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Frequency-to-time mapping by a frequency-shifting loop based on electro-optic phase modulation

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Photonic processing of microwave signals may offer higher bandwidth than conventional electronic methods [1]. Among various functions achievable by optical means, optical real-time Fourier transformation (RTFT) has received special attention because of its high processing speed, which is far beyond conventional digital signal processing methods. In this respect, the frequency-shifting loop (FSL) shows high performance, as compared to dispersion-based methods, by analyzing MHz-range bandwidth signals with a frequency resolution of a few kHz [2]. FSLs up to now mainly rely on the use of acousto-optic frequency shifters, with inherent limitations in efficiency when seeking a high bandwidth. To overcome this limitation, the use of electro-optic modulators inside FSLs was theoretically studied [3]. It was shown that *phase modulators* could be an alternative for realizing RF-photonic frequency-to-time mapping (FTM). Here we give some experimental support to the predictions of Ref. [3], opening a new route to fully integrated microwave-photonic signal analyzers.

Our all-fibered FSL set-up is depicted in Fig.1(a). It includes the phase modulator (EOPM2) that creates a dual-sideband frequency shift $\pm f_m$ at every round-trip, and an optical amplifier (EDFA) to compensate for the losses. The cw seed laser delivers 0.3 mW at around 1550 nm in the C band. A tunable bandpass filter (TBPF) helps to circumvent spurious lasing induced by the spontaneous emission of the EDFA. We choose a frequency-shift f_m applied to the EOPM2 (inside the loop) at an integer multiple of the fundamental loop frequency to meet the Talbot condition $f_m = pf_c$ [2,3]. Here the round-trip time $\tau = 1/f_c$ = 112 ns, and f_m = 8.9 MHz (p = 1).

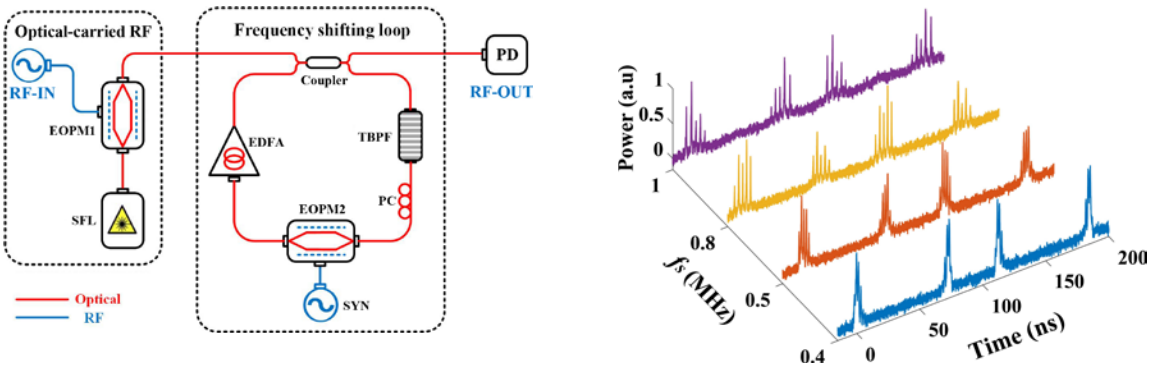

Figure 1. 1 (Left) Experimental set-up. (Right) Illustration of the frequency-to-time mapping property: f_s = 400 kHz (blue), 500 kHz (orange), 800 kHz (yellow), and 1 MHz (violet).

When the loop is injected by a single-frequency laser (at pulsation ω_0), the output power of the loop is calculated to be

$$P_{out}(t) = \left| t_{11} + \frac{t_{21}t_{12}}{t_{22}} L(t) \right|^2 P_0$$

where $[t_{ij}]$ is the transmission matrix of the coupler. The loop function $L(t)$ contains the sum of all, time-delayed, up- and down-shifted frequency components circulating inside the loop. In the integer

Talbot condition $f_m = pf_c$, it can be simply written as

$$L(t) = \frac{t_{22}\gamma e^{j\theta(t)}}{1 - t_{22}\gamma e^{j\theta(t)}}$$

γ being a constant real parameter that includes loss and gain factors inside the loop. and, for a phase-modulated loop, the pulses are located at times defined by

$$\theta(t) = \delta \sin(2\pi f_m t) + \omega_0 \tau,$$

where δ is the modulation depth. From the above equations, one finds that the output power is a function peaked in $\theta(t) = 2k\pi$ ($k \in \mathbb{Z}$), with a repetition rate f_m. This is the basis of the FTM process : one optical frequency at the input yields one pulse at the output (actually a f_m – periodic train of pulses).

To demonstrate the FTM property of this loop, the seed laser is modulated by EOPM1 at frequency f_s in order to generate several sidebands. Depending on the loop parameters, different scenarios can be observed [3]. Here we choose the simplest one, when $\delta = \pi$. Experimental results are shown in Fig. 1(b), where each trace corresponds to a f_s–modulated input. It confirms the FTM process and it also shows a special feature corresponding to this phase-modulated FSL: the spectrum is mapped *twice* per round-trip, i.e., the spectrum and its mirror image, in agreement with the condition on the sine function. Besides, we have also found that the frequency ambiguity of this process is given by the loop fundamental frequency f_c (as in the AO loop); for example modulations at $f_s = f_c + f_0$ ($f_0 < f_c$) or at $f_s = Nf_c + f_0$ ($N \in \mathbb{N}$) yields the same output time trace. We also verify experimentally that the resolution is kept at any Talbot order p, and that such a sine-modulation can also provide an interesting nonlinear FTM.

In conclusion, beyond the real-time spectral analysis demonstrated here [4], this phase-modulated frequency-shifting loop targets applications like pulse compressed lidar, arbitrary waveform generation and velocimetry. The use of electro-optic modulators in FSLs opens opportunities in integrated systems with potentially much shorter loop times and hence higher processing bandwidths.

Références :

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