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Pulse shaping using the optical Fourier transform technique - for ultra-high-speed signal processing

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Abstract—This paper reports on the generation of a 1.6 ps FWHM flat-top pulse using the optical Fourier transform technique. The pulse is validated in a 320 Gbit/s demultiplexing experiment.

I. INTRODUCTION

For ultra-high-speed serial data communications reaching several hundred Gigabits per second, data recognition and signal processing becomes limited by timing issues, such as generation of adequately narrow pulses, identifying sufficiently fast optical switches and obtaining low enough timing jitter on clock and data pulses. To increase the tolerance to timing jitter, in ultra-fast optical switches, flat-top pulses have been demonstrated to be very beneficial [1]–[3].

In this paper, we describe how to use the optical Fourier transform (OFT) technique without the customary, yet cumbersome, active phase modulation and still obtain narrow flat-top pulses. We generate a 1.6 ps flat-top pulse, and characterise it in a demultiplexing experiment at 320 Gbit/s. Numerical simulations based on a model derived from the space-time duality theory [4] show very good agreement with experimental results.

II. BASIC PRINCIPLE

As demonstrated in [4], the evolution of optical pulses in dispersive media is equivalent to free-space diffractive imaging, where the far field image, by virtue of the Fraunhofer diffraction integral, simply becomes the Fourier transform of the object. For optical pulses transmitted through a dispersive medium as e.g. an optical fibre, the equivalent to the *far field image* becomes a temporal waveform which is the Fourier transform of the input pulse temporal waveform (the *object*). The Fourier transform of the input waveform is of course simply the input spectrum. The space-time duality insight is a great tool to design pulse shaping systems, and has already enabled a variety of applications in fibre communication systems, such as a timing jitter reducing *time-lens*, distortion-free pulse transmission [5] and distortion-free compression or expansion of a waveform [6]. In the three examples, a *time-lens* element is added to the set-up, and as the name implies, it acts as the equivalent to an optical lens but on the waveform. To create flat-top pulses, as in [1] and as sketched in figure 1, the basic idea is to create a flat-top spectrum by means of passive filtering, and then Fourier transform its temporal equivalent to create a flat-top temporal waveform. In figure 1, the input and output powers in the spectral and temporal

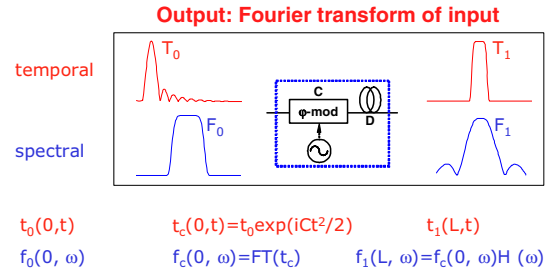


Fig. 1. The basic principle for OFT.

domains are shown. They relate to the electric field amplitudes as $T_j(t) = |t_j(t)|^2$ and $F_j(\omega) = |f_j(\omega)|^2$. Assuming that the accumulated dispersion ($D = \beta_2 \cdot L$) is matched to the chirp added to the pulse ($D = 1/C$), one finds that the intensity at the output of the OFT set-up becomes

$$T_1 = |t_1|^2 = \frac{1}{2\pi D} \cdot |f_0|^2 = \frac{1}{2\pi D} \cdot F_0 \quad (1)$$

i.e. the output waveform is uniquely given by the input spectral shape in the OFT-plane.

1) *Without phase modulation*: If one does not use phase modulation, the same result may be derived, but at longer fibre lengths and generally with broader pulses — as the focusing time-lens element is absent. In this case one has to very strictly assume that $|D| \gg T_0^2$, with T_0 being the pulse width of the input pulse [6]. This is fulfilled in the far field (large $D = \beta_2 L$). Still, we find that with a wide enough input spectrum, it is possible to create flat-top pulses narrow enough for signal processing of ultra-high bit rate data.

III. EXPERIMENTAL SET-UP AND RESULTS



Fig. 2. The experimental set-up.

Figure 2 shows that the output from an Erbium Glass Oscillator (ERGO) pulse source is injected into a wavelength shifter based on 200 m HNLf followed by a 3.5 nm wide tuneable filter. The ERGO runs at 10 GHz and 1550 nm and emits 1.5 ps pulses. In the 200 m HNLf, a super-continuum is generated and a part of this is filtered out through the 3.5

nm filter centered at 1540 nm. This wavelength-shifted pulse is now injected into the second HNLF, again generating a super-continuum, which is filtered by a 15 nm super-gaussian filter. Transmitting this spectrum through 20 m SMF aligns all the spectral components, yielding the transform limited (TL) waveform, a sinc-like 500 fs pulse. It is from this TL-plane that the pulse will propagate into its OFT shape.

