Adaptive Pulse Shaping for High-Speed Optical Communications

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Abstract: Through temporal pulse shaping at a repetition rate of 42.7 GHz, this paper demonstrates a simple method with applications in high-speed optical communications for adaptive, multi-type pulse shaping, repetition-rate multiplication and pulse generation.

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1. Introduction

The synthesis of ultra-short optical pulses with tailored shapes in the time and frequency domains has become increasingly important for a wide range of applications [1-3]. Furthermore, dynamic pulse-shape control is key to the realization of many adaptive techniques [4][5]. For instance, in high-speed optical communications, pulse-shape adaptation has been recently utilized to combat channel impairments and improve system performance [2], whereas adaptive pulse shaping techniques have also been used to overcome pulse distortion caused by dispersion [3].

Traditionally, adaptive pulse shaping has been realized by Fourier synthesis in the space domain [4][5]. In particular, liquid-crystal spatial masks, which provide enhanced flexibility in pulse-shape control, have been widely used. However, space-domain techniques require high-quality bulk optical components and have limitations in terms of modulation speed and integration with waveguide devices [6][7].

On the other hand, Fourier synthesis in the time domain, known as temporal pulse shaping (TPS), has also been proposed [6-8]. This technique has two key advantages that make it attractive for optical communication applications: firstly, it is fully compatible with waveguide-regime devices and, secondly, it can be electronically controlled. Experimental demonstrations of TPS have been carried out with low-repetition-rate input pulse trains at 10 MHz [6] and 76 MHz [7]. Several pulse shapes of interest have been demonstrated at a 625-MHz repetition rate [9]. However, the application of adaptive pulse shaping to high-speed optical communications requires a simple, flexible technique, with high modulation speed and the ability to operate at repetition rates in excess of 10 GHz.

In this paper, we experimentally demonstrate and numerically verify pulse-repetition rate multiplication (PRRM), and the generation of triple-bound soliton, doublet and flat-top pulses, at repetition rates of 10.675 GHz and 42.7 GHz, by using a simple TPS setup with a single 40-GHz Mach-Zehnder Modulator (MZM) as the shaping device. Pulse compression/expansion is also demonstrated at 10 GHz using the same setup. The technique is highly adaptive and can be used in adaptive high-speed optical communication applications.

2. 10.675-GHz Experimental Setup and Results

The setup used in our proof-of-principle experiment is depicted in Fig. 1. First, a hybrid-electrically mode-locked TMLL generates 2-ps pulses at a 10.675-GHz repetition rate with a 1540-nm centre wavelength. Then, these pulses are amplified and transmitted over a length of standard single mode fiber (SSMF) which introduces dispersion. Next, the dispersed signal is passed through a variable delay line, a polarization controller and an amplifier before being fed into a 40-GHz LiNbO3 Mach-Zehnder Modulator (MZM) driven by \( v(t) \) and biased at \( V_{bias} \). The MZM shapes the signal spectrum in a manner determined by \( v(t) \), \( V_{bias} \) and the phase difference between \( v(t) \) and the optical signal. \( v(t) \) is generated by a pattern generator (PG) and consists of a periodically repeating 4-bit

![Diagram](attachment:image.png)

Fig. 1. (a) Experiment setup; (b) temporal shape and (c) spectral shape of the MLL pulses.
programmable word of duration 93.6768 ps. Finally, the modulated signal is transmitted over a Dispersion Compensating Module (DCM), which is tailored to compensate for the dispersion introduced by the length of SSMF. The OSNR of the optical signal is managed throughout the setup using Erbium-Doped Fiber Amplifiers (EDFA), and the launch power into the DCM is -5 dBm. In order to demonstrate synthesis of different pulse shapes several parameters are varied, namely the MZM bias, the driving-signal shape (by changing the 4-bit word from the pattern generator), the driving-signal phase relative to the optical input (by adjusting the variable delay), and the amount of dispersion (by changing the length of SSMF). In a high-speed optical communications system, feedback information may be used to control these parameters in order to introduce predistortion to transmitted pulses and improve system performance.

