Electro-optic frequency combs generated via direct digital synthesis applied to sub-Doppler spectroscopy

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Abstract

Direct digital synthesis in concert with an electro-optic phase modulator was employed to generate optical frequency combs with tooth spacings as low as 100 Hz. These combs were utilized to probe electromagnetically induced transparency (EIT) and hyperfine pumping in potassium vapor cells. Long-term coherent averaging was demonstrated with performance similar to that achieved with a vastly more expensive arbitrary waveform generator. From the potassium EIT transition we were able to determine the ground state hyperfine splitting with a fit uncertainty of 80 Hz. Importantly, because of the mutual coherence between the control and probe beams, which originate from a single laser, features with linewidths several orders-of-magnitude narrower than the laser linewidth could be observed in a multiplexed fashion. This approach removes the need for slow scanning of a traditional cw laser or mode-locked-laser-based optical frequency comb.

Electro-optic frequency combs [1–3] allow for an unprecedented degree of control over their parameters, providing for digital control over their span, comb tooth spacing, and central frequency (e.g., see Ref. [4–7] and the references contained therein). Critically, with the development of waveguide-based electro-optic modulators, the comb tooth spacing is independent of the laser cavity length and can therefore be made essentially arbitrarily narrow. As a result, combs can readily be produced with mode spacings more than six orders of magnitude denser than with a traditional mode-locked-laser-based optical frequency comb. This ultradense tooth spacing is ideally suited to the study of narrow sub-Doppler features in atomic and molecular systems [8–12].

While initial demonstrations of electro-optic frequency combs were performed with overdriven modulators in which a single or pair of continuous wave radiofrequencies is applied to the modulator [1–7], many recent efforts have focused upon the use of tailored radiofrequency waveforms [8–10,13–19]. These approaches have generally utilized either frequency chirps [8,9,15,16], pseudo-random bit sequences [10,13,17–19], or step recovery diodes [14]. The majority of these demonstrations have relied upon arbitrary waveform generators (AWGs) to produce these tailored waveforms [8,9,13,15–17,19], leading to high cost, power consumption, and size while also limiting the frequency agility due to the need to transfer long radiofrequency sequences which are rapidly sampled. Recently, direct digital

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synthesizers (DDSs) have been shown to be powerful alternatives to AWGs for chirped pulse Fourier transform microwave spectroscopy [20]. Here we apply this approach to generate electro-optic frequency combs with a DDS and demonstrate long-term coherent averaging of those combs for spectroscopic applications.

These combs allow for multiplexed, sub-Doppler spectroscopy whereby the entire spectrum can be acquired in a single interferogram, removing the need for slow spectral interleaving [21,22]. We have applied this platform to potassium transitions in the near-infrared region, probing ultranarrow electromagnetically induced transparency (EIT) features in vacuum and buffer gas cells (see Fig. 1 for an energy level diagram). This approach enables the interrogation of features that are as narrow as 1 kHz, significantly narrower than the initial laser linewidth, and therefore, the width of an individual comb line.

The optical setup was similar to that found in Ref. [9] in which a self-heterodyne configuration was utilized [10,13] (see Fig. 1). The laser source was a fiber-coupled, external-cavity diode laser (ECDL) with an estimated linewidth of 50 kHz to 200 kHz at 5 μs and a wavelength range of 758.9 nm to 790.5 nm. For the present measurements the wavelength was set near 770.1 nm to probe $D_1$ transition of $^{39}\text{K}$. The laser was split into probe and local oscillator legs, with the probe path passed through a waveguide-based electro-optic phase modulator (PM) for comb generation. The PM was driven by repeated, linear frequency chirps generated by either an AWG or a DDS. The AWG had a maximum bandwidth of 5 GHz and operated at 12-bit vertical resolution. AWG sampling rates between $1.5\times10^9$ samples per second and $1\times10^{10}$ samples per second were employed for these measurements.

