Low-Power High-Contrast Coded Waveform Discrimination at 10 GHz Via Nonlinear Processing

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***Abstract*—We demonstrate ultrafast optical code-division multiple-access nonlinear waveform discrimination at 10 GHz with less than 1 mW coupled into a nonlinear periodically poled lithium niobate waveguide and greater than 20-dB contrast ratio between coded and uncoded waveforms. Excellent signal-to-noise is observed at the system receiver, pointing toward the practicability of nonlinear waveform discrimination in a system environment.**

***Index Terms*—Nonlinear thresholding, optical code-division multiple-access (O-CDMA), pulse shaper, ultrafast phenomena.**

OPTICAL code-division multiple-access (O-CDMA) is receiving increasing attention due to its potential for enhanced information security, simplified and decentralized network control, improved spectral efficiency, and increased flexibility in the granularity of bandwidth that can be provisioned. In O-CDMA, different users whose signals may be overlapped both in time and frequency share a common communications medium; multiple-access is achieved by assigning different minimally interfering code sequences to different CDMA transmitters. In several O-CDMA approaches, input ultrashort pulses are time-spread during the encoding process into lower intensity noise-like signals [1]–[6]. In the receiver, data corresponding to a desired user is separated from multiaccess interference via a matched filtering (decoding) operation, in which properly decoded signals are converted back to the original pulse-like signals, while improperly decoded signals remain low-intensity noise-like temporally broadened waveforms. However, even for improperly decoded signals, the total time spread may be limited to tens of picoseconds, which is less than the data period for systems at ∼40 Gb/s and below. Therefore, since both properly and improperly decoded signals have similar energy, they will both appear nearly identical to an electronic receiver band-limited to the data rate. Consequently, in such systems, either synchronous optical gating or an asynchronous nonlinear optical intensity discriminator is required to separate the desired data from O-CDMA multiaccess interference. The synchronous optical gating approach was used successfully in [2] in a point-to-point transmission experiment; however, the required picosecond scale optical clock recovery function in the presence of O-CDMA multiaccess interference has not been addressed. In this letter, we demonstrate 10-GHz operation of a highly efficient, asynchronous, nonlinear optical intensity discrimination technology based on second-harmonic generation (SHG) in a periodically poled lithium niobate (PPLN) waveguide.

Previously, an optical fiber nonlinear intensity discriminator, based on the filtering of decoded pulses spectrally broadened through the Kerr nonlinearity, was reported with a suppression ratio in excess of 30 dB, but required a high pulse energy of ∼25 pJ and was demonstrated at only 30 MHz [3]. Recently, a holey fiber technology has been used in a similar scheme to reduce the fiber length to less than 10 m in ∼1-GHz experiments; however, this technique still required high pulse energy (∼100 pJ) [4]. Such high pulse energy requirement could cause serious problems when extending to multiuser network environments. In multiuser networking, each receiver will see a sample of each of the multiple-access signals; therefore, the required amplifier saturation power scales with the number of users (as well as bit rate). As a result, the high pulse energy requirement for a nonlinear discriminator seriously hinders practical application in a high-bit rate and multiuser O-CDMA networking environment. In previous work, it was demonstrated that SHG could provide a much lower operating energy than Kerr effect nonlinearities in fibers [6]. These experiments demonstrated high suppression (∼20 dB) nonlinear discriminator operation using PPLN waveguides at 0.25 pJ per pulse, but were tested at only 40 MHz [6]. In the present work, we demonstrate operation of PPLN waveguide nonlinear discriminators at much higher (10 GHz) speed while simultaneously further reducing the energy per pulse 2.5 times. This technology, which works at pulse energies roughly two orders of magnitude lower than previous discriminators based on nonlinear fiber optics [2]–[5], could be a key enabler for multiuser O-CDMA systems at multigigabit/s individual data rates and at power levels compatible with current fiber communication technologies.

In our system, an actively mode-locked fiber laser followed by a dispersion decreasing fiber soliton compressor producing nearly transform-limited ∼0.4-ps pulses at 10 GHz centered near 1542 nm is used as the pulse source. These ultrashort pulses are input into a fiber coupled Fourier-transform pulse shaper [7], which incorporates a 128-element liquid crystal modulator (LCM) array to spectrally phase code the spectrum

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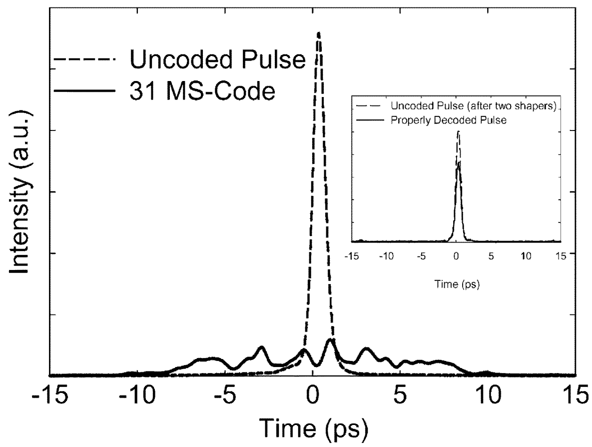

Fig. 1. Cross-correlation measurements of uncoded (dotted line) and 31 MS coded (solid line) pulses. Inset figure shows uncoded and properly decoded pulses after two shapers forming an encoder–decoder pair.

