A Simple, Low Power, Self Referenced Technique for Complete Characterization of Optical Frequency Combs and Arbitrary Waveforms

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Abstract: We demonstrate a simple scheme which uses only an intensity modulator and an OSA to achieve low-power (~100nW,10aJ/pulse at 10GHz), self-referenced, amplitude and phase characterization of optical frequency combs and 100% duty factor arbitrary waveforms.

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In recent years there has been significant work to characterize optical waveforms emanating from high repetition rate frequency combs. An important driving factor is optical arbitrary waveform generation (OAWG) [1,2] wherein individual comb lines are controlled with arbitrary user defined phase and amplitude. This generates very high complexity user defined waveforms useful in various applications like communications, LIDAR, spectroscopy etc. OAWG generation leads to new challenges for characterization of such waveforms. From a source based perspective, modelocked lasers which have been the primary means of generating short pulses do not conveniently scale to high repetition rates (10GHz and above) while maintaining optical frequency stability and so novel techniques have been developed to generate high repetition rates without modelocking [for e.g. 3-6]. Although these sources may provide wide optical bandwidth, they do not generate short pulse outputs due to abrupt spectral phase variations. Therefore characterization is essential if one wishes to compress these sources to the bandwidth limit [6]. Other driving areas include sending timing information over fiber links using frequency combs [7, 8] and coherent WDM (carrier-phase-locked) transmission formats where relative phases of individual carriers become important [e.g., 9]. Although several methods exist to characterize high repetition rate pulse trains, many of them modifications of standard ultrafast pulse measurement techniques, these methods focus on close to bandwidth limited pulses and do not easily handle high waveform complexity. We have previously demonstrated a fast characterization method using dual-quadrature spectral interferometry for OAWG [10] which can also characterize dispersion of fiber links (up to tens of km demonstrated). However, this method requires a frequency-locked, pre-characterized reference frequency comb. For some applications a self-referenced scheme is needed. Here we demonstrate a very easy to implement, low-power self-referenced scheme to characterize arbitrarily complex periodic waveforms over wide bandwidths. Our scheme introduces an implementation of spectral shearing interferometry [11] utilizing only a Mach-Zehnder intensity modulator and an optical spectrum analyzer.

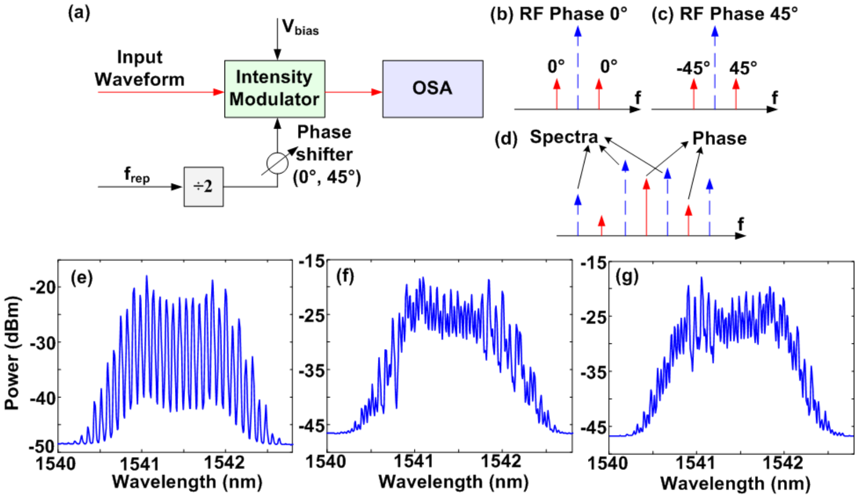

Fig. 1 (a) Experimental Setup; (b), (c) Relative phases between sidebands with RF phase shift; (d) Spectrum – from carriers, Phase – from interference between sidebands (e) OSA spectra with no modulation; (f) 0° “cos” modulation; (g) 45° “sin” modulation

Fig 1(a) shows the experimental setup. The input waveform is sent to a Mach-Zehnder intensity modulator (we use a x-cut LiNOb3 modulator from JDS Uniphase), which is driven by a weak sinusoidal RF signal with half the frequency as the input frequency comb (depending on availability, this can be either from a local oscillator or derived from the signal itself).