Our DDS electronics consisted of an evaluation board containing a high-speed, 12-bit DDS chip (Analog Devices AD9914) [24]. Communication with the DDS chip was performed using a microcontroller (μ-controller) and a serial peripheral interface (SPI) (see Fig. 1). We programmed the DDS to start a new frequency chirp upon receiving a trigger from an external delay generator. A separate phase-locked-loop (PLL) circuit provided the clock signal for the DDS at either 3.6 GHz or 3.75 GHz. The PLL and delay generator were both referenced to the same 10 MHz clock signal that was used to stabilize the oscilloscope, ensuring that each piece of equipment shared a common timebase. The DDS output was filtered to avoid aliased signals above the Nyquist frequency and the amplitude was adjusted to match that of the AWG. See the appendix for more experimental details relating to the DDS.

A comparison of the radiofrequency outputs generated by the AWG and DDS can be found in Fig. 2. Both devices produce exceptionally flat radiofrequency combs with transform-limited comb tooth widths. In the central region of the combs between 250 MHz and 600 MHz, the relative standard deviations of the comb teeth amplitudes are just 6.4% for the DDS and 1.9% for the AWG. The DDS comb flatness is slightly degraded by the external RF amplifier that is necessary to match the amplitude of the AWG. Removing this amplifier and one of the low pass filters improves the relative standard deviation of the DDS comb to 4.1%. While the AWG produces a flatter comb, as we shall see in the results discussion, normalization leads to similar spectroscopic signal-to-noise ratios.
An acousto-optic modulator (AOM) was employed to ensure that the positive- and negative-order comb teeth occurred at unique frequencies in the RF spectrum of the photodetector. After being launched into free space, the probe beam was expanded to a $1/e^2$ diameter which was varied between 2 mm and 6 mm over the course of these measurements and made circularly polarized (which can lead to larger cross sections [25]) before being sent into an atomic vapor absorption cell.

Two separate absorption cells were used during these measurements. The first was an evacuated cell 25 cm long with a diameter of 2.54 cm and contained potassium vapor at natural isotopic abundance. The second cell was 7.5 cm in length with a diameter of 2.54 cm and contained potassium vapor at natural isotopic abundance as well as 2.67 kPa of argon. Millions of collisions of the absorber with a buffer gas can occur before loss of coherence, thus leading to a dramatic reduction of transit time broadening [26–28]. Stray magnetic fields that affect each cell (measured to be ≤ 86 μT) were reduced by roughly three orders of magnitude by a triply shielded nickel-iron alloy chamber. An insulated box was then placed around this chamber to allow for heating to near 36 °C.

After the probe beam passed through the cell it was returned to linear polarization and was then relaunched into an optical fiber where it was combined with the local oscillator beam and sampled using a 1-GHz bandwidth detector with a noise-equivalent power of 31 pW/Hz$^{1/2}$. The detector signal was amplified and then split into two legs; one of which went to a 4 GHz, 8-bit oscilloscope for data acquisition and the other to a phase-locking servo. The latter signal was fed back to the voltage-controlled oscillator which drove the AOM to allow for long-term coherent averaging by removing phase noise in the laser beam caused by thermal and mechanical fiber fluctuations [14]. The laser wavelength was stabilized with a loop bandwidth of 2 Hz using a high precision wavelength meter with 15 MHz resolution. This servo did not have a large effect on the resulting spectra due to the common-mode nature of the pump and probe beams.

The resulting spectra were then normalized against spectra recorded when the laser was detuned 4 GHz from the relevant absorption features. These normalized transmission spectra (i.e., $I/I_0$) were converted to an intensity-based absorbance scale according to $A=-2\ln(I/I_0)$, where the factor of 2 accounts for the heterodyne nature of the measurement in which the time-averaged signal intensity is proportional to the product of the field amplitudes of the local oscillator and transmitted probe beams [29].

An optical frequency comb spanning 200 MHz to 650 MHz from the carrier with a comb tooth spacing of 200 kHz (i.e., containing 2 250 positive-order comb teeth) was used to probe the $D_1$ transitions of $^{39}$K and $^{41}$K near 770.1 nm (see Fig. 3). The unmodulated, carrier frequency of the comb served as the pump (i.e., control) beam to initiate the sub-Doppler spectroscopy. This allows for multiplexed observations of hyperfine pumping and EIT features. Due to the high signal-to-noise ratios, which are enabled via coherent time domain averaging, we are able to also observe the EIT feature for the rare $^{41}$K isotope in our natural isotopic abundance sample. Despite the higher radiofrequency flatness observed when using the AWG (see Fig. 2), the resulting spectra recorded when using the DDS and AWG are similar, indicating that the normalization efficiently accounts for these variations.
Due to the digitally controlled nature of the comb repetition rate, we are able to produce combs with tooth spacings as low as 100 Hz using both the DDS and AWG. The resulting ultrahigh resolution frequency combs can be seen in Fig. 4. The DDS and AWG lead to almost identical optical frequency combs, with the DDS producing a slightly flatter comb.