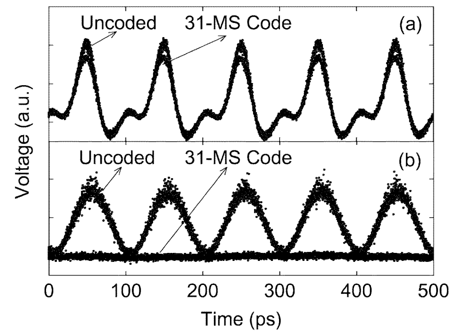

Fig. 2. (a) Output from a 12.4-GHz bandwidth linear detector and (b) PPLN second-harmonic output measured by a 10-Gb/s Ethernet receiver with 7.5-GHz bandwidth. Outputs for 10-GHz uncoded and for length-31 MS encoded waveforms are superimposed. The waveforms are clearly distinct after nonlinear processing but almost indistinguishable using the linear receiver.

of the source laser [8]. The pulse shaper is constructed in a reflective geometry [9], with approximately 4-dB fiber-to-fiber insertion loss (including the circulator). Our pulse shaper is easily programmed under computer control, which allows for convenient testing with different code families. The output of the pulse shaper is connected to a fiber-pigtailed PPLN waveguide chip [10] to perform the nonlinear discrimination function. The PPLN chip is 67 mm long, with 62-mm periodic poling, with a waveguide fabricated by reverse proton exchange [10]. The measured SHG efficiency at the peak of the phase matching curve is 3100%/W for continuous wave and 170%/pJ for ultrashort pulses, which is the highest yet reported. The PPLN waveguide exhibits a sinc^2-shape phase matching spectrum with 0.17-nm bandwidth which is centered at 1542 nm by temperature tuning. The phase matching bandwidth is consistent with 18.6-ps temporal walkoff between the fundamental and SHG fields. The output of the PPLN is coupled to a 7.5-GHz bandwidth photoreceiver, designed for 10-Gb/s Ethernet, operating at the second-harmonic wavelength of 0.77 μm. Fig. 1 shows intensity cross-correlation measurements of uncoded (LCM set for all zero phases) and $\sim$20-ps pseudonoise waveforms resulting from spectral phase coding with a length-31 M-sequence (MS) code (a pseudorandom binary phase code with phase shifts of zero or π) [11]. These traces clearly illustrate the stretching of input short pulses into time-spread noise-like pulses by pseudorandom spectral phase coding. The inset figure shows uncoded and properly decoded pulses after two shapers forming an encoder–decoder pair, which validate the similarity between them except 1.4-dB coding loss by two shapers and almost unnoticeable side lobes. Therefore, hereafter, uncoded and coded pulses passing through a single pulse shaper are applied in this letter to emulate properly decoded and improperly decoded pulses and evaluate performance of our nonlinear O-CDMA discriminator.

The advantage of a nonlinear pulse discriminator is dramatically demonstrated in Fig. 2. To maximize signal-to-noise ratio at a receiver in communication networks, the receiver should be band-limited at the data speed to effectively eliminate white Gaussian noise. Here, we first used a simple 1.5-μm photodetector with a 12.4-GHz measurement system bandwidth to detect the pulse shaper output prior to entering the PPLN waveguide. Fig. 2(a) shows the nonaveraged real-time traces of both uncoded and length-31 MS coded signals as seen on a sampling scope. Although there is a very small amplitude difference associated with an excess coding loss of 0.8 dB by one shaper, the two signals are essentially indistinguishable. This clearly illustrates a key issue in O-CDMA with ultrashort pulses: uncoded pulses (which are essentially the same as properly decoded pulses) and coded pulses (which are essentially the same as improperly decoded pulses) have fundamentally the same energy, which means they produce the same output from an electronic detector band-limited to the data rate, even though they can show strong differences in temporal structure and peak intensity on an ultrafast time scale (which, as in Fig. 1, is much faster than the electronic processing bandwidth).

