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Airy pulse generation in a dispersive injection-seeded frequency-shifting fiber loop

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Abstract. We report the generation of Airy pulses in an injection-seeded, amplified fiber loop incorporating an acousto-optic frequency shifter and a dispersive delay line implemented through a series combination of linearly chirped fiber Bragg gratings. The combined effect of unidirectional frequency shifting and first-order dispersion generates a frequency comb with cubic spectral phase, equivalent in the time domain to a single-sided, bandlimited Airy pulse train. The present approach demonstrates the use of intra-loop phase-only filtering for the generation of tailorable optical waveforms in recirculating fiber loops.

Airy beams of finite energy have received extensive interest due to their distinctive propagation properties, such as invariance under diffraction and transverse acceleration [1]. Their temporal counterparts, finite-energy Airy pulses, are usually generated from a transform-limited mode-locked laser and subsequent cubic phase-only spectral filtering (see, for instance, [2]). This flexible and reconfigurable way of pulse shaping, however, is associated with a higher cost. In this work, we report the compact generation of bandlimited Airy pulses using a frequency shifting fiber loop incorporating first-order dispersion. The recirculation of an optical frequency, which in subsequent roundtrips increases its value by the action of a frequency shifter and also undergoes quadratic spectral phase-only filtering, provides in a natural way the cubic spectral phase of Airy pulses [3]. The present approach extends previous demonstrations of the use of frequency shifting loops for the generation of complex optical waveforms by coherent addition of recirculating waves [4], exemplifying its use in conjunction with passive intra-loop components.

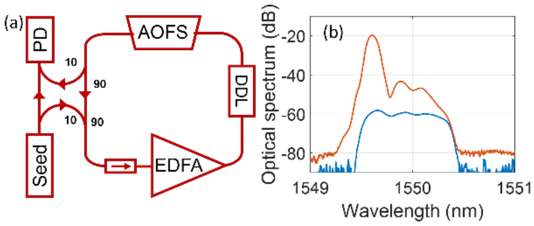

Fig. 1. (a) Experimental setup. (b) Optical spectrum (orange) and DDL reflectivity spectrum (blue).

The experimental setup is shown in Fig. 1(a). The loop is composed of an EDFA, a dispersive delay line (DDL), and an acousto-optic frequency shifter (AOFS), externally injected with a highly coherent wavelength. The DDL consists of three linearly chirped fiber Bragg gratings (Teraxion) placed in series and with a dispersion of 600 ps/nm each. They also act as an intracavity 0.8-nm filter, as is shown in the blue trace of Fig.1(b). The AOFS generates positive frequency shifts at ~80 MHz and controls the loop losses through the driving RF power, achieving a minimum of −12.6 dB at the maximum rated RF power. As is shown in Fig. 1(b) with an orange trace, the loop is seeded with a wavelength of 1549.75 nm, near the edge of the DDL passband to limit the emission bandwidth to about 10 GHz. The FSR is 5.612 MHz, corresponding to a group delay τ_g = 178.2 ns at the seed wavelength. The output power is −6 dBm, and external spectral, intensity and heterodyne measurements are provided, using in this last case a fast photodiode (PD) and a real-time 6-GHz oscilloscope.

The loop's output is a single-sided optical frequency comb whose optical envelope is given by;

$$E(t) = E_0 \sum_{n=0}^{\infty} \rho^n e^{-\frac{j}{2}\Omega_s \tau_g n(n+1) - \frac{j}{6}\varphi \Omega_S^2 n^3 + jn\Omega_s t} \qquad (1)$$

with E_0 the seed's amplitude, n the roundtrip index, $\rho < 1$ the amplitude decay factor per recirculation, $\Omega_s = 2\pi f_s$ the shifting frequency, φ the first-order dispersion coefficient, introduced by the DDL, and we have used that $|\varphi|\,\Omega_s \ll \tau_g$. From (1), at the so-called integer conditions $f_s \tau_g = p$ with p a positive integer, the single-sided frequency comb shows a purely cubic spectral phase and thus represents a sequence of Airy pulses.

In Fig. 2 we show the heterodyne spectrum under typical operation conditions for two values, low (a) and high (b), of injected power. The loop is here operated above threshold with the EDFA saturated by the seed power. Increasing injection thus reduces the EDFA gain and drives the loop from a situation (a) where it is approximately at threshold ($\rho \approx 1$), reflected in the flat-

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top spectral shape, to a situation (b) where it becomes below threshold ($\rho < 1$) and the spectrum is exponentially decaying. The heterodyne signals, shown as insets, illustrate the mapping from the spectrum to the pulse envelope.

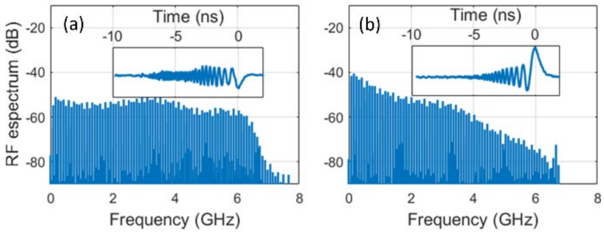

Fig. 2. Heterodyne RF spectrum with low (a) and high (b) injection power. Insets: pulse's temporal heterodyne trace.

