Pulse shaper in a loop: demonstration of cascadable ultrafast all-optical code translation

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We experimentally demonstrate repetitive M-ary spectral phase pulse shaping by placing a programmable pulse shaper driven by a 10-GHz source in a closed loop. This permits generation of encoded and decoded signals in the same apparatus by forming a closed loop to circulate a part of the output back into the pulse shaper. As a result, a series of $M - 1$ distinct encoded waveforms is sequentially generated, followed by generation of a properly decoded pulse.

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The Fourier transform pulse shaper[1] is an important tool for controlling the waveforms of ultrashort optical pulses, with applications ranging from coherent control to ultrafast light-wave communications.[2–6] For light waves, one interesting application of this tool is in optical code-division multiple-access (O-CDMA) communications and networking, in which multiple users share a fiber-optic channel on the basis of different waveforms (codes) assigned to different data channels.[5–9] CDMA is well suited for Internet environments characterized by bursty data and multiple users, and O-CDMA provides the potential to use optical processing to perform certain network applications, such as addressing and routing. Programmable O-CDMA coding would allow the number of required codes to be reduced by code reallocation to share codes among subscribers, whereas all-optical code translation would allow for the capability to form cascadable and (or) routable O-CDMA networks (since modifying the code would be equivalent to modifying the address). The ability to dynamically translate from one code to another in an O-CDMA system would be analogous to that of wavelength translation and switching, which is a key capability for reconfigurable wavelength-division-multiplexing networks. For successful code translation the translated code should represent a waveform distinct from the original waveform but should still remain a member of the original code family. Furthermore, the operation must be cascadable in the sense that high-quality decoding back to a clean ultrashort pulse will eventually be required. We show here that a spectral phase coding scheme[5,6] can satisfy all these requirements by providing a clear path for code translation. Previous efforts to pursue O-CDMA code translation were reported in time-domain coding[10] and two-dimensional time and wavelength coding.[11] Both of these works required a complicated nonlinear optical processing scheme with short code lengths (four to eight chips) and only single-stage translation. In contrast, in our spectral phase coding scheme the code converter is the same as the O-CDMA encoder–decoder and provides code translation in a simple, linear, and delay-free scheme. In particular, for the first time to our knowledge, we demonstrate cascadable (multiple-stage) all-optical O-CDMA code translation in experiments in which a 10-GHz repetition-rate short-pulse laser source is coded and decoded multiple times by use of spectral phase shaping with a pulse shaper placed in a closed-loop optical path. The pulse shaper functions as an encoder, decoder, and converter simultaneously depending on the number of passes through the shaper and on the spectral phase coding format. For M-level (M-ary) spectral phase coding a series of $M - 1$ distinct encoded waveforms and then a properly decoded pulse are sequentially generated in different shaper passes, after which the process repeats. The code-translation function demonstrated here is a fundamental operation required for efficient reconfiguration of O-CDMA networks.

To demonstrate this code-translation capability, we formed a closed-loop pulse shaper for which a portion of the shaper output is fed back to the input so that it experiences multiple passes through the shaper, as shown in Fig. 1. This loop scheme allows testing of the cascadable nature of the coding–decoding process in a simple and convenient setup; in real O-CDMA networking applications, cascaded coding and decoding operations would take place in distinct pulse shapers located at different nodes. An actively mode-locked fiber laser followed by pulse compression in a dispersion-decreasing fiber producing nearly transform-limited ~0.4-ps pulses at a 10-GHz repetition rate centered near 1545 nm is used as the pulse source. A reference beam split from the pulse

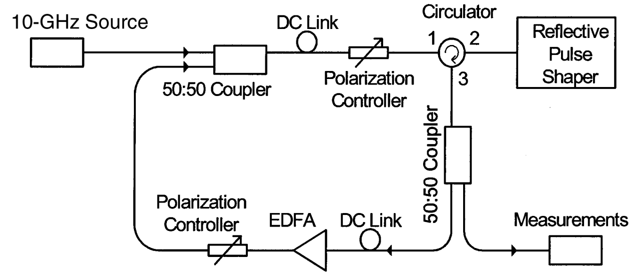

Fig. 1. Closed-loop pulse shaper experimental apparatus. A portion of the coded output is reinjected into the shaper through the input coupler to generate other code-translated or properly decoded signals.

