Microwave Photonic Filter with Rapid Tunability and Arbitrary Reconfigurability

Xinyi Zhu*, Benjamin Crockett, Connor M. L. Rowe, and José Azaña

Institut National de la Recherche Scientifique, Centre Énergie Matériaux Télécommunication (INRS-EMT), 800 de la Gauchetiere Ouest, Suite 6900, Montréal, H5A 1K6, QC, Canada, *xinyi.zhu@inrs.ca

Abstract *We experimentally demonstrate a novel time-varying microwave photonic filtering system for real-time signal manipulation with unprecedented tuning speed (1.5 ns) over 56 GHz full frequency bandwidth and with sub-GHz resolution, enabling ultra-rapid user-defined arbitrary electronic reconfigurability of the filter's spectral response.*

Introduction

A Time-varying filter (TVF), which allows to manipulate the frequency spectrum of an incoming signal as it changes over time, is an essential building block in telecommunications [1], metrology [2], and radar systems [3]. By reconfiguring the spectral transfer function (or filter's response) over time, TVF can provide a complete and precise manipulation of highly non-stationary signals, such as to supress undesired interferences or noise components along the incoming signal. Many modern applications based upon high-speed microwaves require the realization of time-varying filtering operations enabling arbitrary reconfigurability of the filtering spectral response at a rapid speed (nanosecond scale) and over a broad operation bandwidth (few tens of GHz). This is most often carried out by detection of the microwave signal and subsequent digital signal processing (DSP). This offers the needed versatility for realization of fully reconfigurable TVFs. However, the real-time processing speed of this conventional approach is inherently limited to below a few hundreds of MHz [4]. As such, there have been important recent efforts towards the development of reconfigurable microwave TVFs implemented directly in the analog wave domain. A particularly interesting solution is that based on microwave photonic filter (MPF) systems, which can offer operation bandwidths above tens of GHz, and an important degree of flexibility and reconfigurability beyond that of their electrical filter counterparts [5,6]. Yet, MPFs remains limited in terms of their practical tuning speed and/or degree of reconfigurability. A continuous time-frequency filtering with a very high tuning speed based on temporal modulation of a time-mapped spectrogram was previously proposed [7]. However, the processing bandwidth in this approach was inherently limited to a few GHz with only a few frequency analysis points. Thus, to our knowledge, no satisfactory time-varying filtering approach, enabling a high tuning speed, full programmability and real-time broadband processing of microwave signals, has been reported to date.

We recently proposed a set of methods for mapping the short-time Fourier transform (STFT) or spectrogram distribution of an incoming wave along the time domain, in a continuous and gap-free manner [8,9]. By providing direct access to the STFT of a non-stationary signal along the temporal domain, in preliminary work, this method has been shown to enable to manipulate the input signal time-varying frequency spectrum using temporal modulation methods, e.g., an electro-optic Mach-Zehnder modulator (MZM) [10]. In this previous work, we showed implementation of a basic bandpass filtering

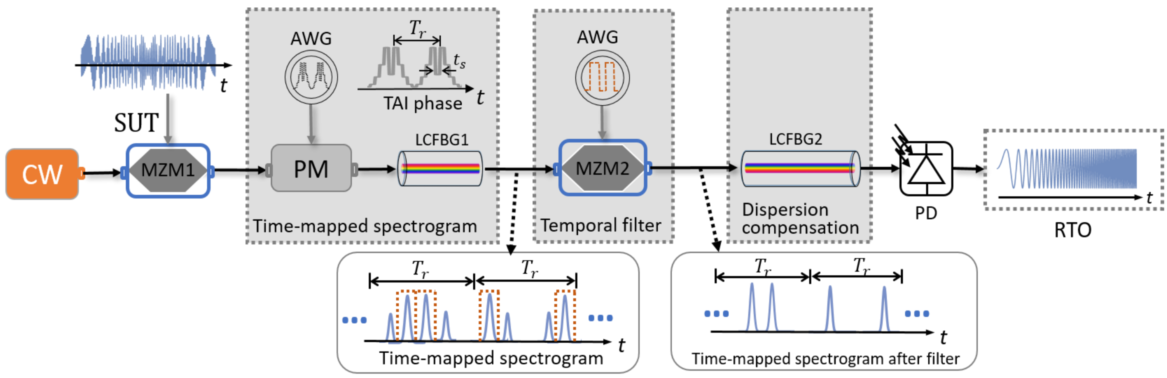

Fig. 1: Principle and experimental setup of the proposed time-varying frequency filtering system.

system in which the central frequency can be rapidly tuned. In this communication, we experimentally demonstrate the capabilities of this method to enable implementation of user-defined time-varying filtering of an incoming broadband signal (with a maximum frequency of 28GHz) in which the filter's response can be electronically programmed at will in a fully arbitrary and rapid manner, with a tuning speed in a nanosecond scale, and with a high (MHz level) resolution. Specifically, we demonstrate here application of this method for mitigation of unwanted time-varying frequency interferences from a sophisticated (double chirped) broadband microwave signal.