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The drive signal passes through a tunable RF phase shifter. Two spectra are recorded by the OSA with the RF phase shifter settings spaced 45° apart (this can be converted into a parallel measurement using a 0-45° hybrid, two intensity modulators and a dual-channel spectrometer [10]). From these two spectra, unambiguous spectrum and phase can be retrieved.

To understand how this technique works, let us first consider only a single frequency which goes through the intensity modulator. Assuming a small RF signal, only first order sidebands at half the repetition rate are created on either side of the carrier with relative phases that depend on the RF phase shift (figs 1(b), 1(c)). With a frequency comb, at every possible sideband position contributions from two adjacent comb lines (at higher and lower optical frequency) will interfere, yielding sideband intensities that depend on the phase difference. Through this interference, the sideband spectra provide us unambiguous phase information, while the spectra remaining at the carrier positions provide spectral amplitude information. If spectral resolution is a concern for lower repetition rate combs, another easy change would be to run the modulator in a carrier suppressed scheme and making 3 measurements – 1 for spectra and 2 for phase.

Let us now briefly look at why we need the phase shifter and two spectra. Whenever we look at the frequency resolved interference between two waveforms, a phase ambiguity arises preventing phase retrieval (just the “cosine” or “sine” interference components are not enough). So, in conventional implementations of both spectral interferometry and spectral shearing interferometry [12,11], this problem is overcome by setting the delay of the interfering pulses to be larger than the individual temporal widths. However, for wide temporal window waveforms this makes large demands on spectral resolution; for >50% duty factors, complete separation of the interfering waveforms by delay is impossible. Another way is to obtain both the components of the interference (“cos” and “sin”); this also makes unambiguous retrieval possible [10,12,13]. In our scheme we obtain both interference components simply by changing the relative phases between the sidebands by 90°, which is achieved by a phase shift of 45° at the RF phase shifter. This is an important difference between our technique and electro-optic spectral shearing interferometry (EOSI) [14, 15], a linear technique which emulates conventional spectral shearing interferometry, but instead uses a phase modulator to generate the spectral shear between a pair of pulses separated by a delay. In EOSI too, similar problems arise as the duty factor of the pulses increase, EOSI breaks down for >50% duty factor waveforms common in OAWG.

Now the expression for the interference between the sidebands of two adjacent lines (‘n’ and ‘n+1’) are -

$$I_{inphase} = c[|a_n|^2 + |a_{n+1}|^2 + 2|a_n||a_{n+1}|\cos(\psi_n - \psi_{n+1})] \tag{1}$$

$$I_{quadrature} = c[|a_n|^2 + |a_{n+1}|^2 + 2|a_n||a_{n+1}|\sin(\psi_n - \psi_{n+1})] \tag{2}$$

Where ‘$|a_i|$’ and ‘ψ_i’are the spectral amplitude and phase of the input comb lines and ‘c’ is a modulation parameter defined as the ratio between the sideband and the carrier for a single frequency input. This parameter depends on the modulator settings and can be easily extracted just from the two spectra without the need for any additional measurements. This ratio experimentally corresponds to the height of the sidebands w.r.t the carrier when a continuous wave (CW) input is used. In our experiments we adjust the modulator parameters like input RF voltage and bias voltage to have a low value for ‘c’ between 0.1- 0.2 to minimize the possible effects of higher order sidebands. For the above expressions we have assumed that the phases of sidebands in each case to be (0°, 0°) and (-45°,45°), but in general there may be a constant offset phase. However, it can be easily shown that this only contributes a constant and linear term to the retrieved phase. Since this is only a constant phase and a constant delay in the time domain, we will ignore it. Figs 1(e) – (g) show representative spectra from OSA for the cases of no modulation and with “cos” and “sin” modulation.