We utilized these optical frequency combs to probe an EIT feature which is dramatically narrower than the laser linewidth (and therefore the comb linewidths). To produce these ultranarrow EIT feature we employed a potassium cell with an argon buffer gas. The presence of the buffer gas leads to a reduction of the transit time broadening, leading to dramatically narrower EIT features \[26–28\]. As can be seen in Fig. 5, the combs can clearly resolve an EIT feature with a width of only 1.0 kHz. Importantly, this width is a factor of 50 to 200 narrower than the estimated laser linewidth. This sub-laser-linewidth resolution is enabled by the mutual coherence between the pump and probe beams, thus allowing for a significant reduction of the apparent frequency jitter \[30–32\]. The ten DDS-based spectra which were averaged in Fig. 5 were then individually fit to a Lorentzian with a linear baseline. These fits led to a fitted center frequency and standard uncertainty for the EIT feature of 461.71980(8) MHz. This value agrees with the microwave value of 461.7197201(6) MHz \[33\] at the 1σ level.

The current self-heterodyne configuration of electro-optic frequency combs enables multiplexed direct frequency comb spectroscopy with unprecedented resolution. Unlike measurement techniques that employ traditional mode-locked-laser-based optical frequency combs, no slow interleaving of combs with relatively coarse tooth spacing is required to achieve high resolution. Further, in comparison to traditional cw laser approaches, the spectra can be recorded in a single shot, thus removing the need for slow spectral scanning. The present approach exploits the high mutual coherence of the pump (control) and probe fields to enable the efficient preparation and highly resolved observation of dressed states.

We have demonstrated a new approach for electro-optic frequency comb generation which overcomes the high cost, size, and power consumption of arbitrary waveform generators while offering higher frequency agility. Further, this approach allows for ultraflat optical frequency combs and coherent time domain averaging, leading to high signal-to-noise ratio spectra which are comparable to that achievable with an arbitrary waveform generator. While the bandwidth of available direct digital synthesizers is lower than that commercially available with high-end arbitrary waveform generators, these type of waveforms can readily be multiplied up to higher frequencies \[34–36\]. Further, a variety of techniques have been demonstrated to extend the bandwidth of electro-optic frequency combs through nonlinear broadening (e.g., \[6,7,19\]) or cascaded modulators (e.g., \[7,17,28\]). These attributes make the present method attractive for high-precision frequency metrology in atomic and molecular systems as well as for comb generation in areas such as distance metrology and communications.

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Appendix

We used the AD9914’s built-in digital ramp generator (DRG) to produce the linear frequency chirps using only a handful of parameters. Although the DDS can be programmed to continuously repeat these ramps based upon internal timing settings, in this configuration the initial phase at the beginning of each chirp is not controlled and therefore multiple ramps do not coherently average. Thus, we set the DDS to start a new ramp with a consistent phase upon receiving a digital trigger on the IUPDATE pin by setting the “Autoclear digital ramp accumulator” and “Autoclear phase accumulator” flags high [24]. The repetition rate (f_{rep}) and therefore comb tooth spacing were then controlled by a series of digital triggers that were generated externally using a digital delay generator (Berkley Nucleonics Corporation Model 745). We find that excess timing jitter on these digital triggers leads to noise in the comb spectrum, so a high-quality timing source is important. Although the nominal clock frequency (f_{clock}) of the AD9914 is 3.5 GHz, we have slightly overclocked the device up to 4.0 GHz without issue. Since the DRG updates at a rate of f_{clock}/24, we found that it is important to use a clock frequency that satisfied the condition f_{clock}/24=mf_{rep}, where m is an integer. Violating this condition led to unexpected comb teeth spacing and offsets. The DDS can be programmed to output a trigger indicating that the completion of a frequency ramp, which can optionally be used to trigger data acquisition.

