Photonic-Enabled Real-Time Frequency-Spectrum Tracking of Broadband Microwave Signals at a Nanosecond Scale

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Abstract: We demonstrate real-time and gap-free continuous frequency-spectrum analysis of broadband (GHz-bandwidth) microwave signals with unprecedented nanosecond resolutions through an analog time-mapped spectrogram approach, enabling detection of frequency interferences and transients with durations down to ~5ns.
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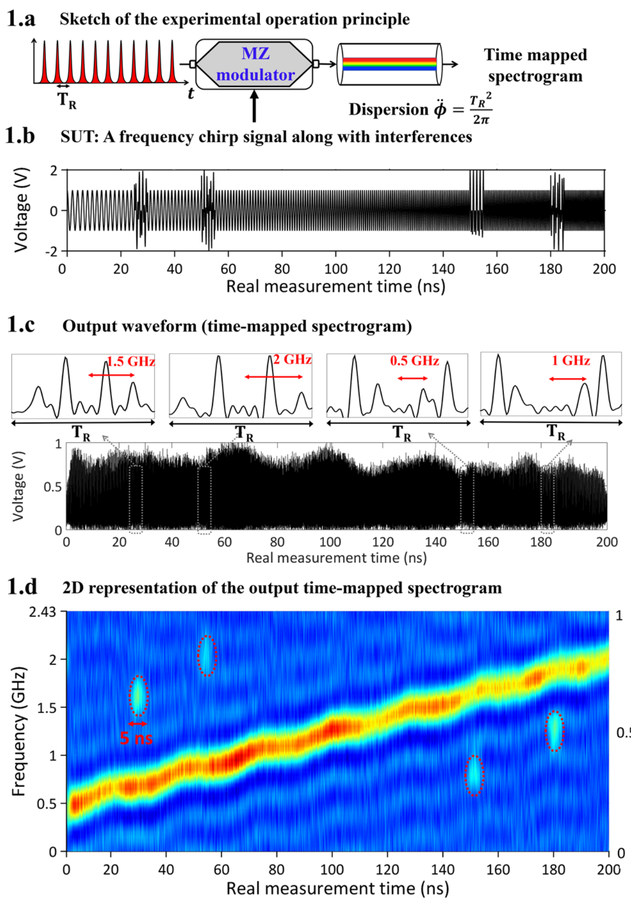
1. Introduction

Real-time Fourier spectral analysis (RT-SA) of non-stationary high-speed microwave signals, with instantaneous frequency bandwidths into the GHz range, is a fundamental tool in waveform characterization, of particular importance for applications that require the detection of rapidly changing signals in crowded wireless scenarios, such as electronic countermeasure [1], and radar/lidar receivers [2], as well as for radio astronomy observations [3,4] etc. A key requirement of RT-SA in the above applications is the capability to capture fast rare and transient frequency events lasting over a few nanoseconds or even shorter, while operating in a continuous and gap-free fashion – no dead time (cyclical or otherwise) in processing or in acquisition. Hence, the Fourier transform (FT) of the signal under test (SUT) in these applications must be evaluated continuously and in real-time, leaving no gaps between consecutive FTs. However, continuous gap-free RT-SA of broadband waveforms with nanosecond resolutions and with instantaneous bandwidths in and exceeding the GHz range remains challenging, and beyond the performance capabilities of available solutions [5]. Conventional digital RT-SA of microwave signals involves analog-to-digital conversion (ADC) followed by digital signal processing (DSP), using computationally intensive fast Fourier transforms [6,7]. As such these digital approaches for RT-SA are severely limited by the available ADC and DSP performance specifications. Current state-of-the-art RT-SA implementations are limited to instantaneous frequency bandwidths up to ~500 MHz with time resolution above a few microseconds [7]. Recently, we demonstrated a simple method for RT-SA of broadband waveforms, by time-mapping the short-time Fourier transform (STFT) [8], or the full spectrogram (SP, squared magnitude of the STFT), of the incoming SUT in the analog physical wave domain [9,10]. This is achieved using a simple combination of short-pulse sampling and dispersion, and the process can be interpreted as an extension of the powerful *frequency-to-time mapping* approach [11] (inherently limited to application on short-pulse waveforms) to the analysis of continuously changing arbitrary frequency spectra. In this communication, we further demonstrate the unique capability of the proposed method to perform broadband continuous gap-free RT-SA of microwave signals with dynamic features of just a few nanoseconds, over an instantaneous frequency bandwidth of nearly 5 GHz. We illustrate this powerful feature by detecting nanosecond-duration microwave interreferences, as well as frequency hopping sequences, such as those typically encountered in the above-mentioned applications [1-4].

