwanted etalons [6]. A Faraday optical isolator providing >25 dB isolation from 500 to 620 nm is placed between the cavities to reduce deviations from the ideal FPC transmission function due to backreflections. The CCM pairs are dielectric mirrors with opposite group delay dispersion (GDD, the change in mirror penetration depth with wavelength), capable of forming an FPC with minimal GDD over a much broader bandwidth than FPCs with identical mirrors, which is critical for matching the FPC FSR to the comb line spacing. We measured a spectral range of about 500–620 nm over which the FPCs in series have small enough variation in FSR to transmit the desired comb lines and high enough finesse to suppress the undesired lines (see Supplement 1, Section S.1, and [6] for details of the measurement).

3. CHARACTERIZATION

In practice, the accuracy and stability of the green astro-comb as a wavelength calibrator are not limited by the atomic clock reference, but rather by finite FPC suppression of the source comb lines between the astro-comb lines, referred to as astro-comb sidebands, which can lead to systematic shifts of astro-comb lines as measured by the HARPS-N spectrograph. Since HARPS-N cannot resolve the undesired sidebands relative to the desired astro-comb lines, finite sideband power contributes to the overall centroid of the astro-comb lines, such that any variation in line-to-line power of the source comb leads to wavelength calibration errors. To achieve <10 cm/s RV accuracy, the power of all sidebands needs to be stabilized or suppressed to better than −40 dB of the astro-comb lines. [The calibration error in RV units is approximately $\delta \mathrm{RV} \approx c f_R / f_A \times (I_{+1} - I_{-1})/I_A$ where c is the speed of light, f_R is the comb repetition rate, f_A is the optical frequency of an astro-comb line, $I_{\pm 1}$ are the intensities of the nearest undesired comb lines, and I_A is the intensity of the astro-comb line. See Supplement 1, Section S.1, for details.] A single FPC, with the FSR set to 16 times the source comb repetition rate and finesse ≈105, theoretically suppresses astro-comb sidebands by >22 dB, giving an expected total suppression >44 dB for the two cavities. To validate the performance of our FPCs, we performed a series of measurements of sideband suppression using three complementary techniques: heterodyne detection, measurement of the FPC transmission profile around 532 nm combined with phase error and finesse measurements across the full astro-comb spectrum using a commercial optical spectrum analyzer, and direct measurements of the sideband relative powers using a Fourier transform spectrometer (FTS) capable of resolving the 1 GHz source comb spectral lines [21]. Figure 4 shows the FTS results. When filtered by one FPC, undesired comb lines at $\pm m$ GHz relative to the astro-comb line ($m = 1, 2, 3, \ldots$) are suppressed by >20 dB but visible with the FTS. Two FPCs in series suppress undesired comb lines by >40 dB, below the FTS measurement sensitivity. Greater than 40 dB suppression, as observed for all sidebands when using two FPCs, ensures RV accuracy of better than 10 cm/s for astro-comb lines when calibrating the HARPS-N spectrograph. While data are averaged across 25 consecutive astro-comb lines, Fourier analysis of suppression at a given offset frequency demonstrates that the raw data have no spectral features at a level lower than the noise floor shown here, confirming that no periodic features are hidden by the averaging process. The complete set of measurements is described in detail in Supplement 1 Section S.2. All three measurement techniques indicate sideband suppression >40 dB relative to the astro-comb lines, ensuring <10 cm/s RV accuracy of astro-comb lines measured on an astrophysical spectrograph across the full green astro-comb bandwidth.

4. OPERATION AT AN ASTRONOMICAL TELESCOPE

In January, 2013 we deployed the green astro-comb at the Telescopio Nazionale Galileo (TNG) on La Palma in the Canary Islands as a wavelength calibrator for the HARPS-N spectrograph. HARPS-N is a fiber-fed echelle spectrograph, using 69 diffraction orders to cover the 383–690 nm spectral band [22]. Light from two different sources, typically an astronomical object (with light acquired by the TNG) and a wavelength calibrator, is coupled into HARPS-N through two multimode input fibers and then measured simultaneously.

