

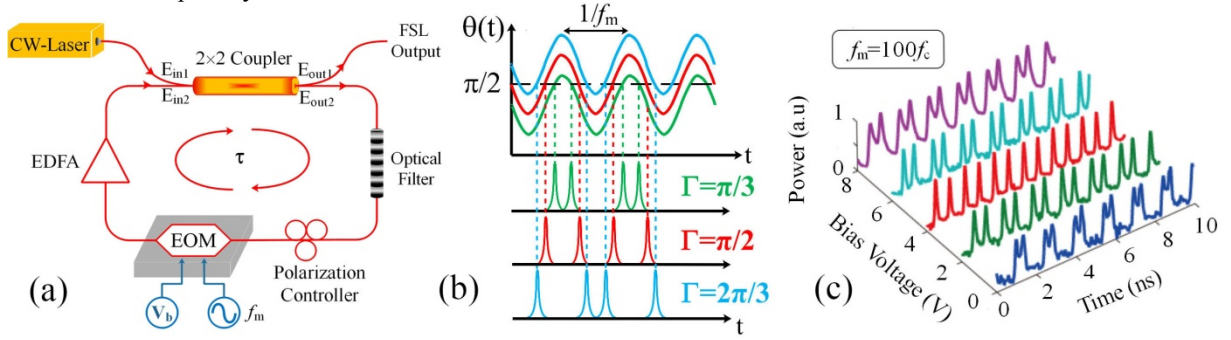
# Pulse doublets generated by a frequency-shifting loop containing an electro-optic amplitude modulator

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Frequency-shifting loops (FSL) are ring resonators containing both an amplifier and a frequency-shifter, usually an acousto-optic modulator (AOFS) [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 side-bands 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  $f_c = 1/\tau$ . The real transfer function of the EOM can be modeled as  $Y(t) = \sin(\Gamma + \Gamma_m \sin(2\pi f_m t))$ , 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  $V_b$ .

When  $f_m = Nf_c$ , according to a time-delayed interference model that we derived, 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  $f_c = 6.737$  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. Surprisingly, when the gain fully compensates the loop losses, mode-locked operation also leads to all the pulse doublets features described by the linear model.

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. 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.

## References

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