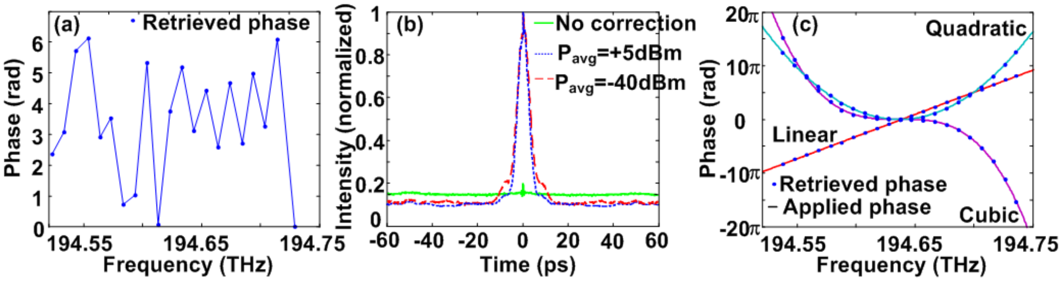

Fig. 2 (a) Retrieved phase of uncompensated comb; (b) Autocorrelation of uncompensated comb, compensated comb with phase measured at 5dBm (~4mW) and -40dBm (~100nW); (c) User defined pulse shaping: Applied and Retrieved phases for linear, quadratic and cubic phases.

Fig 2(a) shows the retrieved spectral phase for a 10GHz frequency comb generated by cascaded Phase and Intensity modulators [6]. The autocorrelation of the output is shown in fig 2(b) (no correction) indicating a flat envelope(100% duty factor). This is because phase modulation does not affect the time domain intensity, though in frequency domain a comb is generated (this corresponds to varying spectral phase). Using a line-by-line shaper, we then compensated the phase (retrieved at 2 different power levels, +5 and -40dBm). We expect a good phase retrieval to manifest as a bandwidth limited compressed pulse in the autocorrelation and this is confirmed in experiments (fig 2(b)) even down to average power levels of -40dBm=100nW (corresponding to 10aJ/pulse at 10GHz). The background level is due to amplifier and detector noise. We then used the pulse shaper to apply different spectral phases onto the comb, after which we measured the reshaped pulses.

This is shown in fig 2(c) for examples of linear, quadratic, and cubic spectral phase. An excellent agreement was seen between applied phases and retrieved phases.

Our next experiment was to measure spectral phases as the frequency comb undergoes dispersive propagation over long lengths of fiber. This capability allows for rapid monitoring of link dispersion useful for applications in coherent communications and for timing dissemination through combs over fiber [7-9]. To simulate the situation where the two ends of the fiber are at two different locations, we derived the repetition rate from the signal itself, by sending a small fraction to a 20GHz photodiode and bandpass filtering to extract the repetition rate. We used a different comb source this time, an optical frequency comb generator [3] to obtain higher bandwidths. Fig 3(a) shows a representative retrieved spectrum for the experiments. The bandwidth now is close to a THz. Fig 3(b) shows the retrieved spectral phase and the cubic fits for a fiber spool (vendor – OFS-Fitel) which is ~ 25km and a DCF module matched to it.

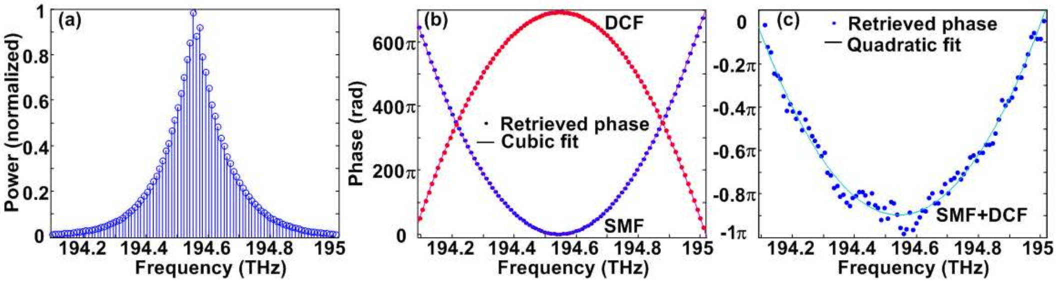

Fig. 3 (a) Representative retrieved spectra; (b) Retrieved spectral phase with cubic fits for ~25km SMF and DCF for 25km SMF, (c) 25km SMF + DCF

The standard deviation of error between the fit and retrieved phase is small (<0.1 π) and the obtained dispersion parameters from the fit which are (393.8ps/nm, 1.5ps/nm^2) and (-392.1ps/nm, -1.6ps/nm^2) agree well with provided specifications. As a further check we measured the residual phase for the dispersion compensated link, the dispersion obtained was (1.2ps/nm) which is close to the expected value of 1.7ps/nm (obtained by taking the difference between the dispersions of the two cases above). This shows the high accuracy as well as the high dynamic range in this method.