In Fig. 3(a) we plot the heterodyne trace obtained at a frequency shift 84.180 MHz (Talbot condition $f_s \tau_g = 15$), together with the corresponding simulation in (b). At large local oscillator power this trace represents the in-phase component of the optical field, and shows the expected increasing instantaneous frequency for negative times. The temporal phase of the Airy pulse is known to follow a nonlinear law given by:

$$\gamma(t) = \frac{\pi}{4} - \frac{2}{3}\kappa(-t)^{3/2} \tag{2}$$

This leads to an instantaneous frequency $\omega_i(t) = \kappa\sqrt{-t}$ with the parameter κ given by $\kappa = (2\Omega_s/|\varphi|)^{1/2}$ in our implementation. The experimental trace confirms the nonlinear flow of $\omega_i(t)$ and thus the Airy character of the pulse. The fitted value of κ is -21.5 rad/ns$^{3/2}$ and amounts to a dispersion $\varphi = -2290$ ps^2/rad consistent with the design values.

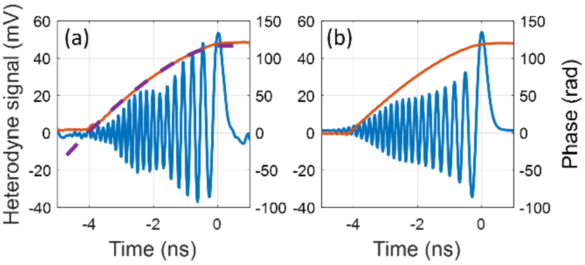

Fig. 3. (a) Heterodyne trace of an Airy pulse at the integer Talbot condition $f_s \tau_g = 15$ (blue trace, left scale), together with its nonlinear phase (red trace, right scale) and its fit (dashed magenta trace, right scale). (b) Simulated in-phase component of the field (blue) and phase (red).

The time-frequency representation of the Airy pulses thus follows a parabola given by:

$$-f_s t = \pi|\varphi| f_i^2 \tag{3}$$

where $\omega_i = 2\pi f_i$. We reconstructed this parabola by the following procedure. It can be shown from (1), and in analogy with [4], that a detuning in the frequency shift from Talbot conditions induces large amounts of first-order dispersion, which stretch the bandlimited Airy pulses [3]. The time-frequency representation of the stretched pulses is described by the same parabola (3) but shifted in both time and frequency [3]. We thus recorded a series of heterodyne traces comprising six pulses, each with frequency shifts mutually separated in steps of 44 kHz and starting from the integer Talbot frequency. This detuning produces a spectral shift of 6 GHz equal to our detection bandwidth, allowing for the reconstruction of the parabola by adjoining different strips. The result is shown in Fig 4(a), together with the parabola (3) in red.

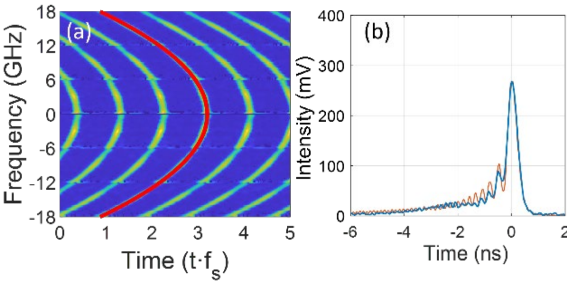

Fig. 4. (a) Piecewise reconstruction of the Airy parabola in the time-frequency plane. Red: parabola (3). (b) Blue: intensity of the Airy pulse. Orange: simulation.

Finally, in Fig. 4(b) we show the intensity of the Airy pulse together with its simulation, with a main peak of width 420 ps (FWHM). Note that the intensity of these pulses does not present sharp nulls as the standard Airy function, consequence of the single-sided character of the pulses described by (1).

In conclusion, we have demonstrated the generation of Airy pulses in a highly dispersive frequency shifting fiber loop. The approach provides a compact alternative to the standard generation method by use of model-locked lasers and external phase-only spectral filters, and opens a route to generate broader classes of optical waveforms by the incorporation of amplitude and phase filters by coherent addition in a recirculating and modulated fiber loop.

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References

1. G.A. Siviloglou and D. N. Christodoulides, *Accelerating finite energy Airy beams,* Opt. Lett. **32**, 979 (2007).
2. D. Hariharan, C. Martijn de Sterke, and A.F.J. Runge, *Experimental observation of linear pulses affected by high-order dispersion,* Opt. Express **31**, 21553 (2023).
3. M. Preciado and M. A. Muriel, *Bandlimited Airy pulses for invariant propagation in single-mode fibers*, J. Lightwave Technol. **30**, 3660–3666 (2012).
4. H. Guillet de Chatellus, L. R. Cortés, C. Schnébelin, M. Burla, and J. Azaña, *Reconfigurable photonic generation of broadband chirped waveforms using a single CW laser and low-frequency* electronics, Nat. Commun. **9**, 2438 (2018).