# Low-Power Spectral Phase Correlator Using Periodically Poled $\mathrm{LiNbO}_3$ Waveguides

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***Abstract*—We report a novel optical spectral phase correlation scheme for coded ultrashort pulses based on the use of long periodically poled lithium niobate second harmonic generation waveguides. Second harmonic efficiency as high as 50%/pJ was obtained, which allowed us to demonstrate nonlinear detection of individual pulses at 0.25 pJ input energies over a 500-MHz detection bandwidth with $>50:1$ signal-to-noise ratio. These results offer the possibility of sub-pJ real-time operation of such devices as nonlinear receivers in ultrashort-pulse optical code-division multiple-access (CDMA) networks.**

***Index Terms*—Code division multiaccess, nonlinear optics, optical fiber communication, optical propagation in nonlinear media, optical pulse shaping, optical signal processing, optical waveguide components.**

IN THIS LETTER, we report a new, low-power nonlinear optical interference suppression method for ultrashort-pulse optical code-division multiple-access (UP-CDMA) communications [1] based on the use of a long periodically poled lithium niobate (PPLN) second harmonic generation (SHG) waveguide [2] as an all-optical spectral phase code correlator [3]. The use of a waveguide structure together with a long nonlinear medium [4] leads to a dramatically increased detection efficiency. This enables real-time all-optical recognition of spectrally phase coded optical pulses at sub-pJ pulse energy levels, which would be crucial for implementation of multiuser CDMA systems at multigigabit/s individual data rates and at power levels compatible with current fiber communication technologies. Our previous CDMA thresholders based on nonlinear frequency shifts in fibers operated typically at much higher energy levels of $\sim 25$ pJ [5]. Therefore, our results address the need for lower power nonlinear optical receivers, which were previously identified as one key bottleneck for realization of UP-CDMA [5].

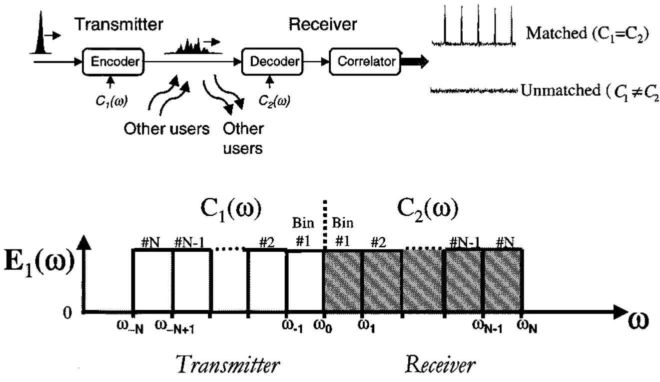

Fig. 1. Scheme of ultrashort-pulse CDMA and scheme of spectral phase coding of ultrashort pulses.

In an optical CDMA system, a unique signature code is assigned to each transmitter-receiver pair and used to encode each bit (optical pulse) of the data stream sent between the pair. The concurrence of signals from different senders generates multiaccess interference (MAI), and effective suppression of the MAI is a key research challenge to realize high system performance [6]. As shown in Fig. 1, in the proposed UP-CDMA network [1], [5] ultrashort optical pulses are first encoded at the transmitter using spectral code $C_1$. The receiver applies another spectral code $C_2$ to the received signals from all the active transmitters in the network. An optical spectral correlator could be used to distinguish between correctly decoded $(C_1 = C_2)$ signals and incorrectly decoded MAI $(C_1 \neq C_2)$ that have comparable average optical power but carry different spectral coding information. UP-CDMA can potentially provide high user counts in bursty networks by deploying coherent optical signal processing techniques, provided that several relatively immature technologies can be made available. Accurate spectral encoding/decoding of ultrashort pulses has been demonstrated using both bulk optics [5] and integrated encoders [7], [8]. However, developing low-power optical signal processing devices compatible with current fiber systems was previously an important bottleneck [5], [9]. An additional issue in UP-CDMA is the need for precise dispersion compensation due to the phase-sensitive encoding process, which we comment on later in this letter.

We recently demonstrated a novel all-optical spectral correlator for optical phase-coded ultrashort waveforms by using SHG in bulk nonlinear crystals [3]. Unlike previous intensity dependent nonlinear detection schemes for the UP-CDMA [5], [9], this new field-dependent scheme is highly phase sensitive. Our previous work achieved very high contrast ratios ($\sim$30 dB) between correctly decoded pulses and MAI. Here, by utilizing a waveguide structure, we lower the operating power by more than two orders of magnitude.

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We note that optical CDMA based on encoding/decoding of picosecond pulses followed by electronic thresholding has also been proposed [7]. Our approach based on shorter (subpicosecond) pulses and nonlinear optical processing is more challenging to implement but offers the potential of much higher MAI suppression.