Operation Principle

Fig. 1 illustrates the proposed method. The microwave signal under test (SUT) is first converted to the optical domain through a MZM (40 GHz bandwidth). The optical SUT is then processed to continuously map its STFT along the time domain, so-called a time-mapped spectrogram (TM-SP), using a Talbot array illuminator (TAI) design [8]. For this purpose, the optical SUT is first phase modulated using an electro-optic phase modulator (PM, 40 GHz bandwidth) driven by a 92 GSa/s arbitrary waveform generator (AWG), providing a suitable Talbot multi-level phase pattern. Specifically, the phase pattern consists of q discrete steps, each with a length of t_s, according to the following expression: $\varphi_n = -\pi n^2 \frac{q-1}{q}$, for $n = 1, 2, \ldots, q$ [11]. This discrete phase pattern repeats periodically along the time domain with period length of $T_r = q t_s$. The duration of a single-phase step t_s determines the instantaneous analysis bandwidth of the performed STFT (or maximum SUT optical bandwidth) $\Delta\omega_s \sim 2\pi/t_s$ and the temporal period of the phase pattern T_r defines the temporal resolution of this STFT analysis [8]. The frequency resolution is inversely related to the temporal resolution $\delta\omega \sim 2\pi/T_r$, such that the number of analysis points is $q \approx \Delta\omega_s/\delta\omega$. Subsequently, the phase modulated signal is propagated through a linear dispersive element providing a second-order dispersion satisfying $\ddot{\phi} = \frac{q t_s}{2\pi}$. Following this processing, the frequency spectra of successive sections of the SUT, each extending over a duration T_r, are then consecutively mapped along the time domain, each within the corresponding analysis period of duration T_r, using the following frequency-to-time mapping law $\Delta\omega_t \rightarrow \Delta t/\ddot{\phi}$, where $\Delta\omega_t$ and Δt are relative to the centre of each analysis window. Subsequently, the signal's frequency spectrum information over every analysis window can be modulated (i.e., filtered) at will using a predesigned temporal modulation process, according to the above time-to-frequency mapping factor, effectively implementing the desired time-varying filtering process. In the experiments reported here, a second MZM (40 GHz bandwidth) is used to modify the time-mapped STFT. The user-defined temporal modulation pattern is generated by another channel of the same AWG, enabling electronically programmability of the filter's time-varying spectral response. Thus, the transfer function of the implemented time-varying filtering process can be reconfigured every T_r, i.e., at a tuning speed of T_r. Finally, the filtered signal can be recovered by reverting the phase transformations used for realization of the TM-SP. For this purpose, we utilize a second dispersive line with the exact opposite dispersion of the first one (i.e., $-\ddot{\phi}$) followed by photodetection to convert the signal back into microwave domain.

Experimental Results

To demonstrate the proposal, we process a highly non-stationary SUT consisting of two crossed linear chirps, one varying from 0.67 to 20 GHz and vice versa for the other (labelled as S_1 and S_2, for reference further below) within the time interval from 0 to 130 ns, and with different frequency interferences of varying temporal durations. The frequency of the interferences varies from 5 GHz to 28 GHz. Fig. 2(a.1) and (a.2) shows the digital SUT that was input to the MZM and the numerically computed spectrogram, respectively. The SUT is modulated on a continuous wave (CW) optical carrier centered at 1553.5 nm. In order to analyse the SUT, we choose $t_s = 1/92\ \mathrm{GHz}$, enabling a theoretical analysis bandwidth of 92 GHz. The Talbot phase modulation pattern is designed to achieve a theoretical number of analysis points $q \approx 139$, which translates into a temporal duration for each analysis window of $T_r \approx 1.5\,ns$ and a corresponding frequency resolution of ~660 MHz. A linearly chirped fiber Bragg grating (LCFBG) is employed to provide the needed second-order chromatic dispersion $\ddot{\phi} \sim 2{,}600\ \mathrm{ps}^2$. Fig. 2(b.1) shows the measured output temporal waveform of the TAI spectrogram with zoomed-in regions over different analysis periods, each with a duration of T_r. To facilitate the evaluation of the obtained results, the captured temporal signal is numerically reshaped into a 2D time-frequency representation, Fig. 2(b.2). As expected, the representation clearly depicts the evolving frequency content of the two chirps (S_1 and S_2) and the different interference terms (denoted as

