High-repetition-rate optical frequency comb technology for ultra-broadband radio-frequency photonics

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1. Introduction

Since its inception in 2000, the optical frequency comb has become a revolutionary tool in the field of optical synthesis and metrology [1]. The ultra-low-noise performance and broadband coherent spectrum have allowed for a non-stop expansion of different applications [2]. However, it is important to understand that there isn't a "once size fits all" technology. For example, applications in the field of optical clocks and remote frequency transfer rely on self-referenced frequency combs, which are typically implemented by Ti:Sa or Erbium fiber mode-locked lasers [2]. In contrast, applications in the field of optical communications [3] and arbitrary waveform generation [4] do not necessarily require self-referenced combs but a technology platform with higher robustness and flexibility, and more importantly, capable to operate at 10+ GHz repetition rates.

In this invited contribution, we will provide an overview of ultra-high-repetition-rate frequency comb technologies and discuss their applications in the fields of radio-frequency photonics and coherent optical communications.

2. High-repetition-rate optical frequency comb technology

2.1 Electro-optic frequency comb generation

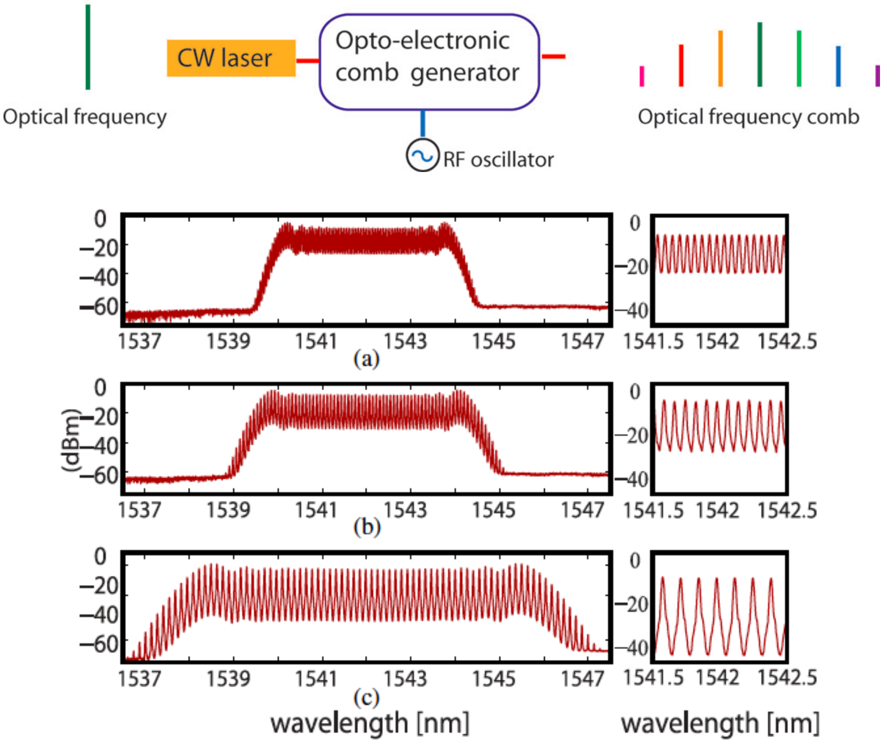

Figure 1 Top. Schematic view of an electro-optic frequency comb generator. Bottom. Repetition rate tuning of an electro-optic comb (7, 10 and 17 GHz examples) [5].

