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Nonlinear frequency chirps from a stabilized injected phase-modulated fiber laser loop

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Abstract. A phase-modulated frequency-shifting loop is injected by a single-frequency laser at 1.5 μm . In so-called Talbot conditions, i.e., when the modulation frequency is an integer multiple of the inverse of the cavity round-trip time, the loop generates a frequency comb whose temporal trace consists in a train of pulse doublets whose positions in time depend on the frequency of the injection laser. When the modulation frequency is slightly detuned from the Talbot condition, nonlinear frequency chirps are predicted and observed in the output pulse train. We demonstrate that these nonlinear chirps are not restricted to sinusoidal shapes, and also that the loop can be stabilized by exploiting the intracavity phase modulation.

Frequency-shifting loops (FSLs) based on acousto-optic modulators are known to generate linear frequency chirps when the round-trip frequency shift is close to the inverse of the cavity round-trip time [1]. Such GHz range chirps can be applied to high-resolution lidar schemes, especially in dual-comb systems [2]. When the loop contains an electro-optic (EO) phase modulator (PM) instead, double-pulse operation and frequency-to-time mapping are observed [3], and sinusoidal frequency chirps can be generated [4]. In such PM loops however, the output waveform depends on the relative stability of the master laser with respect to the loop [3,4], which is detrimental for its use in practical applications. Since an EO-PM scheme is very attractive in view of photonic integration in lidar systems for instance, we design here a stabilization scheme for locking the laser to the loop, in analogy to the well-known Pound-Drever-Hall (PDH) scheme. We also show that stabilization is still effective under the detuning conditions necessary for sinusoidal chirps, and that it extends to other periodic functions, such as triangle- or square-shaped modulations. Stabilized nonlinear chirps in the 15 GHz range are demonstrated, limited by our detection bandwidth.

Let us first describe briefly the set-up, which is similar to the one used in Ref. [3]. The fiber loop includes a 12 GHz bandwidth phase modulator driven by a synthesizer at frequency f_m , an erbium-doped fiber amplifier and a fiber Bragg grating. The whole set-up is made with polarization-maintaining components. The loop is injected by a single-frequency fiber laser at 1.549 μm through a 10 dB coupler. The loop round-trip time is $\tau = 62$ ns, corresponding to a cavity frequency $f_c = 16.13$ MHz. In so-called Talbot conditions, when $f_m = pf_c$ (p integer), all the recirculating up- and down-shifted lines interfere to yield a train of double-pulses that are extracted from the loop through a 10 dB output

coupler. It was shown in preceding works [3] that the peak intensities are found at instants t obeying:

$$\delta \sin(2\pi f_m t) + \omega_0 \tau = 2n\pi \quad (n \in \mathbb{Z}), \quad (1)$$

where δ is the modulation depth, and ω_0 is the pulsation of the master laser. In free-running conditions, the master laser drifts with respect to the fiber loop, leading to unstable dual-pulse emission due to the $\omega_0 \tau$ term in Eq. (1). This is shown in Fig. 1. Hence, in order to be fully applicable, such a loop must be actively stabilized.

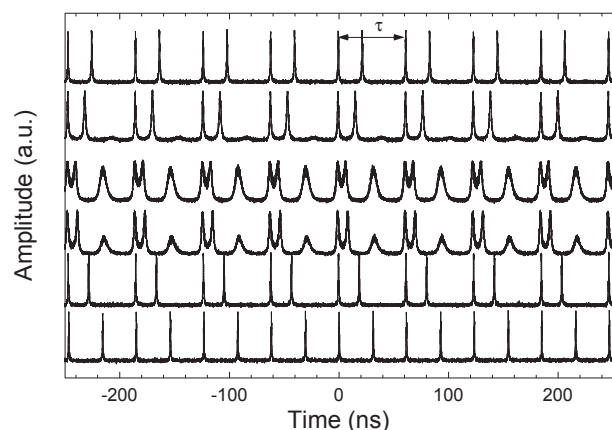


Fig. 1. Free-running double-pulse operation (six successive traces taken a few seconds apart).

In order to stabilize the laser frequency to the fiber loop, we generate an error signal by low-pass filtering the first harmonics of the loop output. Since they come from the EO phase-modulator, the +1 and -1 harmonics have opposite phases. By mixing the photodiode signal with the output from the synthesizer at f_m , we get an error signal that is typical of PDH signals, as shown in Fig. 2.

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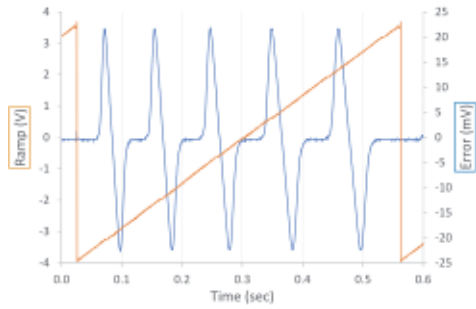


Fig. 2. Stabilization error signal (blue) during a slow sweep of the master laser wavelength (red).

