Sinusoidal phase modulation as a gate for FROG

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Abstract: A sinusoidal phase-modulation gate for cross-correlation frequency-resolved optical gating (PM-FROG) is demonstrated. This low-loss, linear gating technique can be used without separate gate characterization via a blind FROG algorithm with a simple intensity constraint.

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Cross-correlation frequency-resolved optical gating (X-FROG) is becoming an increasingly popular and powerful technique for characterizing telecommunications pulses [1, 2]. X-FROG retrieves full field information from a spectrogram (i.e., time-frequency distribution) which is generated by measuring the temporal evolution of the optical spectrum using the interaction of a gate acting on an optical waveform at successive relative delays. In particular, implementations of X-FROG exploiting linear effects in electro-absorption modulators offer high sensitivity and real-time characterization [1]. X-FROG does not require an amplitude gate and the first demonstration of phase gating in FROG exploited cross-phase modulation in optical fibers to characterize a high repetition rate fiber laser pulse [3]. More recently, X-FROG using cross-phase gating has successfully characterized attosecond bursts [4]. Potentially, sinusoidal phase modulation (PM) in an electro-optic modulator can be used as a gate for an X-FROG measurement (PM-FROG). Electro-optic PM using a RF tone is a simple gate, with almost pure sinusoidal phase modulation and no amplitude modulation. Unlike gates derived from laser pulses and electro-absorption modulation, the shape of the PM-FROG gate can be widely adjusted by merely changing the imparted modulation depth. PM-FROG offers high sensitivity because there is no signal lost due to amplitude modulation, and the loss through an electro-optic phase modulator is typically very low (<3 dB). Additionally, electro-optic PM is widely applicable since various electro-optic materials are available that can be used the ultraviolet, visible or infrared spectral regions. Following is a demonstration of PM-FROG to characterize the intensity and phase of the optical waveforms generated by an optical frequency comb source.

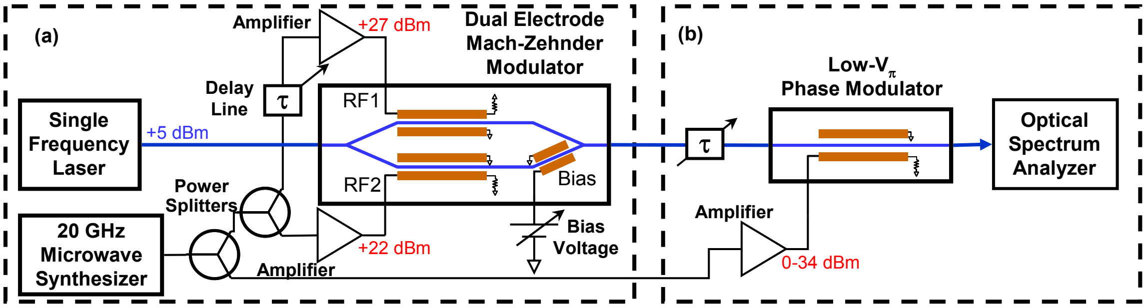

Fig. 1. (a) Generation of an optical frequency comb. (b) PM-FROG measurement apparatus.

The most widely used interaction between a gate and signal is multiplication from second harmonic generation in a nonlinear crystal, but other effects work equally well, such as polarization gating, self-diffraction, and optical parametric amplification [5]. For relatively narrowband signals, the interaction between the electro-optic PM and signal can be assumed to be multiplicative. Thus, the PM behaves on a signal as an optical gate pulse does in an X-FROG measurement. This allows existing X-FROG algorithms to be used to retrieve the fields represented by the spectrogram. The X-FROG algorithm requires a well characterized gate pulse. Although, the electrical waveform applied to the modulator is a sinusoid, its exact effect on the signal waveform is difficult to measure. A blind FROG algorithm based on principle-component generalized-projections (PCGP) is used [6] to retrieve both the gate and signal. To facilitate unambiguous retrievals, the constant intensity of a pure PM gate is integrated as a constraint within the PCGP algorithm (PM-FROG algorithm). The spectrogram is prepared for the algorithm by binning it onto a 64 × 64 grid with frequency spacing equal to the modulation frequency and a time window width equal to one period of the modulating signal. Additionally, each frequency bin contains exactly one optical mode. This binning procedure ensures that complete information of the signal and gate are contained within the spectrogram.

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Fig. 1 depicts the PM-FROG apparatus as it is used to measure the output of an optical frequency comb generator (OFCG). The phase gate is provided by sinusoidal PM occurring within a low V_π phase modulator. The peak phase deviation of the gate can be adjusted between 0 and 9 rad by simply adjusting the phase modulator driving voltage. Both the OFCG output and electrical PM driving signal are synchronous with each other. The OFCG output is optically delayed with respect to the PM in order to translate the gate through the OFCG output. However, this delay can easily be generated by using an electrical phase shifter on the PM driving signal [1]. At each delay, the spectrum after the phase modulator is measured with an optical spectrum analyzer (OSA) to build the spectrogram. The OFCG (Fig. 1(a)) [2] consists of a tunable single-frequency laser which is both phase and amplitude modulated by a $LiNbO_3$ dual-electrode Mach-Zehnder modulator (DEMZM) [7]. The center wavelength of the comb can be tuned from 1480 nm to 1580 nm and the comb spacing (20 GHz) is set by a microwave synthesizer. The RF amplitudes and phase differences are optimized to produce an OFCG output resembling a modelocked laser pulse.