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source is used for cross-correlation measurements of the shaper output. All fiber links are dispersion compensated by use of an appropriate combination of single-mode and dispersion-compensating fiber (DC link). A reflective pulse shaper[12] with a 128-pixel liquid-crystal modulator (LCM) array provides the ability to program arbitrary phase codes of different code lengths. The individual pixels of the LCM can be controlled independently to yield an arbitrary phase shift in the range of $0-2\pi$ with 12-bit resolution. The input-to-output fiber-to-fiber insertion loss of the shaper is less than 5.5 dB (which includes ~2 dB of circulator loss). After the first pass of the pulse shaper, the input pulses are spectrally phase coded, leading to time-spread temporal waveforms. When pseudorandom sequences are applied for spectral coding, the time-spread waveforms exhibit strongly reduced peak intensity. After the pulse shaper, a portion of the coded output is amplified by an erbium-doped fiber amplifier (EDFA) and reinjected into the shaper through the input coupler.

For M-ary phase coding the phase in any particular spectral chip is allowed to take on M possible values, given by $\phi_i = 2\pi k_i/M$, where $k_i = 0, 1, \ldots, (M-1)$. When $k_i = 0$ for all i, no phase modulation is applied and the pulses remain uncoded. For the pulse shaper in a loop, ϕ_i is imposed into the ith spectral chip repetitively during each of p passes through the shaper. Therefore the output phase after p passes corresponds to a new spectral phase $(\phi_i)^p = 2\pi jpk_i/M$. Whenever p is an integer multiple of M, all the spectral phase modulation terms become equal to an integer multiple of 2π, and the pulse shaper produces a properly decoded pulse (same temporal shape as the original input pulse). When the number of passes is not equal to a multiple of M, the pulse shaper output corresponds to a set of $(M-1)$ distinct code signals, according to the number of passes p modulo M.

In our experimental setup the 12.8-mm aperture of the LCM array corresponded to an ~18-nm wavelength span. The focused spot size of any single optical frequency component at the LCM plane was ~300 μm, corresponding to three LCM pixels. This yielded a spectral resolution of 0.4 nm. The programmability of the LCM array pulse shaper permits quick and convenient testing of several different phase coding schemes. Figure 2 shows intensity cross-correlation measurements of uncoded pulses (all zero phases; $k_i = 0$ for all i) and of pulses encoded with length-15 and length-31 maximal-length sequences. The uncoded pulses are similar to the input pulses. Coding clearly results in stretching of the input short pulses into time-spread noiselike pulses. A peak intensity contrast of ~10 dB is observed between uncoded and encoded pulses with a code of length 31. Longer code lengths yielded further stretching (resulting in a greater contrast ratio) until the spectral resolution limit was exceeded.

Figure 3 shows intensity cross-correlation measurements of the output of the phase coder based on the closed-loop pulse shaper. The numbers labeling the pulses represent the number of passes p through the shaper. The delay through the loop was set to ~100 ns and then fine-tuned by use of a fiber stretcher to give an apparent advancement of ~15 ps/pass (relative to the 100-ps periodicity arising from the 10-GHz laser repetition rate). For no phase coding, exponentially decaying pulse trains (with identical shape) were observed, as shown in Fig. 3(a). The attenuation corresponds to a net loop loss of ~3 dB/pass. Residual dispersion in the 21.6-m loop was estimated to be ~4 fs/nm, which in conjunction with the finite EDFA bandwidth led to slight pulse broadening for each pass through the loop. Cross-correlation peaks corresponding to the first seven passes through the pulse shaper are visible. Next, we performed a series of experiments with various length-31 ($N = 31$) M-ary pseudorandom spectral phase codes. For a binary ($M = 2$) maximal-length sequence code the output pulses were broad noiselike waveforms after an odd number of passes, and they were decoded back to their original shape after an even number of passes, as