In this technology, schematically illustrated in Fig. 1 (top), a continuous-wave (CW) laser feeds an array of external modulators, typically electro-optic-based and implemented by lithium niobate. The modulators are driven by an external radio-frequency (RF) oscillator. At the output of the modulation stage, a frequency comb emerges with the central optical frequency defined by the CW laser and the spacing between lines exactly provided by the RF oscillator. This technology was already researched in the 70s and 80s as an alternative scheme to active modelocking for obtaining picosecond-class optical pulses. This platform has re-gained some interest thanks to the latest advances in high-power-handling (both RF and optical) modulators and dielectric RF oscillators featuring sub 100-fs timing jitter at tens of GHz repetition rate. Here, the most attractive characteristic is that, unlike mode-locked lasers, these combs operate without cavity, and therefore the central frequency and repetition rate can be independently and continuously reconfigured over a broad range [5]. Figure 1b displays a high optical power (~ 13 dBm) frequency comb featuring > 60 lines with a repetition rate tunable within the range of 6-18 GHz [5].

2.2 Microresonator frequency combs

The maximum repetition rate at which the above technology can operate is limited by the bandwidth of the electro-optic modulators and is at present <100 GHz (with commercially available technology this becomes ~40 GHz). Applications in the fields of e.g. optical arbitrary waveform generation and optical communications would benefit from higher repetition rates and even more compact platforms. In this direction, there is a new optical frequency comb technology capable to accomplish both features simultaneously, i.e., the microresonator frequency comb [6]. In this new configuration, a CW laser pumps an ultrahigh-Q optical cavity. When the power builds up in the resonator, new frequency components are generated and interact via nonlinear mixing. This structure bears interesting physical properties akin to mode-locked laser systems. The cavity defines the longitudinal modes whereas modulation stability shapes the gain spectrum [6]. Ultrafast pulses [7] and stable cavity solitons [8] have been reported in this new comb generator. However, the noise performance (e.g. spectral coherence) in this configuration is only poorly understood. In this contribution, we shall present our work on the coherence analysis in this type of platform and provide design rules in order to achieve spectrally coherent microresonator combs [9].

3. High-repetition-rate optical frequency comb applications

3.1 Radio-frequency photonics

The advent of low-loss single-mode fiber made it possible to transmit RF signals over much longer distances than what is possible with microwave waveguides [11]. It was soon recognized that by adding additional photonic technologies, these hybrid fiber-microwave links could enable additional functionalities, such as filtering and processing, with characteristics unattainable by microwave counterparts [11]. The field of microwave photonics has grown as a discipline in itself with potential applications beyond microwave links, e.g. analog-to-digital conversion, microwave filtering, coherent wireless communications and arbitrary waveform generation.

The above-mentioned unique features of high-repetition-rate combs offer a significant impact in this field [12]. As an example, Fig. 2 illustrates the temporal compression of an ultra-broadband complex RF waveform [10]. The signal is synthesized with a state-of-the-art microwave RF waveform generator. In order to compress this signal, we use a programmable microwave phase filter using an electro-optic frequency comb [13], which matches the phase of the input RF signal so that the output waveform is almost transform limited. The programmability of the filter is nicely illustrated by the example in the second row, where the chirp of the signal is reversed. The microwave photonic filter is thus re-programmed and the output waveform becomes again transform limited.