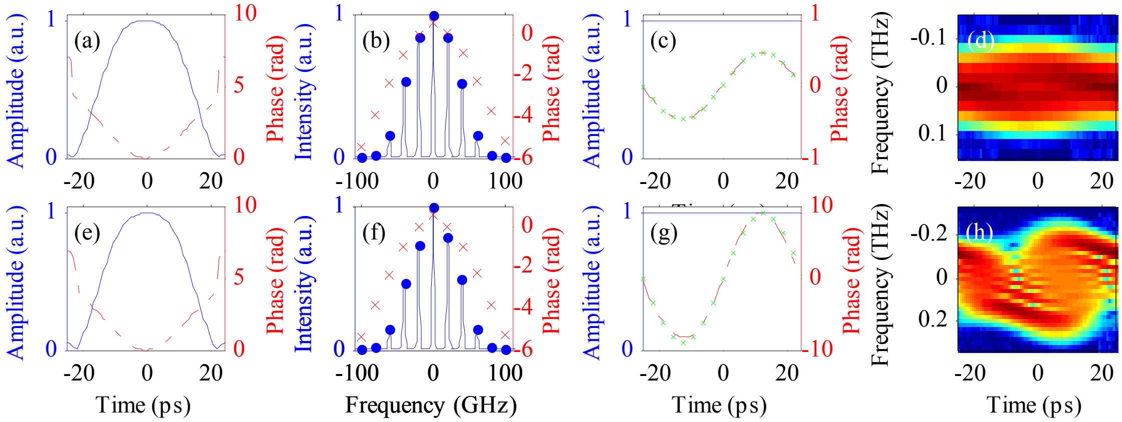

Fig. 2. (a) Retrieved field magnitude (solid) and phase (dashed) using small PM gate (c) ('×' are superimposed sinusoidal). (b) Corresponding retrieved spectral intensity (solid) and spectral phase (×) and independently measured spectrum (solid circles) and (d) binned spectrogram. (e) Retrieved field magnitude (solid) and phase (dashed) using large PM gate (g) ('×' are superimposed sinusoidal). (f) Corresponding retrieved spectral intensity (solid) and spectral phase (×) and independently measured spectrum (solid circles) and (h) binned spectrogram.

Fig. 2 shows retrieval with PM-FROG for small PM case (Fig. 2a-d) and large PM case (Fig. 2e-h). The FROG retrieval error parameter, G, was 0.0014 for the small PM case and 0.0038 for the large PM case on a 64×64 grid. The retrieval error is larger for the large PM case because it occupies almost three times the area of the spectrogram of the small PM case. Nevertheless, the low retrieval errors and matching retrieved and independently measured spectra indicate successful retrieval with PM-FROG for two diverse gates. The retrieved OFCG waveform (Fig. 2(a,e)) is highly chirped and broad (24 ps full width at half maximum (FWHM) of the intensity). Its spectrum contains 9 comb lines within 20 dB of the peak (Fig 2(b,f)). The retrieved small PM gate (Fig. 2(c)) has 0.46 rad peak phase deviation and is almost a perfect sinusoidal. The retrieved large PM gate (Fig. 2(g)) has 9 rad peak phase deviation but deviates slightly from a pure sinusoid as seen in the lower cusp. Additionally, the retrieval does not contain a time-ambiguity which can easily be inferred by the temporal asymmetry of the FROG traces (Fig. 2(d,h)).

In conclusion, using a low-loss electro-optic modulator as a phase gate in PM-FROG can potentially be developed as a real-time pulse characterization tool usable across the visible and infrared wavelengths. Future investigation is needed to determine how the PM-FROG performs for pulses with broader spectra and gates with even deeper phase modulation.

References

[1] Dorrer, C. and I. Kang, "Real-time implementation of linear spectrograms for the characterization of high bit-rate optical pulse trains," *IEEE Photon. Technol. Lett.* **16**, 858-860 (2004).

[2] Fontaine, N.K., R.P. Scott, J. Cao, K. Okamoto, J.P. Heritage, B.H. Kolner and S.J.B. Yoo, "Complete characterization of precise line-by-line optical arbitrary waveform generation with XFROG," in *European Conference Optical Communication*, (2006).

[3] Thomson, M.D., J.M. Dudley, L.P. Barry and J.D. Harvey, "Complete pulse characterization at 1.5 µm by cross-phase modulation in optical fibers," *Opt. Lett.* **23**, 1582-1584 (1998).

[4] Mairesse, Y. and F. Quéré, "Frequency-resolved optical gating for complete reconstruction of attosecond bursts," *Phys. Rev. A* **71**, 011401 (2005).

[5] Trebino, R., *Frequency-resolved optical gating: The measurement of ultrashort laser pulses*., (Boston: Kluwer Academic Publishers, 2000).

[6] Kane, D.J., "Recent progress toward real-time measurement of ultrashort laser pulses," *IEEE J. Quantum Electron.* **35**,421-431 (1999).

[7] Sakamoto, T., T. Kawanishi and M. Izutsu, "Optical frequency comb generation using asymmetrically mach-zehnder modulator," in *31st European Conference on Optical Communication*, (2005).

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