References

1. Kourogi M, Nakagawa K, and Ohtsu M, “Wide-span optical frequency comb generator for accurate optical frequency difference measurement,” IEEE J. Quantum Electron 29(10), 2693–2701 (1993).
2. Kourogi M, Enami T, and Ohtsu M, “A monolithic optical frequency comb generator,” IEEE Photonics Technol. Lett 6(2), 214–217 (1994).
3. Ye J, Ma L-S, Daly T, and Hall JL, “Highly selective terahertz optical frequency comb generator,” Opt. Lett 22(5), 301–303 (1997). [PubMed: 18183182]
4. Torres-Company V. and Weiner AM, “Optical frequency comb technology for ultra-broadband radio-frequency photonics,” Laser Photonics Rev. 8(3), 368–393 (2014).
5. Long DA, Fleisher AJ, Douglass KO, Maxwell SE, Bielska K, Hodges JT, and Plusquellic DF, “Multiheterodyne spectroscopy with optical frequency combs generated from a continuous-wave laser,” Opt. Lett 39(9), 2688–2690 (2014). [PubMed: 24784078]
6. Millot G, Pitois S, Yan M, Hovhannisyan T, Bendahmane A, Hänsch TW, and Picqué N, “Frequency-agile dual-comb spectroscopy,” Nat. Photonics 10(1), 27–30 (2016).
7. Beha K, Cole DC, Del’Haye P, Coillet A, Diddams SA, and Papp SB, “Electronic synthesis of light,” Optica 4(4), 406–411 (2017).
8. Long DA, Fleisher AJ, Plusquellic DF, and Hodges JT, “Multiplexed sub-Doppler spectroscopy with an optical frequency comb,” Phys. Rev. A 94(6), 061801 (2016).
9. Long DA, Fleisher AJ, Plusquellic DF, and Hodges JT, “Electromagnetically induced transparency in vacuum and buffer gas potassium cells probed via electro-optic frequency combs,” Opt. Lett 42(21), 4430–4433 (2017). [PubMed: 29088179]
10. Hébert NB, Michaud-Belleau V, Anstie JD, Deschênes JD, Luiten AN, and Genest J, “Self-heterodyne interference spectroscopy using a comb generated by pseudo-random modulation,” Opt. Express 23(21), 27806–27818 (2015). [PubMed: 26480442]
11. Wilson N, Hébert NB, Perrella C, Light P, Genest J, Pustelny S, and Luiten A, “Simultaneous Observation of Nonlinear Magneto-Optical Rotation in the Temporal and Spectral Domains with an Electro-Optic Frequency Comb,” Phys. Rev. Appl 10(3), 034012 (2018).
12. Hebert NB, Michaud-Belleau V, Perrella C, Truong GW, Anstie JD, Stace TM, Genest J, and Luiten AN, “Real-time dynamic atomic spectroscopy using electro-optic frequency combs,” Phys. Rev. Appl 6(4), 044012 (2016).
13. Bao Y, Yi X, Li Z, Chen Q, Li J, Fan X, and Zhang X, “A digitally generated ultrafine optical frequency comb for spectral measurements with 0.01-pm resolution and 0.7-μs response time,” Light: Sci. Appl 4(6), e300 (2015).
14. Fleisher AJ, Long DA, Reed ZD, Hodges JT, and Plusquellic DF, “Coherent cavity-enhanced dual-comb spectroscopy,” Opt. Express 24(10), 10424–10434 (2016). [PubMed: 27409866]
15. Lou XT, Yuan ZY, and Dong YK, “Rapid spectroscopic gas sensing using optical linear chirp chain,” Opt. Express 27(9), 13160–13171 (2019). [PubMed: 31052845]
