Encoding and decoding of femtosecond pulses

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We demonstrate the spreading of femtosecond optical pulses into picosecond-duration pseudonoise bursts. Spreading is accomplished by encoding pseudorandom binary phase codes onto the optical frequency spectrum. Subsequent decoding of the spectral phases restores the original pulse. We propose that frequency-domain encoding and decoding of coherent ultrashort pulses could form the basis for a rapidly reconfigurable, code-division multiple-access optical telecommunications network.

Diverse communication and signal-processing technologies utilize specially coded signal formats in order to achieve desirable capabilities such as error correction, interference rejection, and secrecy. The ability to encode and decode signals according to a specified format is a crucial component of such systems.

In this Letter we demonstrate frequency-domain encoding and decoding (in the time domain, spreading and despreading) of femtosecond optical pulses. Previously we described the generation of arbitrarily shaped picosecond optical pulses, by spectral amplitude and phase filtering in a fiber and grating pulse compressor.[1–3] Here we utilize a special dispersion-free grating apparatus to manipulate the phase spectra of femtosecond pulses. Specifically, by encoding pseudorandom binary phase codes onto the optical-frequency spectrum, we spread femtosecond pulses into picosecond-duration pseudonoise bursts. Subsequent decoding of the spectral phases restores the original pulse.

We propose that spectral encoding and decoding of coherent ultrashort pulses could form the basis for a rapidly reconfigurable, code-division multiple-access[4] (CDMA) optical telecommunications network. The system would provide tens to hundreds of users with asynchronously multiplexed, random access to a common fiber or free-space channel.

Our experiments utilize 0.62-μm, 75-fsec pulses from a balanced, colliding-pulse mode-locked (CPM) ring dye laser,[5] which are shaped by using the special dispersion-free grating apparatus. This apparatus consists of a pair of 1700-line/mm gratings placed at the focal planes of a unit magnification confocal-lens pair.[6] The grating separation is 60 cm, and the lenses are achromats with focal lengths of 15 cm. Spatially patterned amplitude and phase masks are inserted midway between the lenses at the point where the optical spectral components experience maximal spatial separation. The pulse shape at the output of the grating is the Fourier transform of the pattern transferred by the mask onto the frequency spectrum. The shaped pulses are measured by cross correlation, using femtosecond pulses directly out of the CPM laser as the reference.

We have verified the nondispersive nature of our grating apparatus by performing autocorrelation measurements of pulses incident upon and emerging from the apparatus. Figure 1 shows autocorrelations of 48-fsec pulses with no mask present. The pulse widths are identical. Without the lens pair, the temporal dispersion arising from the 60-cm grating separation would broaden the pulses by more than 3 orders of magnitude. By moving the gratings either closer to or farther from the lens, respectively, either positive or negative dispersion is obtained.[7] The reduction in the wings of the output pulse may be attributed to cancellation of some small chirp on the pulses from the CPM laser.

By using simple amplitude and phase masks, we have generated trains of femtosecond pulses, femtosecond odd pulses, and other shaped femtosecond pulses. These results are an extension of pulse-shaping experiments previously performed on the picosecond time scale and are reported elsewhere.[8] Here the emphasis is on spectral phase coding of femtosecond pulses. The coding work will serve as an example of the high degree of complexity that can be incorporated into the shaped waveforms.

An example of frequency-domain phase coding is

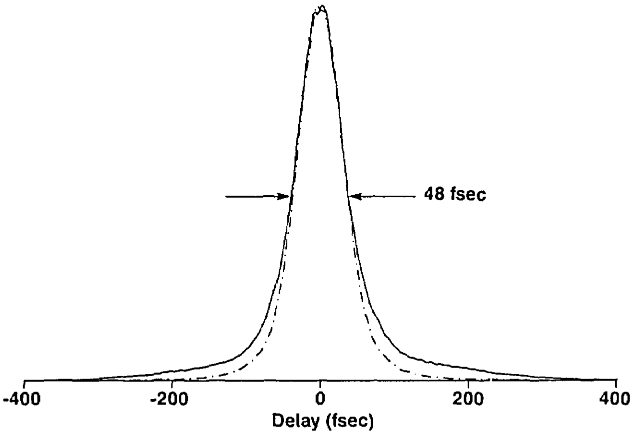

Fig. 1. Autocorrelation traces of 48-fsec pulses from the CPM laser, measured before (solid line) and after (dotted-dashed line) the grating apparatus. With no mask present, the pulse widths are identical.