Fig. 2 shows various pulse shapes that were produced in the experiment along with their corresponding spectrums. Also, the parameters used to generate each pulse are listed in the description. In Fig. 2a pulse-repetition rate multiplication by means of TPS is demonstrated by generating a 21.35-GHz uniform pulse train from the 10.675-GHz input pulse train. By programming the pattern generator to output the 4-bit word “1010”, a 21.35-GHz sinusoidal signal, \( v(t) \), is produced for driving the MZM. The length of SSMF, 16786m, was selected so that the GVD delay between two adjacent frequency components, separated by 10.675 GHz, is half the MZM-driving-signal period. One major difference between this and previous TPS implementations is that here, spectral components from neighboring pulses overlap due to the high amount of dispersion introduced. Thus, the system behaves like a spectrally periodic optical filter with FSR = \( T/2\pi\beta_2L_D \) where \( T \) is the period of \( v(t) \) and \( \beta_2 = \frac{d^2\beta(\omega)}{d\omega^2} \) is the frequency-dependent second order dispersion coefficient, and \( L_D \) is the length of SSMF. By using a different FSR, multiplication factors greater than 2 may be implemented [10].

The pulses shown in Fig. 2b are characterized as having a \( \pi \)-phase-shift between neighboring pulses. This feature is also found in multi-bound solitons [11]. Therefore, these pulses may be utilized for triple-bound soliton excitation in optical fiber. Pulse compression and expansion was also demonstrated (Figs. 2c and 2d respectively). Slight pulse compression, with 1.6-ps FWHM pulses, is achieved by flattening the spectrum of the input pulse train,
whereas, for pulse expansion, 4-ps FWHM pulses are obtained by allowing only a portion of the central spectrum to pass, hence the system’s behavior is akin to an optical band-pass filter. Additional pulse shapes of interest are the doublet and flat-top pulses, displayed in Fig. 2e and 2f respectively.

3. Temporal Pulse Shaping at 42.7 GHz

In order to demonstrate the functionality of this method at higher bit-rates an additional experiment was performed at a repetition rate of 42.7 GHz. In order to generate the 42.7-GHz pulse train from the 10.675-GHz input, an optical multiplexer (OMUX) is introduced after the first optical amplifier, EDFA1 in Fig. 1. ν(t) is a 3.3-Vpp 42.7-GHz sinusoidal signal. The shaping process is controlled by the length of SSMF, the variable delay line and the MZM bias. Results are presented in Fig. 3.

Pulse repetition rate multiplication, Fig. 3a, was demonstrated by producing an 85.4-GHz pulse train from the 42.7-GHz input. Furthermore, the generation of triple-bound solitons (Fig. 3b), doublet pulses (Fig. 3c), and flat-top pulses (Fig. 3d), were also demonstrated. Experimental pulses appear to be slightly wider than the numerical simulation results suggest, due to the uncompensated dispersion introduced by the OMUX.

Fig. 3. Measured (black solid line) and simulated (red circles) time pulses, and input (dashed-blue line) and output (red solid line) measured spectrum for (a) PRRM, $L_D=2100$m, $V_{bias}=4.2$V, (b) triple-bound-soliton-like pulses, $L_D=400$m, $V_{bias}=5.0$V, (c) doublet, $L_D=400$m, $V_{bias}=3.0$V, and (d) flat-top pulse, $L_D=400$m, $V_{bias}=5.4$V, generated at 42.7 GHz.

4. Conclusions

We have experimentally demonstrated pulse-repetition rate multiplication and the generation of triple-bound solitons, doublet pulses and flat-top pulses, by temporal pulse shaping at 10.675-GHz and 42.7-GHz repetition rates, in addition to pulse compression/expansion at 10.675 GHz. This technique can be applied in high-speed optical communications, in order to improve system performance and overcome pulse distortion due to dispersion.

5. References