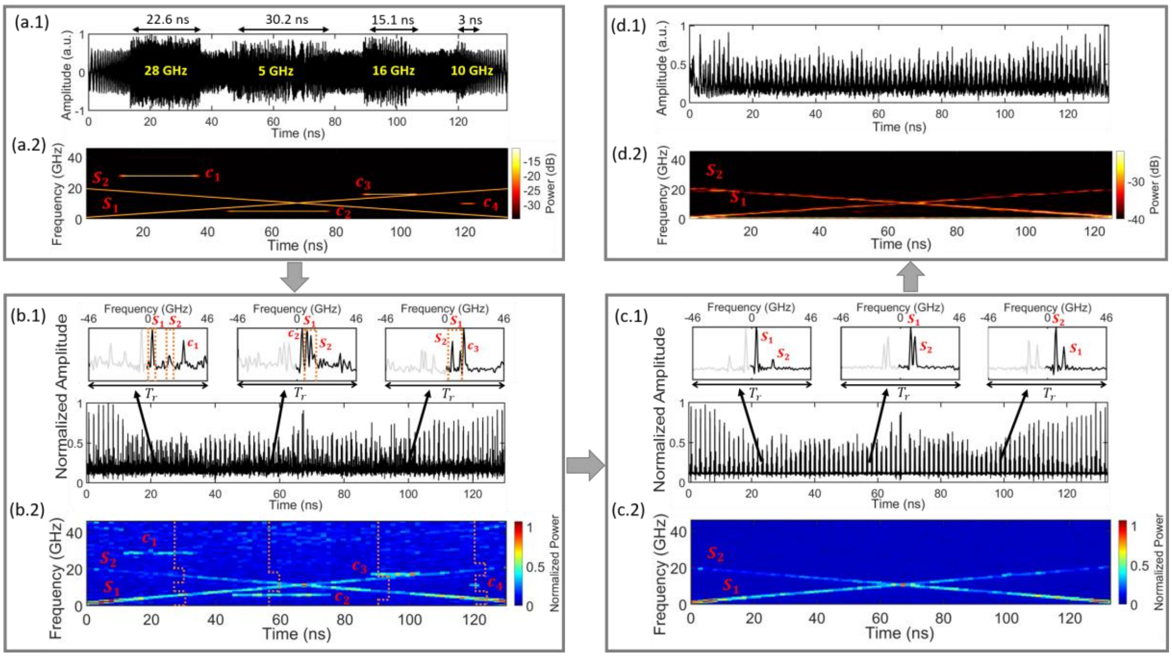

Fig. 1: Experimental results. (a.1) Temporal waveform of the SUT. (a.2) Numerical STFT spectrogram of the SUT. (b.1) The temporal waveform of the TM-SP, along with the temporal filtering waveform (dashed). (b.2) 2D representation of the TM-SP along with the gating waveform. (c.1) The TM-SP after T-F filtering. (c.2) 2D representation of the filtered TM-SP. (d.1) The recovered signal after the second dispersive element. (d.2) Numerical STFT spectrogram of the recovered signal.

'c_i' with i = 1, 2, 3, …). Notice that the proposed system maps the corresponding full (double sideband) frequency spectrum along the time domain every T_r, including both the positive and negative sides of the input SUT spectrum, according to the frequency-to-time mapping law defined above. The equivalent frequency axis is shown at the top of each zoomed waveform. In order to clearly show the evolving frequency, here we only plot the positive spectra. The temporal waveform is then modulated by the user-defined filtering pattern through a second MZM. The temporal filtering mask is designed to be composed of rectangular shapes, each with a temporal width equal to t_s, corresponding to a filter passband equal to the frequency resolution $\delta\omega \sim 2\pi \times 660\ \mathrm{MHz}$ of the time-mapped spectrogram. In order to select the two chirped waveforms (S_1 and S_2), two rectangular pulses with varying time locations according to the frequency-to-time mapping factor are implemented in every analysis time window T_r, shown with the dashed orange traces in the 2D TM-SP representation, Fig. 2(b.2). Thus, the response of the filter can be effectively programmed every $T_r = 1.5\ \mathrm{ns}$. The output of the second MZM used for time filtering is shown in Fig. 2 (c.1) and the zoomed-in regions clearly confirm that the pulses representing the interference terms have been greatly mitigated while the ones corresponding to the chirped signal terms, S_1 and S_2, are maintained nearly undistorted. The corresponding 2D representation is shown in Fig. 2 (c.2), again showing a clear reduction of the unwanted interferences. Finally, a second LCFBG with the exact opposite dispersion to the first LCFBG is used for dispersion compensation and the recovered microwave signal is measured using a 50-GHz photodiode (PD) connected to a 28-GHz real-time oscilloscope (RTO), shown in Fig. 2(d.1). The corresponding numerical spectrogram is also shown in Fig. 2 (d.2). Compared with the input, the output STFT spectrogram clearly confirms that the unwanted interferences have been successfully mitigated using the proposed T-F filtering system.

Conclusions

We have proposed and experimentally demonstrated a photonics-based time-varying frequency filtering system of broadband microwave signals enabling rapid tuning speed and arbitrary reconfigurability beyond the potential of present solutions. We envision that this approach should be particularly interesting for implementation of the software-defined paradigm in emerging communication and remote sensing systems that require ultrahigh speed dynamic information analysis and manipulation.

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