Characterization of an actively linearized ultrabroadband chirped laser with a fiber-laser optical frequency comb

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The optical frequency sweep of an actively linearized, ultrabroadband, chirped laser source is characterized through optical heterodyne detection against a fiber-laser frequency comb. Frequency sweeps were measured over approximately 5 THz bandwidths from 1530 nm to 1570 nm. The dominant deviation from linearity resulted from the nonzero dispersion of the fiber delay used as a reference for the sweep linearization. Removing the low-order dispersion effects, the residual sweep nonlinearity was less than 60 kHz rms, corresponding to a constant chirp with less than 15 ppb deviation across the 5 THz sweep.

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Active linearization of tunable laser sources using delayed self-heterodyne fiber interferometers [1–3] has generated ultrabroadband stabilized linear frequency chirps (LFCs). Their extreme linearity has led to record frequency modulated continuous wave ladar range resolutions ($<50\,\mu$m) with ranging precision of well below an optical wavelength [4]. In addition to high resolution ranging for length metrology and imaging [5], LFCs can improve precision in areas, such as swept wavelength optical spectrum analysis [6] and tunable laser spectroscopy.

Based on in-loop residuals, our LFC source [4] could achieve 6 ppb linearity, or less than 30 kHz deviation over a 5 THz bandwidth. However, to realize this performance in a system, the chirp coefficient, C, must be calibrated on a comparable level. Moreover, sweep nonlinearities due to dispersion or other systematic effects invisible to the in-loop signals must also be calibrated and removed either physically or in processing. Optical frequency combs, with their broad bandwidths, narrow linewidths, and accuracy, are by far the most direct and accurate way to calibrate the ultrabroadband LFC sources [7,8]. This Letter describes the characterization of an actively linearized, ultrabroadband (≈5 THz) LFC source with a fiber-based comb using optical in-phase/quadrature (IQ) detection of the coherent heterodyne beat signal between the LFC and comb source. We demonstrate that the LFC source can generate a known linear sweep with less than 15 ppb deviations.

The LFC source consists of an extended cavity diode laser that is mode-hop-free tunable from approximately 1520 to 1630 nm [4]. The laser frequency, $f(t)$, is measured by use of an ≈53 m delayed self-heterodyne fiber interferometer, which has an output beat frequency of $f_b(t) \approx \frac{df(t)}{dt}\tau_d$, where τ_d is the delay of the interferometer. This beat frequency is phase locked to an RF reference, f_{LO}, by feeding back to the frequency actuators of the laser. Since Ref. [4] was published, improvements to the servo electronics have reduced the in-loop sweep residuals from 170 kHz rms to below 30 kHz rms.

The fiber-based comb spans from 1530 to 1570 nm, roughly matching the 4.7 THz LFC sweep. It is stabilized by locking to ultrastable laser sources at 1535 and 1560 nm [8]. Its repetition rate of 99919108.60645 Hz was monitored by a 12-digit frequency counter referenced to an H-maser, making the uncertainty introduced by the comb repetition rate negligible. The characterization of the LFC against the comb was accomplished by analyzing the heterodyne signal between the two sources for a single full 4.7 THz sweep over ≈1 sec, corresponding to an approximate chirp of 5 THz/s. The LFC and comb sources were mixed by use of a 90° optical hybrid IQ demodulator (Kylia COH24). The I and Q signals were detected with commercial balanced detectors and captured with a 12 bit, 100 Ms/s digitizer (Gage CS8287) (see Fig. 1). After correcting for DC offsets, a 0.1 rad phase imbalance in the IQ demodulators, and gain differences, we construct the complex signal $S = I + iQ$.

From the complex signal S, the relative phase evolution of the LFC source and the nearest comb tooth can be determined. This relative phase evolution is a parabolic curve that corresponds to the LFC frequency approaching, crossing, then moving away from the individual comb tooth, consistent with a frequency chirp [see Fig. 2(a)]. The cusps between the parabolas correspond

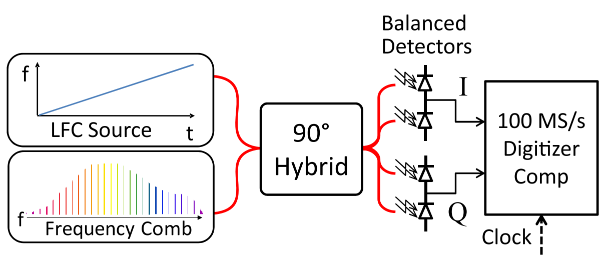

Fig. 1. (Color online) Basic schematic of the LFC source characterization against the fiber-laser frequency comb using optical IQ demodulation.