This error signal is then sent after correction to the modulation input of the master laser. When the loop is closed, we observe a robust stabilization of the output doublets. Furthermore, by controlling the relative phase of the discrimination signal with respect to the in-loop phase modulation, we are able to precisely choose the inter-pulse time delay. Experimental time traces and frequency comb optical spectra corresponding to the stabilized loop are shown in Fig. 3. For $p = 1$ ($f_c = 16.2$ MHz), we find 2 ns-long pulses and a 3-GHz wide optical spectrum. For $p = 70$ ($f_m = 1.135$ GHz), we observe detection limited 35 ps pulses and a 175 GHz wide spectrum (155 lines above the noise floor).

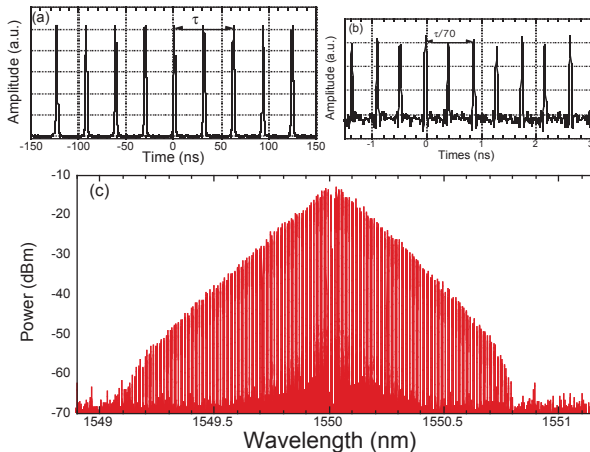


Fig. 3. Stabilized injected PM laser. (a) $p = 1$. (b) $p = 70$. (c) Optical spectrum corresponding to (b).

Under these stabilization conditions, we now show a few interesting extensions of this loop. At modulation frequencies slightly detuned from an integer Talbot condition, we can generate nonlinear frequency chirps as predicted by Yang *et al.* [4]. Fig. 4 shows some traces obtained when $f_m = f_c + \Delta f$, yielding typical sinusoidal frequency chirps as a consequence of the sine phase modulation. The RF chirps are revealed by mixing the loop output with the master laser itself [5]. Besides, we find that the result of Eq. (1) is not restricted to sinusoidal waveforms, and that *any* $1/f_m$ -periodic function F leads to peak intensities as soon as:

$$F(2\pi f_m t) + \omega_0 \tau = 2n\pi \quad (n \in \mathbb{Z}). \quad (2)$$

For example, square-shape modulations yields the output signals depicted in Fig. 5(a). Remarkably the short-term

Fourier transform of these experimental signals show the frequency chirps follows the shape of the intracavity phase modulation. It is also noteworthy that low-frequency modulation (MHz range) is converted to GHz bandwidth microwave chirps, with a chirp bandwidth proportional to the order p , and inversely proportional to the detuning Δf .

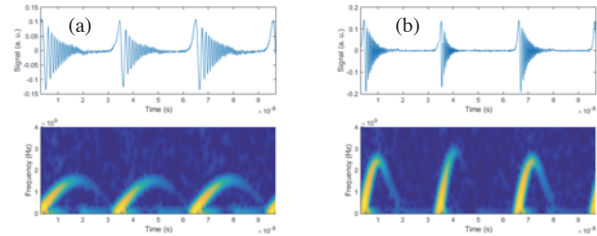


Fig. 4. Stabilized sinusoidal frequency chirps at $p = 1$. (a) $\Delta f = 150$ kHz, and (b) $\Delta f = 50$ kHz, and corresponding short term Fourier transforms (STFT) below.

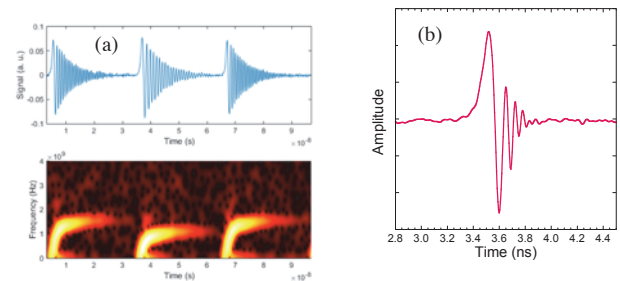


Fig. 5. (a) Chirps obtained at $p = 1$ with a square-shaped phase modulation (STFT below). (b) Single chirped pulse at $p = 9$ ($f_m = 145.175$ MHz) with $\Delta f = 20$ kHz.

In conclusion, we have shown that an injected phase-modulated laser loop can be efficiently stabilized to yield controllable picosecond double-pulse trains, and that nonlinear frequency chirps appear as soon as the modulation frequency is detuned from the integer Talbot conditions. Such waveforms could be useful for ranging, the scheme can be extended to dual-combs, and it has the potential to be fully integrated [6].

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