16. Wang S, Fan XY, Xu BX, and He ZY, “Fast MHz spectral-resolution dual-comb spectroscopy with electro-optic modulators,” Opt. Lett 44(1), 65–68 (2019). [PubMed: 30645549]
17. Wang S, Fan X, Xu B, and He Z, “Dense electro-optic frequency comb generated by two-stage modulation for dual-comb spectroscopy,” Opt. Lett 42(19), 3984–3987 (2017). [PubMed: 28957178]
18. Yan X, Zou X, Pan W, Yan L, and Azaña J, “Fully digital programmable optical frequency comb generation and application,” Opt. Lett 43(2), 283–286 (2018). [PubMed: 29328260]
19. Xu B, Fan X, Wang S, and He Z, “Broadband and high-resolution electro-optic dual-comb interferometer with frequency agility,” Opt. Express 27(6), 9266–9275 (2019). [PubMed: 31052734]
20. Finneran IA, Holland DB, Carroll PB, and Blake GA, “A direct digital synthesis chirped pulse Fourier transform microwave spectrometer,” Rev. Sci. Instrum 84(8), 083104 (2013). [PubMed: 24007050]
21. Sautenkov VA, Rostovtsev YV, Ye CY, Welch GR, Kocharovskyaya O, and Scully MO, “Electromagnetically induced transparency in rubidium vapor prepared by a comb of short optical pulses,” Phys. Rev. A 71(6), 063804 (2005).
22. Meek SA, Hipke A, Guelachvili G, Hänsch TW, and Picqué N, “Doppler-free Fourier transform spectroscopy,” Opt. Lett 43(4), 162–165 (2018). [PubMed: 29328222]
23. Falke S, Tiemann E, Lisdat C, Schnatz H, and Grosche G, “Transition frequencies of the D lines of 39K, 40K, and 41K measured with a femtosecond laser frequency comb,” Phys. Rev. A 74(3), 032503 (2006).
24. “AD9914 Data Sheet”, retrieved 12 July 2019, https://www.analog.com/media/en/technical-documentation/data-sheets/AD9914.pdf.
25. McGloin D, Dunn MH, and Fulton DJ, “Polarization effects in electromagnetically induced transparency,” Phys. Rev. A 62(5), 053802 (2000).
26. Brandt S, Nagel A, Wynands R, and Meschede D, “Buffer-gas-induced linewidth reduction of coherent dark resonances to below 50Hz,” Phys. Rev. A 56(2), R1063–R1066 (1997).
27. Ezekiel S, Smith SP, Shahriar MS, and Hemmer PR, “New opportunities in fiberoptic sensors,” J. Lightwave Technol 13(7), 1189–1192 (1995).
28. Nikonov DE, Rathe UW, Scully MO, Zhu SY, Fry ES, Li XF, Padmabandu GG, and Fleischhauer M, “Atomic coherence effects within the sodium D1 manifold. II. Coherent optical pumping,” Quantum Opt. 6(4), 245–260 (1994).
29. Fleisher AJ, Long DA, and Hodges JT, “Quantitative modeling of complex molecular response in coherent cavity-enhanced dual-comb spectroscopy,” J. Mol. Spectrosc 352, 26–35 (2018).
30. Xiao Y, Wang T, Baryakhtar M, Van Camp M, Crescimanno M, Hohenese M, Jiang L, Phillips DF, Lukin MD, Yelin SF, and Walsworth RL, “Electromagnetically induced transparency with noisy lasers,” Phys. Rev. A 80(4), 041805 (2009).
31. Mikhailov EE, Sautenkov VA, Rostovtsev YV, Zhang A, Zubairy MS, Scully MO, and Welch GR, “Spectral narrowing via quantum coherence,” Phys. Rev. A 74(1), 013807 (2006).