2. Experimental results and discussion

The operation principle of gap-free continuous RT-SA of broadband microwave signals using the time-mapped SP (TM-SP) concept is described through the experimental results in Fig. 1. The experimental setup is shown in Fig. 1(a). The microwave SUTs are generated from an electronic arbitrary waveform generator (AWG) with an analog bandwidth of 10 GHz and a sampling rate of 24 GS/s. The SUT in the first example, Fig. 1(b) is a linear microwave chirp with frequencies increasing from 500 MHz to 2 GHz, over a total duration of 200 ns. Whereas the time-mapped SP scheme can operate fundamentally in a purely continuous fashion, the input signal duration is here limited to facilitate the demonstration and analysis of the proposed methodology. Interfering signals with central frequencies at 1.5 GHz, 2 GHz, 0.5 GHz and 1 GHz, each extending over a duration of 5 ns, are purposely inserted on top of the chirped microwave at 25 ns, 50 ns, 150 ns and 180 ns, respectively, relative to the starting time of the incoming signal. Each of the interferences exhibit the same instantaneous power as the underlying chirped waveform. The incoming SUT is temporally sampled with an optical pulse train (with repetition rate $\omega_R = 2\pi \times 4.86$ GHz and pulse width



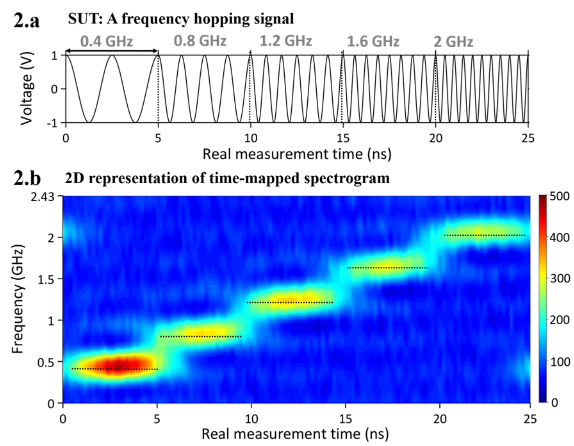


Fig. 1: (a) Experimental setup **(b)** Signal under test (SUT): Microwave chirp signal along with interferences. **(c)** A single-shot real-time scope trace at the output, showing the mapping of the changing input frequency spectrum and interferences, along each time slot of duration T_R (205.7 ps) **(d)** 2D representation of the signal SP, recovered by rescaling the output temporal trace along each consecutive analysis period into the corresponding frequency axis (vertical axis). Only the positive side of frequencies is represented here. The dashed circles represent the detected interferences of the input SUT.

Fig. 2: (a) SUT: A frequency hopping sequence. **(b)** The 2D joint TF representation (SP) that is directly mapped from the measured output temporal trace.

$\Delta t_{\text{pulse}} = 7$ ps) in a Mach-Zehnder (MZ) modulator biased at the half-wave voltage level. The maximum bandwidth of the microwave signal that can be analyzed with this scheme is dictated by the Nyquist criterion of the sampling process, i.e., limited to 4.86 GHz in our setup. Under this criterion, the sampling process creates non-overlapping spectral copies of the microwave SUT, spaced by ω_R. The sampled SUT is propagated through a second-order dispersive medium, which is implemented using a dispersion-compensating fiber (DCF) with group-velocity dispersion $\ddot{\phi} = T_R/\omega_R = {T_R}^2/2\pi = 6738.3\ \text{ps}^2/\text{rad}$. Under this condition, the neighboring SUT spectral copies are relatively delayed by the sampling period T_R. At the system output, the delayed and frequency-shifted copies of the input SUT interfere with each other, leading to a temporal waveform that follows the windowed Fourier transform i.e., the STFT (or SP = |STFT|^2) of the SUT [9]. In particular, the spectra of consecutive time-windowed sections of the SUT are time mapped along consecutive temporal slot, each with a duration equal to the sampling period, T_R. This is produced in a continuous and gap-free fashion as the consecutive analyzed signal sections are heavily overlapped (see further discussions below). For the demonstration shown herein, the output temporal waveform (trace in Fig. 1(c)) is measured with a 50-GHz photo-detector connected to a 63-GHz bandwidth real-time oscilloscope. The output temporal waveform in Fig. 1(c) is mapped into the equivalent frequency axis, along each slot of duration T_R (sampling period = 205.6 ps), using the mapping law defined in [9], namely, $\Delta\omega \rightarrow \Delta t/\ddot{\phi}$. A zoom-in over different analysis periods (each with a duration T_R), such as those shown in the insets of Fig. 1(c), reveals the predicted time mapping of the instantaneous spectral content of the SUT, including the interfering frequencies. Fig. 1(d) shows the two-dimensional (2D) representation of the SUT's time-frequency (T-F) energy distribution (SP) that is directly mapped from the measured real-time scope trace, precisely following the instantaneous frequency chirp of the microwave signal and interfering frequency components, each with a 5-ns duration. Fig. 2(a) shows another example of the analysis of a different relevant SUT, namely, a sequence of 5-ns duration frequency hops, linearly increasing along the time domain. Fig. 2(b) shows the corresponding T-F representation of the detected frequency hopping sequence, in excellent agreement with the expected frequency hop variations (dashed lines).

