Photonics-enabled Nanosecond Scale Real-time Spectral Analysis with 92-GHz Bandwidth and MHz resolution

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Abstract: We demonstrate gapless and real-time spectral analysis of broadband waveforms with >250 analysis points per spectrum. The concept is based on a discretization of an electro-optic time-lens to implement a phase modulation equivalent to 206.25π.

1. Introduction

Precise knowledge of the evolving spectral characteristics of a waveform is fundamental to a wide range of fields including microwave photonics, Radar/Lidar technologies, telecommunications and biomedicine [1–3]. To obtain the most comprehensive representation of a signal of interest, the analysis is generally required to be done in real-time and without any gaps in the signal acquisition and processing. This effectively corresponds to measuring the joint time-frequency representation or spectrogram [4–8], such that the spectral characteristics of the signal under test (SUT) are analyzed on time scales commensurate with the bandwidth of the analyzed waveform. Another key requirement for many of these applications is that the spectrum must be also captured with a sufficiently high definition, corresponding to a fine frequency resolution. Yet, it remains very challenging to capture the full spectrogram of EM waves over a large analysis bandwidth (e.g., in the 10s of GHz range and above) and with a simultaneous high frequency resolution (e.g., down to the MHz regime). In the case of radio and microwave signals, the most common solutions rely on electronic digital post-processing to implement multiple fast Fourier transform (FFT) algorithms. Although they can easily access frequency resolutions down to the kHz regime, the instantaneous operation bandwidth (or frequency span) remains limited to just a few hundreds of MHz [3]. On the other hand, photonic analog processing can overcome the analysis bandwidth limitation of electronic-based methods [4–8] but at the cost of a greatly impaired time or frequency resolution. Specifically, present photonic solutions are mainly based on temporal imaging schemes (or frequency-to-time mapping) using a linear electro-optic sampling or time-lens process [6–8]. However, all techniques that can capture the dynamic spectra of signals in the GHz regime, corresponding to a time resolution on the nanosecond scale, are inherently limited by design to provide a relatively coarse frequency resolution, with ~10 points per measured spectrum at best. This stringent limitation is mainly due to the maximum phase excursion that can be achieved in practice through electro-optics modulation (limited to a few π). Whereas nonlinear optics implementations of similar designs might enable overcoming this main design trade-off, these would necessarily incur in excessive energy consumption and low efficiency. Thus, to the best of our knowledge, no technique has been proposed and demonstrated that can capture the evolving spectrum of an incoming broadband signal at a nanosecond scale and with an ultrafine resolution, especially using an efficient linear-optics scheme.

In this communication we demonstrate a novel temporal imaging technique for nanosecond-scale ultrahigh-definition spectral analysis simultaneously enabling a broadband analysis bandwidth, up to 92 GHz (i.e., corresponding to microwave frequencies up to 46 GHz) and up to 252 analysis points (corresponding to a frequency resolution <400 MHz). The method employs phase-only linear optics manipulations, such that it is inherently highly

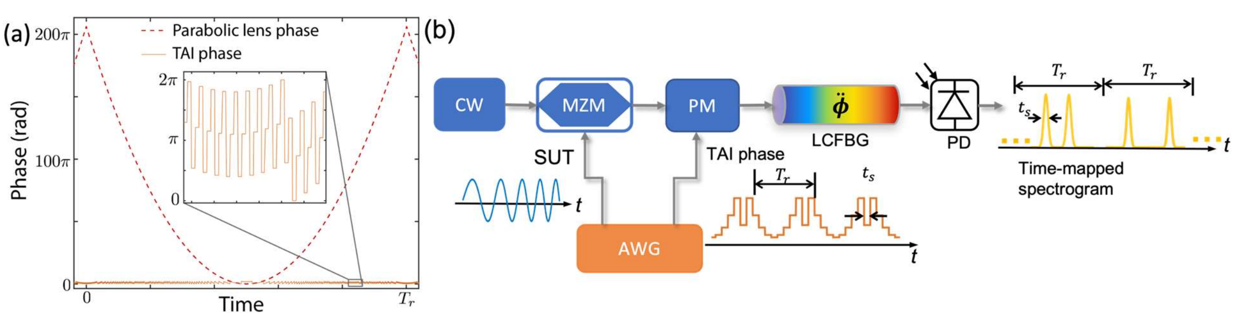

Fig. 1. (a) The TAI temporal phase modulation we implement can be interpreted as the discretization of a very deep parabolic phase that can efficiently be limited to a maximum phase excursion of 2π (b) Experimental setup. Acronyms defined in the main text.

sensitive and energy efficient. The key concept is to use a discrete and bounded temporal phase modulation profile, which is determined by the framework of the temporal Talbot array illuminator (T-TAI) [9]. As shown in Fig. 1(a), this concept can be interpreted as a form of discretization of a conventional time lens (continuous quadratic phase modulation profile), allowing to effectively limit the maximum phase excursion to 2π while implementing a manipulation equivalent to a conventional time-lens with a total phase excursion of 206.25π using a single electro-optic phase modulator.

