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## GHz-rate pulse pairs generated by a frequency-shifting loop containing an electro-optic modulator

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We investigate an all-fibered frequency-shifting loop (FSL) which includes an electro-optic amplitude modulator (EOM) and an optical amplifier, and is seeded by a continuous-wave laser. We demonstrate an original double-pulse regime when the loop length is a multiple of the RF modulation wavelength applied to the modulator (integer Talbot condition). The inter-pulse interval is governed by both the bias voltage and modulation depth of the EOM. The system is modeled by an interference model that takes the amplitude modulation function and loop delay into account. Above threshold the FSL generates mode-locked picosecond pulse doublets with a continuously adjustable delay.

## GHz-rate pulse pairs generated by a frequency-shifting loop containing an electro-optic modulator

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Frequency-shifting loops (FSL) are ring resonators containing both an amplifier and a frequency-shifter, usually an acousto-optic modulator (AOF) [1]. They are promising solutions to generate pulses with tunable and high repetition rates or for arbitrary RF waveform generation. Here we investigate an all-fibered frequency-shifting loop that includes an electro-optic amplitude modulator (EOM). At variance with preceding research, e.g. [1-3], the EOM creates at each round-trip two sidebands that recirculate inside the loop. We demonstrate an original double-pulse regime when the loop length is a multiple of the RF modulation wavelength applied to the modulator. By changing the bias voltage applied to the EOM, the interval between the pulses can be continuously adjusted. The system is modeled by a linear interference model that takes the amplitude modulation function and loop delay into account.

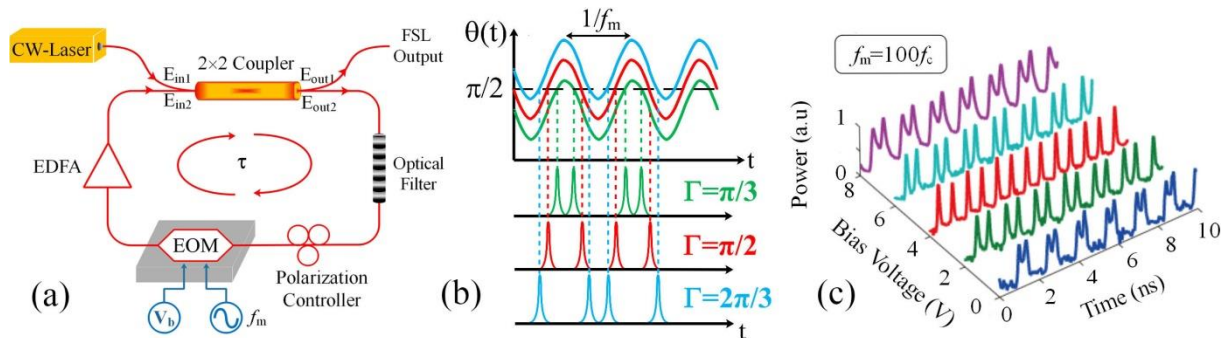


Fig. 1. (a) Dual side-band FSL; (b) Sketch of the output signal vs time at different EOM biases; (c) Example of the experimental pulse doublets.

We consider the FSL depicted in Fig. 1(a). The EOM induces a dual-sideband frequency shift per round-trip  $f_m$ . The erbium-doped fiber amplifier (EDFA) provides gain that partially compensates for the loop losses and enhances the number of relevant round-trips inside the loop. The round-trip time is  $\tau = nL/c$ , where  $n$  is the group index of the fiber. This leads to a fundamental loop frequency  $f_c = 1/\tau$ . At  $p^{\text{th}}$  round-trip, the real transfer function of the EOM can be modeled as  $\Upsilon^{(p)}(t) = \sin[G + G_m \sin(2\rho f_m(t - pt))]$ , where  $\Gamma_m$  is the modulating depth that depends on the RF power  $P_{dc}$ .  $\Gamma$  is the static phase retardance of the EOM that can be controlled by the applied bias voltage  $V_b$ . The experimentally accessible and useful signal is at the output port 1. If the input field at port 1 is a single-frequency continuous-wave with power  $P_{in}$ , then a time-delayed interference model yields

$$E_{out1}(t) = t_{11}\sqrt{P_{in}} + t_{21}t_{12}\sum_{p=1}^N t_{22}^{p-1}g^p \prod_{l=1}^p \Upsilon^{(l)}(t)\sqrt{P_{in}}, \quad (1)$$

where  $t_{ij}$  are the complex amplitude transfer coefficients of the 2x2 coupler, and  $\gamma$  takes the loop losses and EDFA gain into account. According to Eq. 1, when  $f_m = Nf_c$ , the FSL output is a sharp function peaked in  $\theta(t) = \Gamma + \Gamma_m \sin(2\pi f_m t) = \pi/2$ . The important point is that two temporally separated solutions appear in one period  $1/f_m$ , as illustrated in Fig.1 (b).

Experiments are performed with a continuous-wave single-frequency laser, which delivers 0.3 mW in the C band. The EOM is a 10 GHz-bandwidth Mach-Zehnder modulator with a half-wave voltage of 4 V. The loop fundamental frequency is measured to be  $f_c = 6.737\text{MHz}$ . For example, Fig. 1(c) reports the experimental results when  $N = 100$  (673.7 MHz). The delay between 130 ps long pulses is shown

to be continuously adjustable from  $\Delta t = 0$  to  $\Delta t = 1/(2f_m)$  by changing the bias voltage  $V_b$ . This regime has been observed up to  $N = 500$ , with 80 ps pulses at  $f_m = 3.4$  GHz (limited by the detection). Additional features, such as tunable rectangle waveforms (when the two pulses merge), or saw-tooth waveforms (when  $f_m \neq Nf_c$ ), are found experimentally and theoretically.

Finally, when the gain fully compensates the loop losses, we are then in a situation of a loss-modulated ring laser, that leads to the mode-locked regime. Surprisingly, mode-locked operation also leads to the pulse doublets features described by the linear model, as shown in Fig. 2.

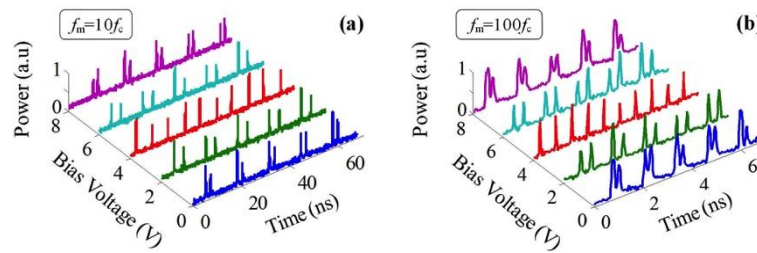


Fig. 2. Harmonic mode-locked double-pulse operation. Experimental laser output when (a)  $f_m = 76.11$  MHz,  $\tau_p = 210$  ps (b)  $f_m = 761.1$  MHz,  $\tau_p = 70$  ps.

In summary, we have evidenced an original regime of pulse doublets that finds its origin in the transfer function of the EOM. The model explains well the formation of pulse doublets. This experiment shows an alternative approach to AOFS loops, taking advantage of the inherent bandwidth and tunability of the EOM. Beyond this first demonstration, careful characterization and reduction of jitter issues need further work that is under progress. Designing a loop with all polarization-maintaining fiber components, as well as acoustic and thermal isolation, would improve the stability. Such loops could find applications in pump-probe experiments or to photonic sampling of RF signals. From the theoretical point of view, it would be interesting to elucidate connections with Talbot quadratic phases as observed in AOFS loops.

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