The lower limit on the duration of the signals that can be detected is dictated by the time resolution of the TM-SP. This is in turn imposed by the width of the analysis time window that is effectively implemented by the scheme

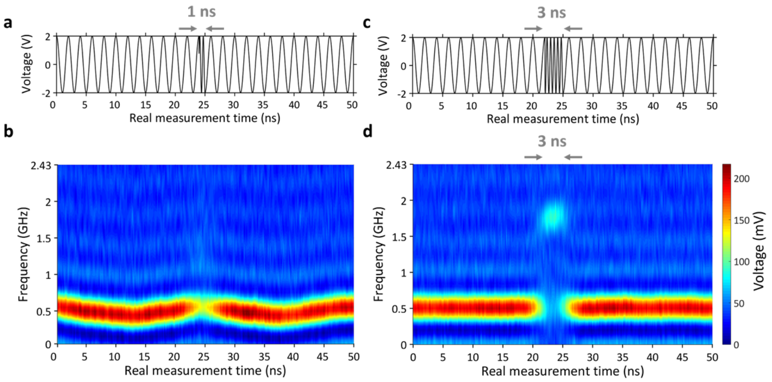


Fig. 3: Experimental results for evaluation of joint time-frequency resolutions of the time-mapped spectrogram (TM-SP) analysis. **(a)** and **(c)** Test signals. **(b)** and **(d)** The 2D SP distributions of the two analyzed signals.

for the STFT calculation. Our mathematical derivations show that the width of the analysis time window implemented by this system (i.e., time resolution of the STFT) is $\delta t_{\mathrm{resolution}} \approx |\ddot{\phi}| \times \Delta\omega_{\mathrm{pulse}} \sim 2.5$ ns. Notice that this time resolution is significantly longer than the temporal shift between consecutive analyzed signal sections (consecutively delayed by $T_R = 205.6$ ps), ensuring that the performed STFT is gap free. The FT uncertainty principle imposes that the frequency resolution of the obtained SP is directly given by the inverse of the time resolution [8], $\delta\omega_{\mathrm{resolution}} \approx \Delta t_{\mathrm{pulse}}/|\ddot{\phi}| \sim 2\pi\times160$ MHz. This frequency resolution estimate is valid assuming that the detection bandwidth is high enough to resolve the sampling pulses; otherwise, one should rather consider the temporal width of the detected pulses for this estimate. In our setup, the frequency resolution is limited by the detection bandwidth to $\delta\omega_{\mathrm{resolution}} \approx \Delta t_{\mathrm{detected}}/|\ddot{\phi}| \sim 2\pi\times340.3$ MHz. Note that the limited detection bandwidth does not modify the time resolution of the calculated SP. The joint T-F resolutions of the performed SP analysis are further validated through the test signals shown in Fig. 3. Fig. 3(a) shows a 1-ns-duration 1.7-GHz tone occurring in between two 500-MHz tones. Fig. 3(b) shows the corresponding time-mapped SP, where the 1.7-GHz tone is not observed, as its duration is below the predicted temporal resolution (~ 2.5 ns). Fig. 3(c) shows a similar test signal, except that the duration of the 1.7 GHz tone is increased to 3 ns. The corresponding time-mapped SP in Fig. 3(d) shows that the 1.7-GHz tone is clearly intercepted in this case. As discussed, the temporal and frequency resolutions of the proposed method can be tuned by changing the temporal width and/or repetition period of the sampling pulses. Thus, the system offers an important degree of versatility to design this main specification. For instance, we anticipate that a realistic scheme could be designed to detect GHz-bandwidth microwave signals with sub-nanosecond resolutions.

3. Conclusions

We have performed gap-free, continuous RT-SA of broadband microwave signals with nanosecond resolutions, through an analog time-mapped SP approach, entirely avoiding the use of digital fast Fourier transforms. Through this approach, we have demonstrated efficient detection of nanosecond-duration frequency transients over an instantaneous frequency bandwidth of ~5GHz, a performance that is well beyond the reach of present instrumentation. Moreover, the time-mapped SP approach provides additional important capabilities to process the signal's joint T-F distribution in an efficient and direct fashion using well-established time-domain waveform manipulation methods, including for instance the potential for real-time frequency interference suppression, joint T-F filtering, etc.

4. References

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