In summary, we have demonstrated a very simple, self referenced technique to characterize optical frequency combs and arbitrary waveforms with low power requirements going down to 100nW average power (~10aJ/pulse). The optical measurement bandwidth is potentially very large, only limited by the bandwidth of the intensity modulator. In this paper we reported experiments relevant to pulse compression, user-defined pulse shaping, and fiber dispersion measurements. Our future work is to generalize the technique to also include low repetition rate sources (e.g Femtosecond fiber lasers). In conclusion our method promises to provide a easily usable, low power alternative to a variety of pulse measurement needs.

References

[1] Z. Jiang, C.-B. Huang, D.E. Leaird, A.M. Weiner, “Optical arbitrary waveform processing of more than 100 spectral comb lines,” Nature Photonics, Volume 1, Issue 8, pp. 463-467 (2007).

[2] V. R. Supradeepa, Chen-Bin Huang, Daniel E. Leaird, and Andrew M. Weiner, "Femtosecond pulse shaping in two dimensions: Towards higher complexity optical waveforms," Opt. Express **16**, 11878-11887 (2008).

[3] M. Kourogi , K. Nakagawa and M. Ohtsu “Wide-span optical frequency comb generator for accurate optical frequency difference measurement,” IEEE J. Quantum Electron. **29**, 2693, (1993).

[4] H. Murata, A. Morimoto, T. Kobayashi, and S. Yamamoto, “Optical pulse generation by electroopticmodulation method and its application to integrated ultrashort pulse generators,” IEEE J. Sel. Top. QuantumElectron. 6, 1325-1331 (2000).

[5] P. Del’Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth and T. J. Kippenberg, "Optical frequency comb generation from a monolithic microresonator," Nature 450, 1214-1217 (2007).

[6] C.-B. Huang, S.-G. Park, D.E. Leaird, and A.M. Weiner, "Nonlinearly broadened phase-modulated continuous-wave laser frequency combs characterized using DPSK decoding," Opt. Express 16, 2520-2527 (2008).

[7] Seth M. Foreman, Kevin W. Holman, Darren D. Hudson, David J. Jones, and Jun Ye, “Remote transfer of ultrastable frequency references via fiber networks,” Rev. Sci. Instrum. 78, 021101 (2007).

[8] F. Narbonneau, M. Lours, S. Bize, A. Clairon, G. Santarelli, O. Lopez, Ch. Daussy, A. Amy-Klein, and Ch. Chardonnet, “High resolution frequency standard dissemination via optical fiber metropolitan network,” Rev. Sci. Instrum. 77, 064701 (2006).

[9] A.D. Ellis; F.C.G. Gunning, "Spectral density enhancement using coherent WDM," Photonics Technology Letters, IEEE, vol.17, no.2, pp.504-506, Feb. 2005.

[10] V. R. Supradeepa, Daniel E. Leaird, and Andrew M. Weiner, "Optical arbitrary waveform characterization via dual-quadrature spectral interferometry," Opt. Express **17**, 25-33 (2009).

[11] Ian A. Walmsley and Christophe Dorrer, "Characterization of ultrashort electromagnetic pulses," Adv. Opt. Photon. **1**, 308-437 (2009).

[12] L. Lepetit, G. Cheriaux, and M. Joffre, "Linear techniques of phase measurement by femtosecond spectral interferometry for applications in spectroscopy," J. Opt. Soc. Am. B 12, 2467- (1995).

[13] Houxun Miao, Daniel E. Leaird, Carsten Langrock, Martin M. Fejer, and Andrew M. Weiner, "Optical arbitrary waveform characterization via dual-quadrature spectral shearing interferometry," Opt. Express **17**, 3381-3389 (2009) .

[14] Christophe Dorrer and Inuk Kang, "Highly sensitive direct characterization of femtosecond pulses by electro-optic spectral shearing interferometry," Opt. Lett. **28**, 477-479 (2003).

[15] Inuk Kang, Christophe Dorrer, and Francesco Quochi, "Implementation of electro-optic spectral shearing interferometry for ultrashort pulse characterization," Opt. Lett. **28**, 2264-2266 (2003).