2. Operation Principle

As shown in the experimental setup, Fig. 1(b), the microwave SUT is generated from a 92-GSa/s arbitrary waveform generator (AWG) and brought to the optical domain by carving continuous wave (CW) light using a Mach-Zehnder modulator (MZM) biased at V_π. The optical SUT then enters the TAI spectrogram unit, composed of an electro-optic phase modulator (PM) driven by an AWG providing the needed multi-level phase pattern, where the n^{th} phase step follows $\varphi_n = -\pi n^2(q-1)/q$, for n=1…q [9]. Thus, the modulation phase profile consists of q phase levels each of length t_s, forming a periodic pattern of length T_r=qt_s. The analysis bandwidth is given by the inverse of the duration of a single phase step, i.e. $1/t_s$ = 92 GHz, while the temporal resolution is approximately given by the period of the phase pattern T_r, which is inversely related to the frequency resolution. Here we demonstrate two different spectrogram designs with q=139 and 825 analysis points corresponding to the theoretical frequency resolutions of 660 MHz and 110 MHz (and associated temporal resolutions of 1.5 and 9.1 ns), respectively. This phase modulated signal then propagates through a linearly-chirped fiber Bragg grating (LCFBG) providing a second-order dispersion satisfying $2\pi|\ddot{\phi}| = qt_s$, corresponding here to $\ddot{\phi}$~2,600 and 15,500 ps^2, respectively. The resulting temporal signal corresponds to consecutive time-mapped spectra within each period T_r, measured using a 50-GHz photodiode (PD) connected to a 28-GHz real-time oscilloscope.

3. Experimental Results

In a first instance, we analyze a highly non-stationary SUT, composed of two crossed linear chirps, one varying from 0.67 to 46 GHz and vice versa for the other (here labeled S_1 and S_2, for reference further below), over a total duration of 136 ns. Fig. 2(a) shows the digital SUT that was given to the AWG, while the temporal signal at the output of the TAI spectrogram is shown in Fig. 2(b), with four different zoomed-in regions showing the details over different analysis periods. Notice that the proposed spectrogram method returns the double-sided spectrum, such that it is also