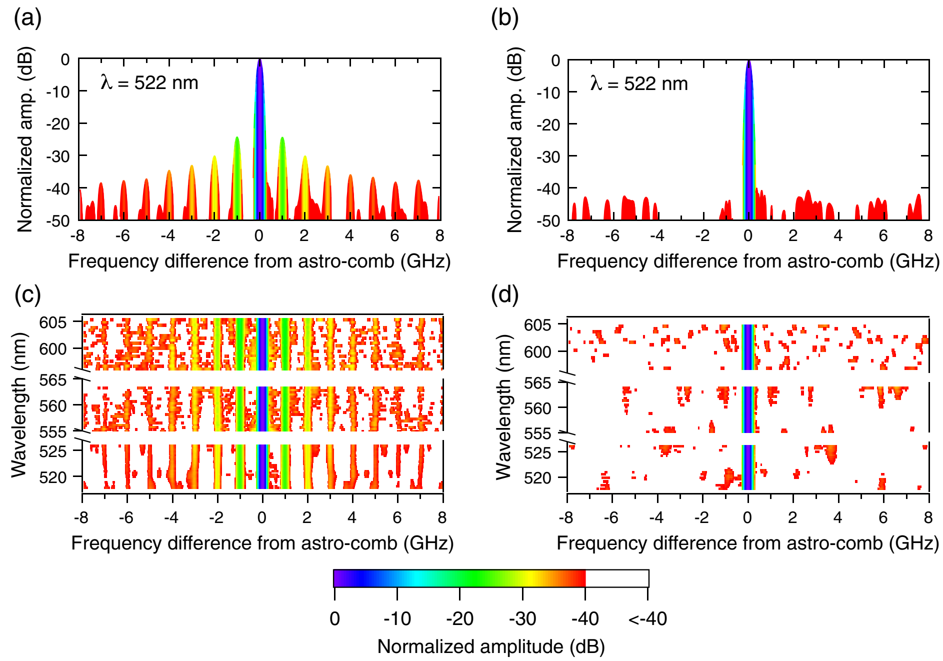

Fig. 4. Suppression of undesired comb lines when filtered by (a), (c) one Fabry–Perot cavity (FPC) and (b), (d) two FPCs as measured with a high-resolution Fourier transform spectrometer (FTS). Examples of measured sideband suppression for (a) one and (b) two FPCs averaged across 25 consecutive astro-comb lines and across a wide range of representative wavelengths for (c) one and (d) two FPCs, in 10 nm bands centered at 520, 560, and 600 nm. See text and Supplement 1, Section S.2, for details.

As a demonstration of the green astro-comb serving as the HARPS-N wavelength calibrator for a bright astronomical object, we observed reflected sunlight from the asteroid Vesta 4 coupled into one input fiber and the green astro-comb coupled into the second input fiber. The use of multimode fibers is essential for collecting enough starlight to make high-precision RV measurements, but it limits the SNR of the astro-comb calibration as measured by HARPS-N to ∼50 due to speckle pattern noise [9–11]. To mitigate the speckle-induced noise, an additional length of multimode fiber carrying astro-comb light, located before the HARPS-N input fiber, is mechanically shaken at a rate much faster than the integration time per exposure of the HARPS-N detector (∼100 s), washing out the speckle pattern. Using this technique we achieve a typical peak SNR of >350 for the green astro-comb as measured by HARPS-N, which is within 10% of the theoretical SNR due to photon shot noise. We also find that the green astro-comb typically provides a single exposure RV calibration of HARPS-N with a one-sigma uncertainty ≈6 cm/s. When comparing averages of eight exposures, the RV calibration approaches a 1 cm/s uncertainty, which is consistent with photon shot noise, in the calibration difference between the science and calibration fibers with comb light injected into both (Fig. 5).

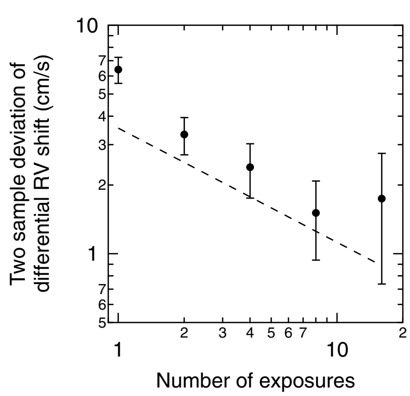

Fig. 5. Two-sample deviation of the measured spectral shift between the two HARPS-N fibers when both are illuminated by green astro-comb light, with one-sigma error bars. Differences between exposures are derived from cross correlations with the sum of all exposures. Dashed line is the expected photon shot noise limit.