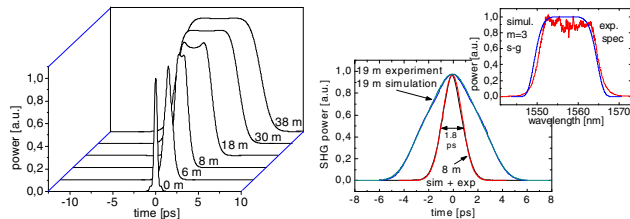


Fig. 3. Experimental and simulation results. Left: Simulated pulse evolution through x m SMF fibre. Right: Experimental and simulated auto-correlations at 8 and 19 m SMF. Inset: The original 15 nm super-Gaussian spectrum.

Figure 3 shows how the pulse with a 15 nm input third order super-gaussian spectrum evolves through dispersion corresponding to 0-38 m SMF. At 0 m, the pulse is in the TL-plane and is sinc-like and very narrow (500 fs FWHM). At 38 m, the pulse has turned into a perfect time-domain replica of the initial spectrum (9 ps FWHM). Even before, at 30 m, the pulse is almost perfectly transformed (7.4 ps FWHM). Upon further propagation, the pulse will be in the far field and maintain its super-gaussian shape, and simply grow broader. The auto-correlation traces for the same pulses, corresponding to the inserted 15 nm 3rd order super-gaussian spectrum (fitted very well to the experimental curve), show a very good agreement between simulations and experiments. One will also notice that after only 8 m of SMF, the pulse may not be perfectly transformed yet, but has a flat-topped appearance, and is quite narrow. Intercepting the pulse here, should thus provide a pulse applicable for ultra-high bit rate signal processing. Figure 4 shows an optimised pulse, where

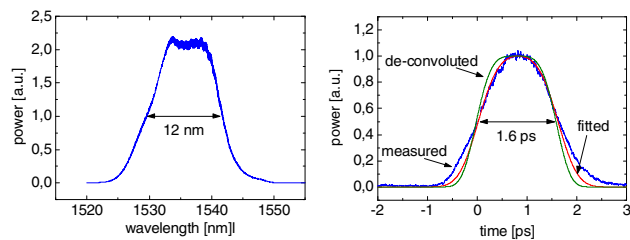


Fig. 4. Experimental 1.6 ps pulse before OFT-plane. Left: Flat-top spectrum, 12 nm wide. Right: Cross-correlation with (500 fs sampling pulse) at 10 m SMF after LT-plane. Also shown is a de-convoluted waveform corresponding to 1.6 ps $m=2$ super-gaussian and the fit of this to the measured when convoluting with the sampling pulse.

the spectrum is very flat-topped and shaped around 1536 nm, though only 12 nm wide. The pulse is measured before the OFT-plane at 10 m after the TL-plane, i.e. before it has evolved into a perfect OFT-image, and before it has broadened too

much. The pulse is seen to have a top matching the super-gaussian, but wider tails, as expected. This pulse is applicable to ultra-fast signals reaching towards 640 Gb/s data.

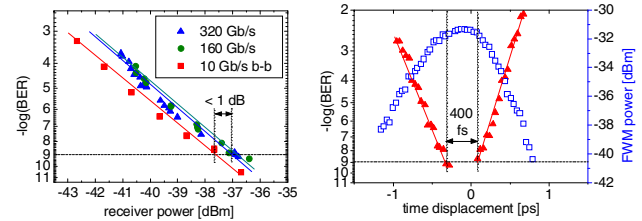


Fig. 5. Experimental BER validation of the OFT pulse. Left: BER curve from 160 and 320 Gb/s. Right: Timing tolerance and switched power.

To validate the quality of the generated flat-top pulse, it is used in a demultiplexing experiment. The demultiplexer is a 100 m PM-HNLF, in which four wave mixing between the OFT control pulse and the high-speed data signal takes place. Error-free operation is readily obtained for bit rates up to 320 Gb/s with excellent performance and less than 1 dB power penalty to the 10 Gb/s back-to-back (b-b), see figure 5, left. Displacing the control pulse from the center position of a data pulse, enables one to measure a timing tolerance. The FWM power is monitored simultaneously, effectively revealing the central part of the switching window. As can be seen in figure 5, right, this switching window has a very small slope on the top, over the 400 fs, where the BER is $\leq 10^{-9}$.

IV. CONCLUSION

We have reported on using the optical Fourier transform technique to generate a 1.6 ps flat-top pulse, which is the shortest reported so far using this technique. The pulse has been thoroughly characterised both experimentally and numerically, with very good agreement. The pulse quality was validated in a 320 Gb/s demultiplexing experiment, showing 400 fs timing tolerance.

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