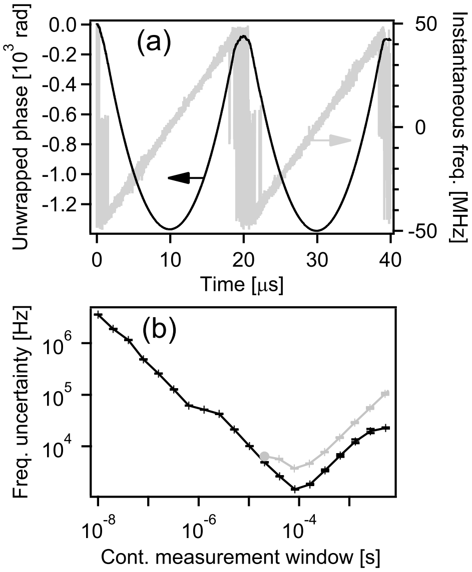

Fig. 2. (a) Unwrapped phase (black) of the IQ demodulated heterodyne signal over two comb line crossings. Also shown in gray is the numerical derivative of the phase approximating the instantaneous optical frequency difference between the LFC and nearest comb tooth. (b) Frequency measurement uncertainty (calculated with the overlapping Allan deviation algorithm) for the LFC source at zero chirp (black line) and for the LFC source at 5 THz/s chirp evaluated from the measured $f(t)$ (see Fig. 3) after removing the constant chirp (gray curve). At a $20\,\mu$s measurement window, the uncertainty is 5 kHz.

to regions where the LFC frequency is halfway between two comb teeth and the phase is ambiguous. A quadratic fit to the central portion of the parabolas shows a quadratic coefficient consistent with the expected chirp of ≈5 THz/s. The minimum of the parabola gives the “crossing time” at which the instantaneous LFC frequency, $f(t)$, matches a given comb tooth. In a similar approach to Ref. [7], we plot the comb tooth frequencies versus these crossing times to retrieve $f(t)$ over a broad bandwidth, shown in Fig. 3(a). For the 5 THz/s chirp, the point spacing in time is ≈$20\,\mu$s and the frequency uncertainty is ≈5 kHz [see Fig. 2(b)].

For an ideal interferometer, the delay τ_d is constant with frequency and the sweep should be perfectly linear. However, dispersion in the fiber will cause the delay to vary with frequency, leading to quadratic and cubic deviations [see Fig. 3(b)]. Dispersion compensating fiber (DCF) was included in the interferometer to reduce this effect. We can calibrate the remaining dispersion-related nonlinearities by fitting $f(t)$ to

$$f(t) = f_0 + Ct + Dt^2 + Et^3, \tag{1}$$

where f_0 is the absolute optical frequency at $t = 0$, and $C = f_{\mathrm{LO}}/\tau_d$ is the constant chirp that would result from a zero dispersion interferometer with delay τ_d and RF reference frequency f_{LO}. The second-order chirp, D, is related to the fiber dispersion coefficient β_2 at f_0 and fiber length L as $D = -\pi C^2 \beta_2 L/\tau_d$ [9], and E can be similarly related to the dispersion slope. A fit to the data in Fig. 3 gives $C = -5.00154792(1)$ THz/s, $D = -42.63(3)$ MHz/s^2, and $E = 4.75(2)$ MHz/s^3 at $f_0 = 195614.79$ GHz, which was determined from simultaneous measurement of

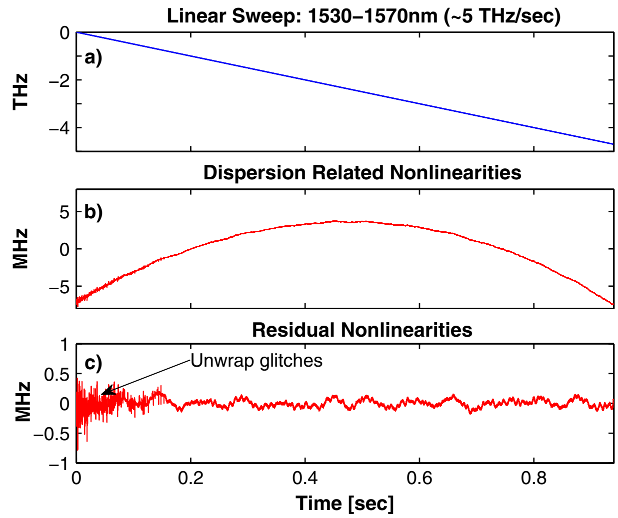

Fig. 3. (Color online) (a) Measured linear sweep of the LFC source over ≈5 THz. (b) Residuals from a linear fit to (a). The main deviation from linearity is quadratic due to the residual dispersion of the fiber interferometer. (c) Residuals from a cubic fit to (a), which removes the dispersion-related nonlinearities. The residuals have an rms deviation of only 60 kHz rms over the full 5 THz. At early times, the signal-to-noise ratio is not quite sufficient to avoid phase-unwrapping glitches due to low comb spectral power.