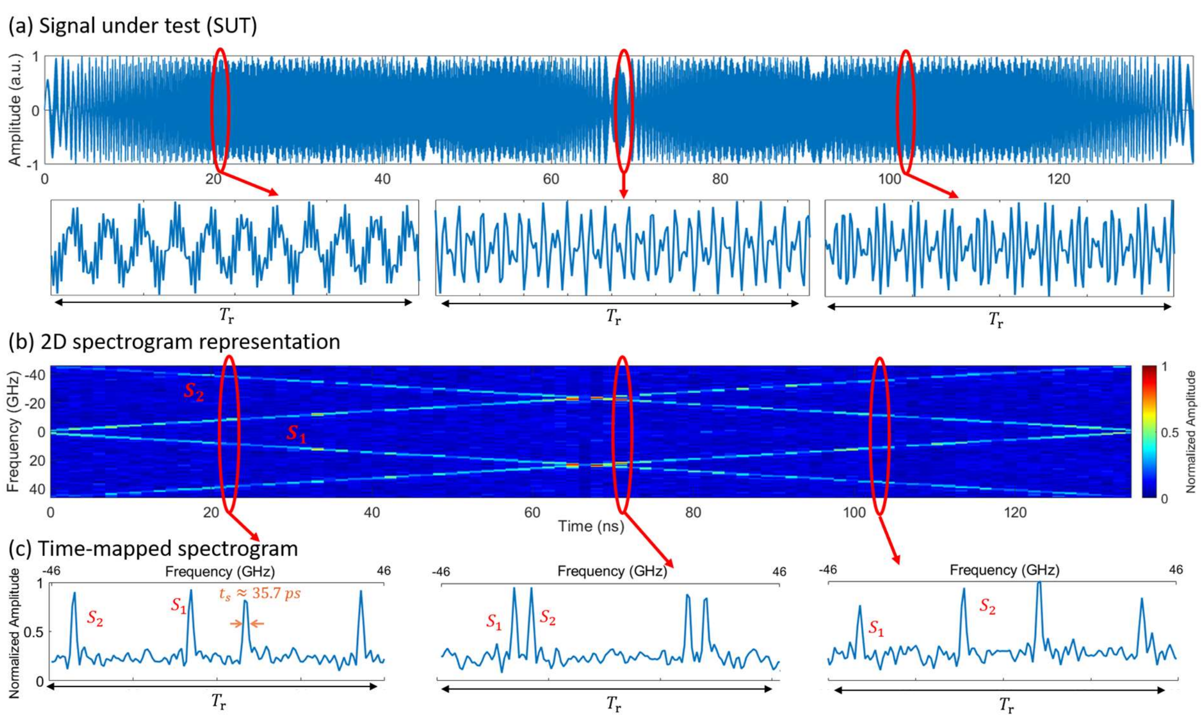

Fig. 2. Time-frequency analysis of a chirped signal over a broad bandwidth of 92 GHz with 2.2 GHz frequency resolution (a) The SUT is composed of two crossed chirp signals. (b) Temporal signal of the T-TAI spectrogram showing the two chirp components (S_1 and S_2). (c) The 2D spectrogram representation that is numerically recovered from the measured output temporal trace.

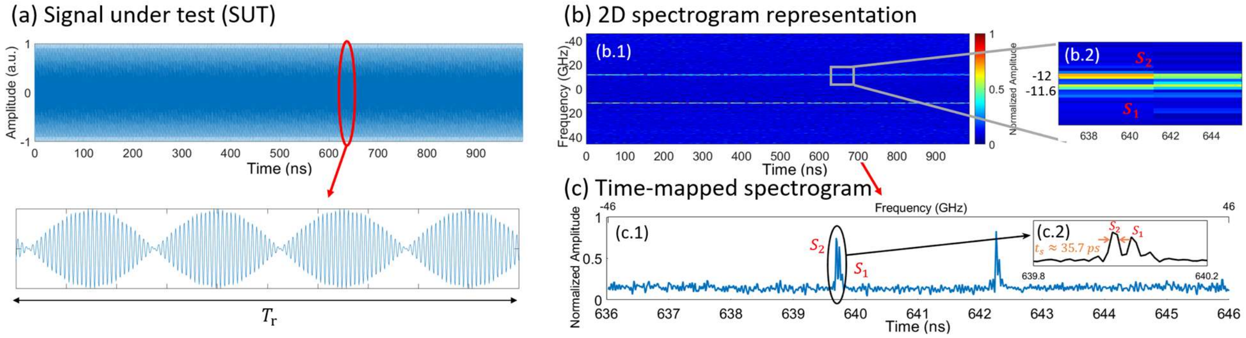

Fig. 3. (a) The SUT employed for measuring the frequency resolution of the system is composed of two closely spaced frequency tones (at 11.6 and 12 GHz, respectively). (b.1) These are clearly resolved by the TAI spectrogram, which exhibits high stability over long time durations. The close-up in (b.2) demonstrates a clear distinction between the two components. (c) Sample of the output temporal trace of the two-tone experiment for frequency resolution verification.

compatible with the analysis of complex signals. This signal can be reshaped into the common 2D spectrogram representation by simply plotting adjacent spectra vertically, shown in Fig. 2(c), clearly depicting the evolving frequency content of the individual chirps (i.e., S_1 and S_2) with a very high definition. Here each spectrum is measured with q=139 analysis points, which corresponds to the ratio of an analysis period to the pulse width, or the ratio of the full bandwidth to the frequency resolution. The frequency resolution can be estimated by frequency-to-time mapping of the pulse widths following $t_s/(2\pi|\ddot{\phi}|)$: the measured pulse width of ~35.7 ps (rather than ~11 ps, mainly limited by the time resolution of the scope) leads to an effective frequency resolution of ~2.2 GHz, instead of the theoretically expected value of 660 MHz. Indeed, we note that insufficient detection bandwidth leads to a temporal broadening of the spectrogram pulses corresponding to a deterioration of the frequency resolution, while the maximum operation bandwidth and temporal resolution remain unaffected.

In a second instance, we reconfigure the system for a higher spectral resolution using q=835 analysis points to discern two closely spaced frequency components, namely at frequencies of 11.6 and 12 GHz, see temporal profile of the SUT in Fig. 3(a), with a zoomed-in representation. The 2D representation is shown in Figs. 3 (b.1) and (b.2), clearly displaying that the two tones can be separated. The measured pulse widths of ~35.7 ps shown in Fig. 3(c) correspond to a frequency resolution of ~366 MHz, resulting in the measurement of 252 analysis points per spectrum. As such, the frequency components can be clearly discerned from each other.

4. Conclusions

In conclusion, we have demonstrated efficient and ultrahigh-definition joint time-frequency analysis of broadband microwave signals, in a real-time manner and with unprecedented performance, using a novel concept based on a temporal Talbot array illumination (T-TAI). In contrast to time-lens techniques, our theoretical analysis shows that adjacent windows provide a controllable amount of overlap, and we predict that the ultrahigh frequency resolution may also enable efficient frequency-domain manipulations directly in the temporal domain.

5. References

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