

## A fiber frequency-shifting loop for RF up-conversion and waveform generation

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Ring interferometers containing both an amplifier and a frequency-shifter have been proposed in different contexts, either for enhancing the performance of self-heterodyne laser line-width measurements [1], or for frequency-shifted feedback lasers and mode-locked operation [2]. It has received considerable interest recently, leading to accurate frequency-to-time mapping [3], rapid wavelength scanning [4], or pulsed laser high-frequency modulation [5] for instance. These schemes rely on the multiple interference of frequency-shifted and time delayed laser waves. Here we investigate a fully fibered frequency-shifting loop containing an optical amplifier in the context of microwave photonics. The aim of this research is to show that the recirculating frequency-shifting ring interferometer is a convenient method for radio-frequency up-conversion and waveform generation. Compared with previous works based on similar set-ups, we focus on (i) loop lengths shorter than the coherence length of the seed laser in order to provide high-purity RF harmonic beats, and (ii) sub-threshold operation in order to control the RF phase and amplitudes of the recirculating components. We provide a theoretical model to derive a time-delayed interference equation, in order to obtain the output intensity of the loop, and we compare it with an all-fibered experiment.

The schematic diagram of the loop is shown in Fig.1(a). Our set-up is based on standard 1  $\mu\text{m}$  fiber optics. The source is a cw single-frequency fiber laser at 1064 nm with an output power of 50 mW and a linewidth of 2 kHz. It is connected to the input port 1 of the 2x2 fiber coupler. The loop starting from the output port 2 includes an acousto-optic frequency shifter (AOFS) with a driving radio frequency tunable around 200 MHz ( $\pm 5\text{MHz}$ ). The up-converted wave is then regenerated by an ytterbium-doped fiber amplifier (YDFA), and connected to the input port 2, closing the loop. The amplifier is operated at low gain, in order to avoid the loop oscillation and uncontrolled pulsed operation. The useful up-converted signal is extracted from the output port 1 and sent to a fibered 3.5 GHz-bandwidth photodiode. Hence we find on the photodiode the interference of the input wave with the summation of time-delayed, frequency-shifted, recirculating loop waves. The recorded signals are compared to an analytical multi-interference model similar to the ones in [3,5], that includes the time delay  $\tau$ , the frequency-shift  $f_{\text{AO}}$ , and the net gain  $\gamma$ . If the input field at port 1 is a monochromatic field with infinite coherence time and power  $P_{\text{in}}$ , one can show that the useful output power reads

$$P_{\text{out}}(t) = \left| t_{11} + t_{12} g t_{21} \sum_{p=0}^{\infty} (t_{22} g)^p e^{j2p f_{\text{AO}}(p+1)t} e^{-ip f_{\text{AO}}(p+2)(p+1)t} \right|^2 P_{\text{in}} \quad (1)$$

where the  $t_{ij}$  are the 2x2 coupler amplitude transmissions. In agreement with previous descriptions of the ring interferometer, Eq. (1) shows the influence of the relevant experimental parameters that can be modified experimentally: delay, frequency-shift, and net gain.

First, we investigate the influence of the loop length with respect to the fundamental beat length. Namely, constructive interference among the successive harmonic components are obtained when the loop length is a multiple of the beat length. Consequently a slight change in the driving RF leads to important waveform modification, because the loop length determines the RF phase factor of each harmonics, which leads to the different interference waveforms. Typical experimental output waveforms are shown in Fig. 1(b). We also checked the influence of the delay by adding different discrete fiber lengths (typical loop length is 19 m, the delay

time  $\tau$  of the order of  $10^{-7}$  s). Second, we observe that the YDFA permits to expand the harmonics comb. The loop length and shift frequency are fixed, and the fiber YDFA is set to different powers. Indeed, the insertion of an amplifier in the recirculating loop permits to reduce the impact of losses over many round-trips. For example, with a typical intensity gain of 3, we obtain up to 19-fold up-conversion of the modulation frequency leading to a RF frequency comb up to 3.8 GHz [see Fig.1(c)]. The experimental results are in good agreement with the model.

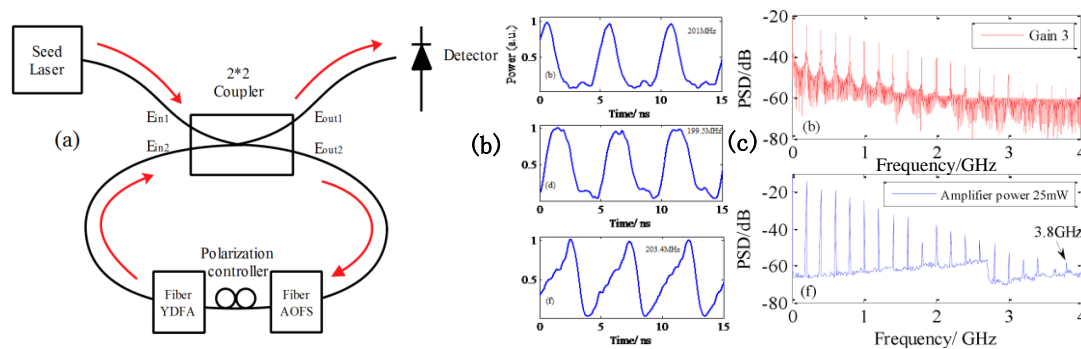


Figure 1. (a) Experimental setup. (b) Output intensity in the time domain showing pulse-like, square, or saw-tooth waveforms depending on the AOFS driving frequency (c) Simulated (red) and experimental (blue) spectra showing up-conversion of the AOFS driving frequency, from 200 MHz to 3.8 GHz.

We also evaluate the spectral purity of the beat notes generated by this method, we compare the fundamental and high-order harmonics. The line-width (FWHM) of 15<sup>th</sup> harmonics (3 GHz) is as narrow as of 1<sup>st</sup> harmonics (200 MHz), i.e., limited by the 10 Hz-resolution bandwidth of the instrument. Indeed, as long as the cumulative delay stays below the coherence time of the laser source, high-order harmonics keep narrow line-widths.

This method offers a programmable and integrable scheme for complex modulation formats. An additional frequency-doubling stage could yield a source for underwater communications [5-6]. Extension of the scheme to the 1.5  $\mu\text{m}$  telecommunication window is straightforward, for radio-over-fiber applications. It also provides a simple means to generate high-frequency modulated waves that can face the challenge of ultra-low velocity Doppler frequency shifts. Applications include lidar-radar detection for instance [7-8].

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