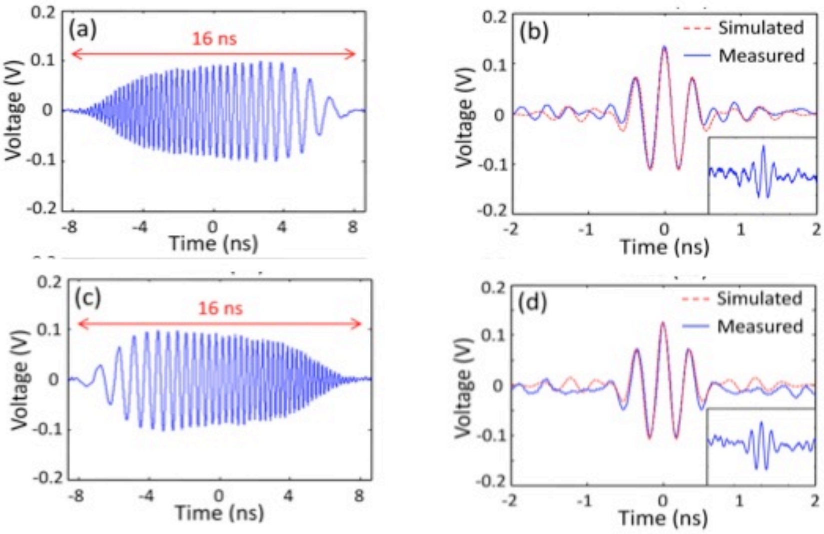

Figure 2 Compression of complex microwave pulses using a programmable frequency-comb-based microwave phase filter. (a) input waveform (b) output compressed; (c) input waveform with reversed chirp (d) corresponding output compressed signal. Results from [10].

3.2 Optical coherent communications

One of the most successful technologies in the history of fiber-optic communications is wavelength division multiplexing (WDM). Here, optical carriers located at different frequencies are independently modulated by external modulators with the data to be transmitted. In modern coherent communications, the digital data are encoded by exploiting all the physically available degrees of freedom of the light source, i.e. polarization, amplitude and phase. An important figure of merit to quantify the utilization of the available optical bandwidth in optical fiber link becomes the spectral efficiency, defined as the ratio between the bit rate and the optical bandwidth needed to achieve it.

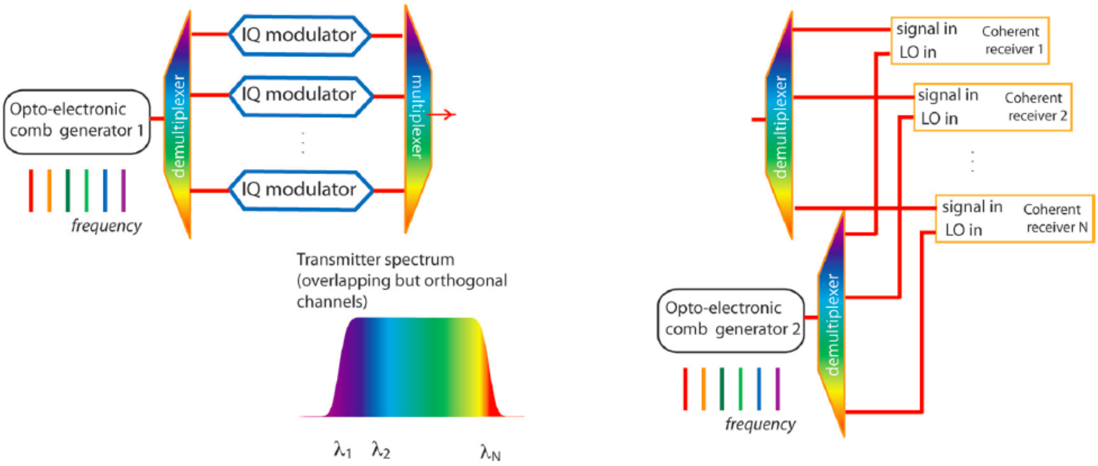

Figure 3 Frequency-comb-based optical OFDM transmitter (left) and receiver. I & Q stands for in-phase and quadrature modulations, whereas LO is Local Oscillator.

It is recognized that optical frequency comb technology is a key enabler because it can boost the spectral efficiency in communication systems [14,15]. The key relies on the broadband phase coherence and the equidistance between comb lines. These two features have allowed for implementing novel modulation formats formerly developed in the realm of wireless communication systems (e.g. orthogonal frequency division multiplexing) [15]. The idea is that the comb allows for stitching more closely together independent WDM channels. If time allows, this application (schematically illustrated in Fig. 3) will be highlighted.

4. Conclusions

The most suitable optical frequency comb technology depends on the target application. In this contribution, we have considered high-repetition-rate (> 10 GHz) frequency comb generators for radio-frequency photonics and optical communications. These applications demand very high repetition rates in a compact platform and do not require self-referencing. We have provided a few practical examples regarding electro-optic frequency comb generators. We have also discussed the promises and the challenges that lie ahead in the implementation of microresonator frequency comb in this type of applications.

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