As shown in Fig. 1, in our spectral CDMA coding scheme, we assume a flat-topped and unchirped fundamental spectrum that is divided into 2N “bins” with an equal frequency width, each of which is given a phase shift $\Phi_i$ $(i = -N, \ldots, -1, 1, \ldots, N)$. This is a different coding/decoding scheme compared to those described in earlier UP-CDMA publications [1], [5]. The spectrum is now split in half: The transmitter applies the phase code $C_1$ to the low-frequency side, while $C_2$ is applied at the receiver to the high-frequency side. For SHG in long nonlinear crystals, the phase matching wavelength is adjusted to the center frequency $\omega_0$. Due to the material dispersion, the pump and second harmonic (SH) pulses have different group velocities. The large group velocity mismatch (GVM) causes the two pulses to walk off from each other in the time domain, and thus, a long SH pulse is generated whose spectral bandwidth is severely narrowed. Then, the output SH power $P_{\rm SHG}$ is given by [3]

$$P_{\rm SHG} = \frac{2\pi\Gamma^2 L}{|\alpha|} \left| \int_0^\infty E_1(\Omega') E_1(-\Omega')\, d\Omega' \right|^2 \qquad (1)$$

where $\Gamma$ is the nonlinear coupling coefficient, $\alpha$ is the GVM parameter (units ps/mm), $L$ is the length of the SHG crystal, and $E_1$ is the spectral envelope function of the input field. Thus, the SHG signal is determined by the magnitude of the correlation of two spectral codewords, $C_1 = \{\Phi_{-1} \ldots \Phi_{-N}\}$ and $C_2 = \{\Phi_1 \ldots \Phi_N\}$. In our work, we select $C_1$ and $C_2$ from a family of binary codes with low cross correlations. When $C_1$ and $C_2$ match each other, a large SH signal is produced, while for the MAI where $C_1$ and $C_2$ are uncorrelated, very weak outputs are generated. Compared to other matched filtering CDMA decoding schemes [6], our spectral correlator naturally suppresses the sidelobes of the correlation functions [10] and, therefore, realizes superior contrast ratio. It should be noted that, for orthogonal codes, the contrast ratio is not directly related to the length of the codes, provided that sufficiently narrow spectral filtering is realized. The spectral correlator design can be readily applied to the network with different number of users, without increase in the complexity of the correlator, and thus is scalable to networks of various sizes. Also, the contrast ratio does not depend on the input optical power. Thus, the device is able to work at low-input power levels without sacrificing its ability to suppress interference noise.

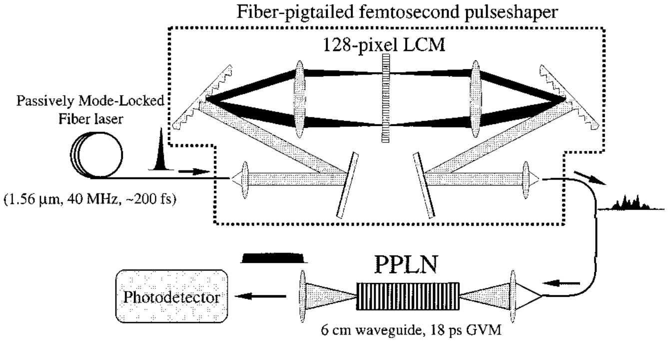

Fig. 2. Experimental setup. LCM: Liquid crystal modulator. PPLN: Periodically poled lithium niobate.

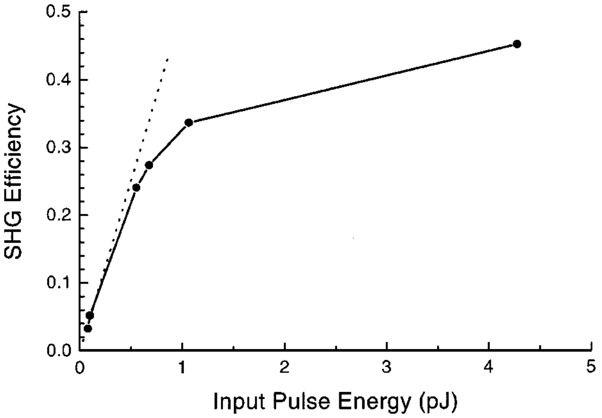

Fig. 3. Internal SHG conversion efficiency versus internal input pump pulse energy. The dotted line is the 50%/pJ line.

In our experiments, as shown in Fig. 2, a fiber-pigtailed femtosecond pulse shaper [5] with a 128-pixel amplitude/phase liquid crystal modulator (LCM) array [11], [12] was used to apply spectral phase codes consisting of different choices of $C_1$ and $C_2$ to the femtosecond optical pulses from a passively mode-locked femtosecond fiber laser at 1560 nm. The laser had a repetition rate of ~40 MHz. The pump spectrum was ~18 nm wide, and the LCM array was programmed to equalize its spectral amplitude and compensate for any phase chirp. The light was linearly polarized and free-space launched into the TM00 mode of the PPLN waveguide [2]. The annealed proton exchanged waveguide had a 55.5-mm-long SHG section with a uniform grating period of 14.75 $\mu$m and tapered sections at the input and output ends to facilitate better light coupling. The SHG phase matching wavelength was temperature tuned to ~780 nm. The GVM of this annealed proton exchanged waveguide is ~0.37 ps/mm, corresponding to a total GVM of ~20.5 ps. This implies a theoretical second harmonic phase matching bandwidth of ~0.1 nm, which is much smaller than the frequency width of each “bin” in the coding process (~1.1 nm at 1560 nm) so that the assumptions of (1) are satisfied. The observed SHG bandwidth was ~3 times wider than the ideal value, presumably due to small nonuniformity in the device structure.