the transmission through an ≈10 Torr hydrogen cyanide (HCN) cell. The numbers in parentheses indicate the uncertainties in the last digit and are estimated from the residuals of the fit assuming Gaussian noise statistics. This chirp, C, corresponds to an RF reference frequency, $f_{\mathrm{LO}} = 1.3080139$ MHz, which gives a relative delay of the fiber interferometer of $\tau_d = 261.52182$ ns (corresponding to the expected ≈53.4 meters of fiber). The second-order chirp corresponds to a residual dispersion coefficient of $\beta_2 = 2.66\,\mathrm{ps}^2/\mathrm{km}$ or about an order of magnitude smaller and the opposite in sign to normal telecom fiber ($\beta_2 \approx -23\,\mathrm{ps}^2/\mathrm{km}$); this residual dispersion can be reduced further by adjusting the length of DCF in the reference interferometer appropriately. Regardless, through this or other types of calibration [10], dispersion-induced nonlinearity could be accurately compensated in post-processing of ranging or spectroscopic measurements.

The residuals from the cubic fit are shown in Fig. 3(c) and reveal some higher order residual nonlinearities. During initial characterization runs these nonlinearities were much larger, repeatable, and not observed in the in-loop residuals of the phase-locked loop. After investigation, these deviations were attributed to the wavelength dependent variation of the LFC polarization in combination with polarization mode dispersion (PMD) and variations in output signal strength of the fiber interferometer. By adding an in-line fiber polarizer in front of the interferometer, the residual nonlinearities were reduced below 60 kHz. We observe about 30 kHz rms of variations between two nominally identical sweeps, consistent with the known in-loop errors; the remainder of the 60 kHz is attributed to remaining PMD related effects. The residual nonlinearity of the LFC source is estimated as this rms residual divided by the total sweep bandwidth or 60 kHz/4.7 THz ≈13 ppb. Note that the average value of the chirp over the sweep is known to a much higher level of ≈2 ppb.

Ideally, the LFC source would hold this tight calibration between infrequent comb measurements. However, there are a number of considerations. First, because the reference fiber interferometer has a temperature coefficient of about 6 to 8 ppm/K, the calibration can only be as good as the temperature stability. With only passive isolation, two sweeps characterized about a minute apart agree to less than 10 ppb implying short-term stability better than 2 mK. Active temperature control at this level should be possible under laboratory conditions. Second, the fiber dispersion causes the average chirp, C, to change with f_0 by ≈2 ppb/GHz. However, since we have calibrated the dispersion parameters and since f_0 is known to <1 GHz by use of an HCN cell, this effect is negligible. Finally, as evidenced by the observed polarization induced nonlinearities, first-order PMD in the single-mode fiber interferometer could introduce 100 ppb level drifts in the chirp, C, and must ultimately be removed either with a polarization-maintaining fiber interferometer or a Michelson interferometer geometry utilizing Faraday rotating end mirrors [3].

On a final note, optical frequency combs have also been directly utilized for many of the same applications of ultrawideband LFC sources, such as precision spectroscopy, high resolution ladar, and length metrology. For applications where accuracy is paramount, combs are preferable as they are readily referenced to high accuracy absolute RF frequency standards. However, in many cases LFCs have distinct advantages over optical frequency combs. For example, in high sensitivity spectroscopic applications only a single or at most a few modes of the comb will interact with the absorption feature lowering the effective signal-to-noise ratio [11]. In addition, optical frequency combs are generally more expensive and complex than tunable laser sources. Therefore, for many applications, an LFC source with a stabilized interferometer that has been calibrated with a comb may be a suitably accurate source.

In conclusion, we have coherently characterized an ultrabroadband actively linearized chirped laser source against an optical frequency comb. This measurement calibrated the average chirp of the LFC source output and the dispersion-related nonlinearities. It also allowed for the diagnosis and amelioration of previously unobserved linearity errors caused by polarization effects in the fiber interferometer used for sweep linearization. The deviation from linearity after removing dispersion effects was less than 60 kHz rms over a 4.7 THz bandwidth. In the end, if the starting frequency of the stabilized LFC laser is known and reference interferometer temperature are well controlled (less than 5 GHz and less than 2 mK, respectively), the relative frequency trajectory of an ≈5 THz (40 nm) sweep could be linearized to less than 15 ppb, which is more than sufficient for length metrology applications that are performed in atmosphere.

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