5. CONCLUSIONS

In conclusion, we developed, installed, and successfully operated a green astro-comb with 16 GHz spectral line spacing as a wavelength calibrator for the HARPS-N spectrograph at the TNG telescope on La Palma. The green astro-comb is composed of a Ti:sapphire, octave-spanning, 1 GHz comb laser; a custom-tapered PCF to spectrally broaden the comb spectrum to 500 nm; and two broadband FPCs to increase the comb line spacing to 16 GHz so that spectral lines can be resolved by HARPS-N. The system delivers reliable astro-comb operation in the environment of an astronomical telescope, with minimal tending (∼1 h per day). We measured the accuracy of each astro-comb line to be better than 10 cm/s across the astro-comb spectrum, in terms of effective RV sensitivity, using a high-resolution FTS and other characterization methods. We plan to employ the green astro-comb as a high-performance wavelength calibrator for HARPS-N enabling RV measurement precision and stability <10 cm/s for observations of bright, low RV-jitter stars, with the potential to detect and characterize long-period, Earth-like exoplanets.

FUNDING INFORMATION

Harvard University Origins of Life Initiative; National Aeronautics and Space Administration (NASA); National Science Foundation (NSF); Smithsonian Astrophysical Observatory (SAO).

ACKNOWLEDGMENT

We thank Emilio Molinari and the entire staff of the TNG telescope and Francesco Pepe and Christophe Lovis from the Geneva Observatory for their support and advice.

†These authors contributed equally to this work.

See Supplement 1 for supporting content.