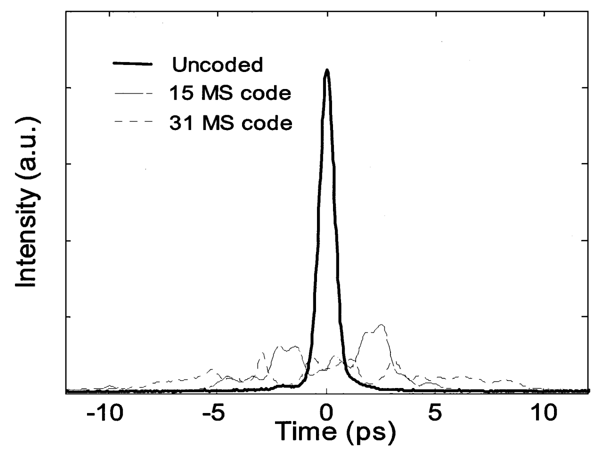

Fig. 2. Cross-correlation measurements of uncoded (solid curve), length-15 (dashed curve), and length-31 (dotted curve) maximal-length sequence (MS) coded pulses. The input short pulses are time spread after spectral coding.

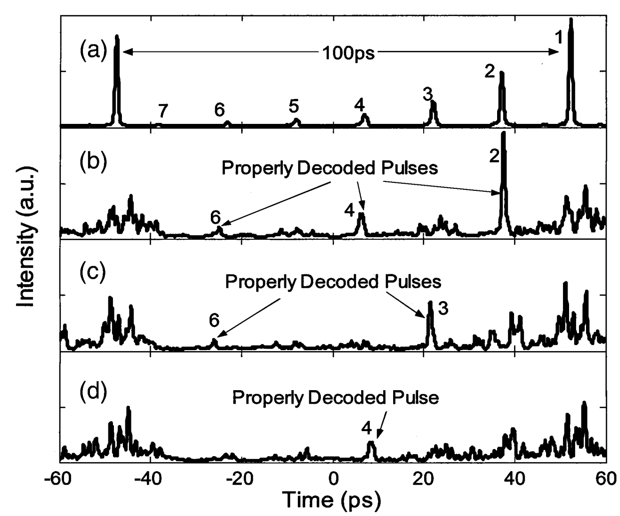

Fig. 3. Cross-correlation measurements of the M-ary coder outputs: (a) uncoded, (b) $M = 2$, (c) $M = 3$, (d) $M = 4$ coded pulses. The numbers labeling the pulses represent the number of shaper passes.

shown in Fig. 3(b). Three complete coding–decoding cycles can be observed. This clearly demonstrates the cascadable nature of the encoding–decoding process. Figure 3(c) shows results obtained with an $M = 3$ code for which the phases of each chip were randomly selected. Two distinct encoded signals appear at the delay positions corresponding to $p = 1, 4$ and to $p = 2, 5$, respectively, whereas decoded short pulses appear at $p = 3, 6$. For $M = 4$ we used the family $\mathcal{A}$ sequence, which is a quaternary pseudorandom phase code.[13] Three different encoded signals were observed before the pulse was successfully decoded, as shown in Fig. 3(d). These results clearly demonstrate the cascadable nature of the coding–decoding process for binary as well as M-ary encoding and also demonstrate the ability to successfully cycle through multiple different codes before decoding.

Our key results, namely, demonstration of high-quality cascadable encoding–decoding and multiple-stage code translation, are possible due to the properties of spectral phase coding. In our experiments we implemented spectral phase coding by use of a Fourier transform pulse shaper, which allowed for convenient code reprogrammability. However, it is important to note that cascadable encoding–decoding and code translation should also be possible for other implementations of phase-only or all-pass filters, such as devices based on cascaded ring resonator structures.

In summary, we have experimentally demonstrated cascadable (multiple-stage) code translation in an M-ary spectral phase coder based on programmable Fourier transform pulse shaping at 10 GHz. Our setup enables us to generate sequentially encoded and decoded signals in the same apparatus by forming a closed loop to circulate a part of the output back into the pulse shaper. Our results suggest the possibility of add–drop multiplexing and routing in ultrafast O-CDMA networks based on all-optical code translation. Furthermore, our pulse shaper in a loop concept may also find application in O-CDMA systems studies, in which the ability to simultaneously generate a multiplicity of distinct encoded signals by use of a single apparatus can facilitate emulation of a large number of users for interference suppression studies.

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