32. Jeong T, Bae I-H, and Moon HS, “Noise filtering via electromagnetically induced transparency,” Opt. Commun 383, 31–35 (2017).

33. Chan YW, Cohen VW, and Silsbee HB, “Measurement of hyperfine structure in ground states of 39K, 41K and 23Na,” Bull. Am. Phys. Soc 15, 1521 (1970).

34. Brown GG, Dian BC, Douglass KO, Geyer SM, Shipman ST, and Pate BH, “A broadband Fourier transform microwave spectrometer based on chirped pulse excitation,” Rev. Sci. Instrum 79(5), 053103 (2008). [PubMed: 18513057]

35. Neill JL, Harris BJ, Steber AL, Douglass KO, Plusquellic DF, and Pate BH, “Segmented chirped-pulse Fourier transform submillimeter spectroscopy for broadband gas analysis,” Opt. Express 21(17), 19743–19749 (2013). [PubMed: 24105522]

36. Gerecht E, Douglass KO, and Plusquellic DF, “Chirped-pulse terahertz spectroscopy for broadband trace gas sensing,” Opt. Express 19(9), 8973–8984 (2011). [PubMed: 21643150]
Fig. 1.
(a) Energy level diagram for $^{39}\text{K}$. The upper state, $^2\text{P}_{1/2}$, splitting is 55.5MHz while the lower state, $^2\text{S}_{1/2}$, splitting is 461.7MHz [23]. (b) Direct digital synthesizer (DDS) architecture for chirp generation. A low jitter digital gate delay generator is used to control the chirp repetition rate ($f_{\text{rep}}$). (c) Experimental schematic. The probe laser is divided into probe and local oscillator legs in a self-heterodyne configuration. The probe comb is generated by an electro-optic phase modulator (PM) driven with an RF source (either the arbitrary waveform generator or a direct digital synthesizer). An acousto-optic modulator (AOM) is used to separate the positive and negative order comb teeth in the resulting interferogram and as an actuator for the phase lock. This phase lock (using a phase-frequency detector, PFD, and voltage-controlled oscillator, VCO) cancels out thermal and mechanical fluctuations between the probe and local oscillator legs and allows for coherent averaging.
Fig. 2.
(Lower panels) Magnitude of the Fourier transform of typical radiofrequency outputs from the direct digital synthesizer (left) and arbitrary waveform generator (right). Each trace contained $5\times10^6$ samples recorded at $5\times10^9$ samples per second. The resulting radiofrequency combs span 200MHz to 650MHz with a spacing of 200 kHz. (Upper panels) These panels give a zoomed-in-view. The relative standard deviations of the shown 11 comb teeth are 1.4% (left) and 1.0% (right).
Electromagnetically induced transparency (EIT) and hyperfine pumping spectra for the $^{39}$K and $^{41}$K $D_1$ transitions in the evacuated gas cell using the arbitrary waveform generator (AWG) and direct digital synthesizer (DDS) for comb generation. The x-axis is given as detuning relative to the carrier. The cell was held near 37 °C and contained potassium at natural isotopic abundance. The shown spectra were recorded with a comb tooth spacing of 200 kHz. One thousand interferograms were coherently averaged in the time domain before being Fourier transformed and normalized to produce a spectrum. Each interferogram contained $5\times10^6$ samples recorded at $5\times10^9$ samples per second. Ten of these spectra were then averaged to produce the shown traces.
Fig. 4.
Typical ultrahigh resolution optical frequency combs containing 400 comb teeth spaced at 100Hz. The x-axis is given as detuning relative to the center of the frequency comb which is located 461.73MHz from the carrier. The top comb was generated via direct digital synthesis while the bottom comb was generated with the arbitrary waveform generator. The shown self-heterodyne spectra are the average of five off-resonance frequency domain traces. Each component trace was the magnitude of the Fourier transform of one thousand coherently averaged interferograms which contained $5 \times 10^7$ samples recorded at $1 \times 10^9$ samples per second. The inset shows a zoomed-in-view of the optical frequency combs. Note that the comb teeth are resolution bandwidth limited. The relative standard deviation of the magnitudes of the twenty-one comb teeth shown in the inset are 1.2% (direct digital synthesizer, top) and 1.7% (arbitrary waveform generator, bottom).
Fig. 5.
Electromagnetically induced transparency (EIT) spectrum for the $^{39}\text{K} D_1$ transition in the buffer gas cell using the arbitrary waveform generator (AWG) and direct digital synthesizer (DDS) for comb generation. The x-axis is given as detuning relative to the carrier. The DDS trace was shifted down vertically one division for clarity. The cell contained 2.67 kPa of argon buffer gas and was held near 36 °C. The shown spectra were recorded with a comb tooth spacing of 100Hz. One thousand interferograms were coherently averaged in the time domain before being Fourier transformed and normalized to produce a spectrum. Each interferogram contained $5 \times 10^7$ samples recorded at $1 \times 10^9$ samples per second. Ten of these spectra were then averaged to produce the shown traces. The differences in the baseline curvature are likely due to temporal variations of the normalization procedure rather than due to inherent differences between the AWG and DDS.