REFERENCES

1. C. Lovis, M. Mayor, F. Pepe, Y. Alibert, W. Benz, F. Bouchy, A. C. M. Correia, J. Laskar, C. Mordasini, D. Queloz, N. C. Santos, S. Udry, J.-L. Bertaux, and J.-P. Sivan, "An extrasolar planetary system with three Neptune-mass planets," Nature **441**, 305–309 (2006).
2. M. T. Murphy, T. Udem, R. Holzwarth, A. Sizmann, L. Pasquini, C. Araujo-Hauck, H. Dekker, S. D'Odorico, M. Fischer, T. W. Hänsch, and A. Manescau, "High-precision wavelength calibration of astronomical spectrographs with laser frequency combs," Mon. Not. R. Astron. Soc. **380**, 839–847 (2007).
3. C.-H. Li, A. J. Benedick, P. Fendel, A. G. Glenday, F. X. Kärtner, D. F. Phillips, D. Sasselov, A. Szentgyorgyi, and R. L. Walsworth, "A laser frequency comb that enables radial velocity measurements with a precision of 1 cm/s," Nature **452**, 610–612 (2008).
4. T. Steinmetz, T. Wilken, C. Araujo-Hauck, R. Holzwarth, T. W. Hänsch, L. Pasquini, A. Manescau, S. D'Odorico, M. T. Murphy, T. Kentischer, W. Schmidt, and T. Udem, "Laser frequency combs for astronomical observations," Science **321**, 1335–1337 (2008).
5. D. A. Braje, M. S. Kirchner, S. Osterman, T. Fortier, and S. A. Diddams, "Astronomical spectrograph calibration with broad-spectrum frequency combs," Eur. Phys. J. D **48**, 57–66 (2008).
6. C.-H. Li, A. G. Glenday, A. J. Benedick, G. Chang, L.-J. Chen, C. Cramer, P. Fendel, G. Furesz, F. X. Kartner, S. Korzennik, D. F. Phillips, D. Sasselov, A. Szentgyorgyi, and R. L. Walsworth, "*In-situ* determination of astro-comb calibrator lines to better than 10 cm/s," Opt. Express **18**, 13239–13249 (2010).
7. A. J. Benedick, G. Chang, J. R. Birge, L.-J. Chen, A. G. Glenday, C.-H. Li, D. F. Phillips, A. Szentgyorgyi, S. Korzennik, G. Furesz, R. L. Walsworth, and F. X. Kärtner, "Visible wavelength astro-comb," Opt. Express **18**, 19175–19184 (2010).
8. F. Quinlan, G. Ycas, S. Osterman, and S. A. Diddams, "A 12.5 GHz-spaced optical frequency comb spanning > 400 nm for near-infrared astronomical spectrograph calibration," Rev. Sci. Instrum. **81**, 063105 (2010).
9. G. G. Ycas, F. Quinlan, S. A. Diddams, S. Osterman, S. Mahadevan, S. Redman, R. Terrien, L. Ramsey, C. F. Bender, B. Botzer, and S. Sigurdsson, "Demonstration of on-sky calibration of astronomical spectra using a 25 GHz near-IR laser frequency comb," Opt. Express **20**, 6631–6643 (2012).
10. T. Wilken, C. Lovis, A. Manescau, T. Steinmetz, L. Pasquini, G. Lo Curto, T. W. Hänsch, R. Holzwarth, and T. Udem, "High-precision calibration of spectrographs," Nature **485**, 611–614 (2012).
11. D. F. Phillips, A. G. Glenday, C.-H. Li, C. Cramer, G. Furesz, G. Chang, A. J. Benedick, L.-J. Chen, F. X. Kärtner, S. Korzennik, D. Sasselov, A. Szentgyorgyi, and R. L. Walsworth, "Calibration of an astrophysical spectrograph below 1 m/s using a laser frequency comb," Opt. Express **20**, 13711–13726 (2012).
12. T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical frequency metrology," Nature **416**, 233–237 (2002).
13. W. J. Merline, "Radial velocity information in solar-type spectra," in *Stellar Radial Velocities*, A. G. D. Philip and D. W. Latham, eds. (L. Davis Press, 1985), pp. 87–98.
14. R. P. Butler, G. W. Marcy, E. Williams, C. McCarthy, P. Dosanjh, and S. S. Vogt, "Attaining Doppler precision of 3 m/s," Publ. Astron. Soc. Pac. **108**, 500–509 (1996).
15. G. Chang, C.-H. Li, D. F. Phillips, R. L. Walsworth, and F. X. Kärtner, "Toward a broadband astro-comb: effects of nonlinear spectral broadening in optical fibers," Opt. Express **18**, 12736–12747 (2010).
16. G. Chang, L.-J. Chen, and F. X. Kärtner, "Fiber-optic Cherenkov radiation in the few-cycle regime," Opt. Express **19**, 6635–6647 (2011).
17. L.-J. Chen, G. Chang, C.-H. Li, A. J. Benedick, D. F. Phillips, R. L. Walsworth, and F. X. Kärtner, "Broadband dispersion-free optical cavities based on zero group delay dispersion mirror sets," Opt. Express **18**, 23204–23211 (2010).
18. L.-J. Chen, G. Chang, C.-H. Li, A. Glenday, A. J. Benedick, D. F. Phillips, R. L. Walsworth, and F. X. Kärtner, "High-finesse dispersion-free cavities for broadband filtration of laser comb lines," in *International Conference on Ultrafast Phenomena* (Optical Society of America, 2010), p. TuF1.
19. C.-H. Li, G. Chang, A. G. Glenday, N. Langellier, A. Zibrov, D. F. Phillips, F. X. Kärtner, A. Szentgyorgyi, and R. L. Walsworth, "Conjugate Fabry–Perot cavity pair for improved astro-comb accuracy," Opt. Lett. **37**, 3090–3092 (2012).
20. G. Chang, C.-H. Li, D. F. Phillips, A. Szentgyorgyi, R. L. Walsworth, and F. X. Kärtner, "Optimization of filtering schemes for broadband astro-combs," Opt. Express **20**, 24987–25013 (2012).
21. A. G. Glenday, D. F. Phillips, M. Webber, C.-H. Li, G. Furesz, G. Chang, L.-J. Chen, F. X. Kärtner, D. D. Sasselov, A. H. Szentgyorgyi, and R. L. Walsworth, "High-resolution Fourier transform spectrograph for characterization of echelle spectrograph wavelength calibrators," Proc. SPIE **8446**, 844696 (2012).
22. R. Cosentino, C. Lovis, F. Pepe, A. C. Cameron, D. W. Latham, E. Molinari, S. Udry, N. Bezawada, N. Buchschacher, P. Figueira, M. Fleury, A. Ghedina, A. G. Glenday, M. Gonzalez, J. Guerra, D. Henry, I. Hughes, C. Maire, F. Motalebi, and D. F. Phillips, "HARPS-N @ TNG, two year harvesting data: performances and results," Proc. SPIE **8446**, 84461V (2012).