Fig. 2(b) shows the second-harmonic output of the nonlinear PPLN waveguide as measured by the 7.5-GHz photoreceiver and sampling scope for both uncoded and coded waveforms. For ease of comparison, we superimpose the two waveforms on the same plot. The random noise at the peaks of the discriminator output for uncoded pulses was increased relative to Fig. 2(a) mainly due to the enhancement of pulse amplitude jitter by the nonlinear process as well as temperature fluctuations in the PPLN. The use of a long nonlinear waveguide structure [10], together with a long nonlinear medium, leads to dramatically increased SHG conversion efficiency for uncoded (bandwidth-limited) pulses; on the other hand, SHG is strongly suppressed for spectral phase coded pulses. Roughly speaking, two distinct mechanisms can contribute to suppression of the SHG signal. First, in conventional SHG with large phase matching bandwidth, the SHG efficiency scales inversely with the pulsewidth. Second, in SHG with large group velocity walkoff, where the phase matching bandwidth is much narrower than the input spectrum (as in our experiments), phase modulation on the pulse can also strongly suppress the conversion efficiency. More precisely, one can control the SHG yield by changing the correlation properties of the applied spectral phase code sequences [6]. In this way, the ability to discriminate between uncoded and coded pulses is greatly enhanced. As a result, a contrast between the discriminator outputs for uncoded and coded waveforms is observed in Fig. 2(b). Uncoded short pulse signals generated clear 10-GHz

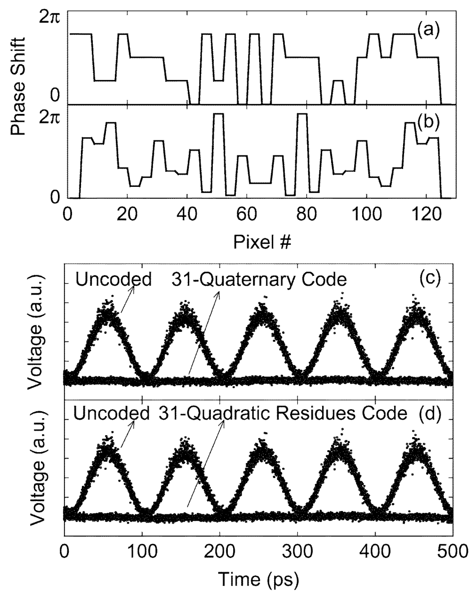

Fig. 3. (a) Length-31 quaternary (4-level) phase codes and (b) quadratic residues (31-level) phase codes, (c) and (d) corresponding to nonlinear receiver outputs.

sinusoidal signals from the photoreceiver, while the phase coded pulses generated only a very weak signal which was buried in the electronic noise. Second-harmonic power contrast ratios of up to 20.1 dB were observed when coding with a length-31 MS code at 0.9-mW average power (0.09 pJ per pulse) in the PPLN waveguide. The energies of uncoded and coded pulses at the 1542-nm fundamental wavelength are essentially the same, except for 0.8-dB excess loss incurred during the coding process. The second-harmonic power generated by uncoded pulses was -8.4 dBm, exceeding the receiver sensitivity by 5.5 dB, yielding the excellent signal-to-noise ratio seen in Fig. 2 (the noise at the baseline of the data is simply the receiver noise). These data clearly demonstrate real-time discrimination between uncoded and coded pulses through nonlinear processing with strong $\sim$20-dB suppression of coded pulses. A key point is that the pulse energies required here are more than two orders of magnitudes lower than those required in previous O-CDMA decoding experiments based on nonlinear fiber optics.

Our programmable pulse shaping technique provides flexibility and ease of use in switching to different spectral codes. This could be very helpful in a network environment since code sequence selection plays a critical role in determining performance of CDMA communication systems. For example, we have tested all 31 cyclic shifts of the length-31 MS and have determined that the second-harmonic power contrast ratio averaged over all the cyclic shifts is 14.7 dB, still a reasonable level for a multiuser environment. We also measured shorter MS code lengths of 7 and 15 and observed best case contrast ratios of 13.6 and 17.2 dB, respectively. In addition to binary MS codes, we also applied a 4-level (quaternary) family $\mathcal{A}$ code [12] and a 31-level quadratic residue code [13], as shown in Fig. 3(a) and (b). Based on the coding literature, multilevel code families can provide a larger number of distinct code sequences with smaller cross-correlation bound compared to binary sequences, which is important to minimize multiaccess interference due to competing simultaneous traffic across the channel [12]. Fig. 3(c) and (d) shows best nonlinear discriminator results as measured at the output of the PPLN waveguide. The programmability of the pulse shaper as an encoder enables us to select arbitrary phase codes which can be used to optimize their correlation properties and minimize multiaccess interference in future multiuser O-CDMA demonstrations.

In summary, we have demonstrated ultrafast O-CDMA waveform discrimination at 10 GHz using a PPLN waveguide nonlinear element. Excellent contrast ratios of greater than 20 (best case) and 14.7 dB (average) were observed for the family of length-31 MS codes. These nonlinear processing experiments required less than 1 mW of fundamental power in the waveguide ($<$0.1 pJ per pulse), which is roughly two orders of magnitude lower than previous experiments using nonlinear fiber optics.

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