We first measured the SHG efficiency using the uncoded pulses. The results shown in Fig. 3 show a small signal efficiency of ~50%/pJ. This is more than 500 times higher than the efficiency demonstrated using bulk PPLN under the small GVM condition [13], due to the high interaction intensity in the waveguide and the long interaction length of the sample under the large GVM condition. The high efficiency and the spectral narrowing effect caused by the large GVM enabled the use of a high-speed avalanche photodiode (APD) for direct real time detection for pump pulse energies <1 pJ, in contrast to the lock-in detection in [3]. To study the phase code dependence, we used phase codes from a set of eight length-8 orthogonal Hadamard codes, which should yield large contrast in the SHG

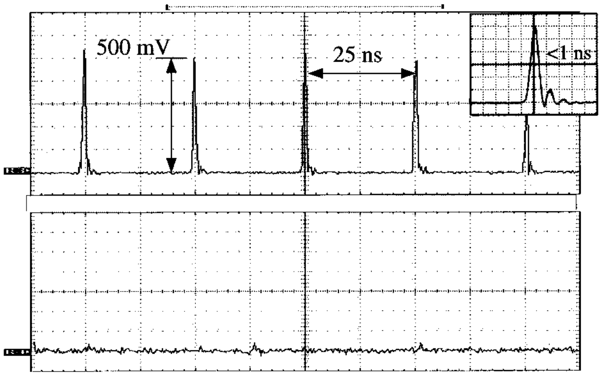

Fig. 4. SHG signals measured by a photodetector under different spectral phase coding situations. Top: matched phase codes $(C_1 = C_2)$. Bottom: unmatched phase code $(C_1 \neq C_2)$.

signal. Fig. 4 shows the SHG signals displayed on a digital oscilloscope driven by the APD with an internal transimpedance amplifier. The APD had a quantum efficiency of ~70% at 780 nm wavelength and a total avalanche plus amplifier gain of $\sim 10^4$. For coded pulses with $C_1 = C_2$, significant SHG comparable to the no coding case was generated for each input pulse, and an electrical pulse train at ~40 Mb/s was observed. At only ~10 $\mu$W average power input (0.25 pJ per pulse before the coupling lens), the electrical signal was as large as 500 mV peak-to-peak and had a pulsewidth of ~1 ns, limited by the 500-MHz scope bandwidth and ~1 GHz photodetector bandwidth. The voltage signal-to-noise ratio (SNR) is ~50 : 1, which should be sufficient for low error rate detection. For each of the seven other cases where $C_1 \neq C_2$, the SHG signal was significantly suppressed so that at the same input power level no observable electrical pulses were present in the trace shown in Fig. 4. Compared with the uncoded pulse case, the total SHG signal was suppressed by at least 50 for all seven unmatched codes. We expect that potentially higher suppression ratios, as demonstrated in [3], should also be possible in the waveguide experiments, through improved precision in the coding process and by using SHG devices with a more ideal (hence, narrower) SHG tuning curve or by applying external spectral filtering (at the expense of increased loss).

Based on these observations, we believe that these optical spectral correlators offer the potential to operate at ~0.1-pJ pulse energy level (for example, 0.5-mW average power per channel at the bit rate of 10 Gb/s) with sufficient SNR for high-quality communications. It is also noted that a polarization-independent device can be realized by methods demonstrated in [14].

We note that in a system including fiber transmission over significant distance, dispersion compensation will be essential in order to utilize this spectral phase coding and correlation detection scheme. Nearly chirp-free transmission of 250-fs pulses over 139 km has recently been demonstrated in a scheme involving synchronous modulation [15]. Distortion-free transmission of 400-fs pulses over 10 km was demonstrated earlier using spectral phase equalization in a completely asynchronous scheme [16]. In both cases, third-order spectral phase (i.e., dispersion slope) posed one of the greatest challenges to these experiments. From (1), however, our spectral phase correlator is not sensitive to third-order spectral phase. This could significantly ease the requirements placed on the dispersion compensation system.

In summary, we have demonstrated a novel yet simple scheme for distinguishing between different, phase coded ultrafast optical waveforms for proposed coherent CDMA networking. Because of the high conversion efficiency using PPLN SHG waveguide devices, we believe that it should be possible to realize nonlinear code recognition operation at many gigabits/s per user at <1-mW average power per user. This advance offers the possibility of ultrashort-pulse CDMA systems operating at realistic power budgets.

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