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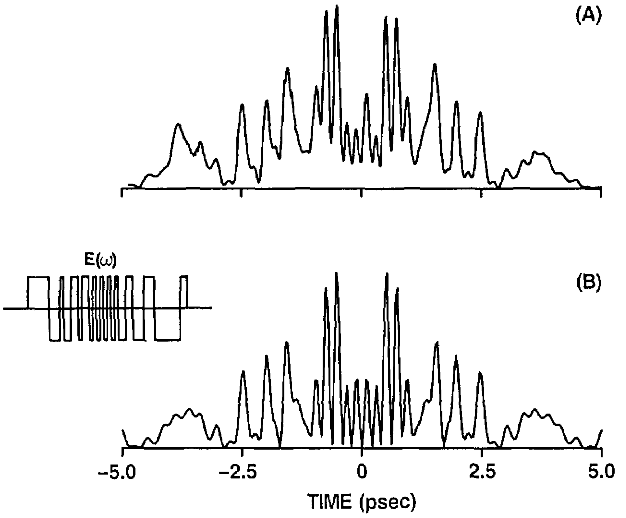

Fig. 2. Frequency-domain phase coding of femtosecond pulses. (A) Cross-correlation measurement of the coded waveform. The inset shows the 44-element phase code; the individual phases are either zero or π. (B) Calculated intensity profile.

shown in Fig. 2. A 44-element pseudorandom binary phase mask, shown in the inset, is used to scramble (encode) the spectral phases. The mask consists of a 2.23-mm clear aperture, corresponding to an optical bandwidth of 5.86 THz (7.52 nm). The spectrum of the incident CPM laser pulses is nearly flat over this bandwidth. The 2.23-mm window is divided into 44 equal pixels, each of which corresponds to a phase shift of zero or π. The masks are fabricated on fused silica by standard microlithography; the π phase shifts are obtained by reactive ion etching to a depth $D = \lambda/2(n-1) \simeq 0.68\ \mu\text{m}$, where n is the refractive index of the fused silica.

The intensity cross-correlation measurement of the encoded waveform is shown in Fig. 2(A). As seen, spectral encoding spreads the incident 75-fsec pulse into a complicated pseudonoise burst within a 10-psec temporal envelope. The peak intensity is reduced to $\simeq$8% compared with an uncoded pulse spectrally windowed[9] to the same bandwidth. For comparison, we show in Fig. 2(B) the theoretical intensity profile, obtained by squaring the Fourier transform of the spectral phase mask. The calculation includes no adjustable parameters. The excellent agreement between theory and experiment underscores the high degree of precision available with our technique.

Autocorrelation measurements of uncoded, coded, and decoded pulses are shown in Fig. 3. Figure 3(A) depicts the autocorrelation of the incident, uncoded pulses together with that of the encoded pulses of Fig. 2. The contrast ratio of $\simeq$25:1 illustrates the dramatic reduction in intensity that accompanies encoding. In order to reconstitute the original femtosecond pulse, we place a second, phase-conjugate mask adjacent to the first mask. This phase-conjugate mask decodes (or unscrambles) the spectral phases scrambled by the first mask, thus restoring the initial pulse. On the other hand, if the second mask does not match the first, the spectral phases are rearranged but not unscrambled. In that case the waveform remains a spread, low-intensity pseudonoise burst. Autocorrelations of such successfully and unsuccessfully decoded pulses are shown in Fig. 3(B).

For ultrashort-pulse CDMA (see below), it is desirable to choose codes that spread the incident pulses as widely and as uniformly as possible. One type of code that appears suitable is the so-called maximal length sequence (or M sequence). These binary sequences have been utilized widely in spread-spectrum communications, and their properties are well known.[4] Figure 4 shows the autocorrelation of a pseudonoise burst spread to a duration exceeding 10 psec by spectral phase coding with a 127-element M-sequence code. The autocorrelation contains a coherence spike riding upon a broad pedestal, as expected for a noise burst.[10] The observed contrast ratio is $\approx$1.4:1, in agreement with calculation and significantly lower than the 2:1 contrast ratio expected when the field is a Gaussian random variable. This observation indicates that this pseudonoise burst spread by spectral M-sequence coding is smoother and more nearly uniform than a Gaussian noise burst, obtained, for example, as the output of an imperfectly mode-locked laser.[10]

We propose that frequency-domain phase coding of coherent ultrashort pulses could form the basis for an

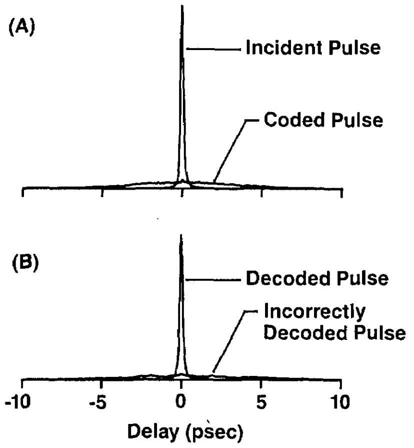

Fig. 3. Autocorrelation measurements of uncoded, coded, and decoded pulses. (A) Uncoded and coded pulses. (B) Successfully and unsuccessfully decoded pulses.

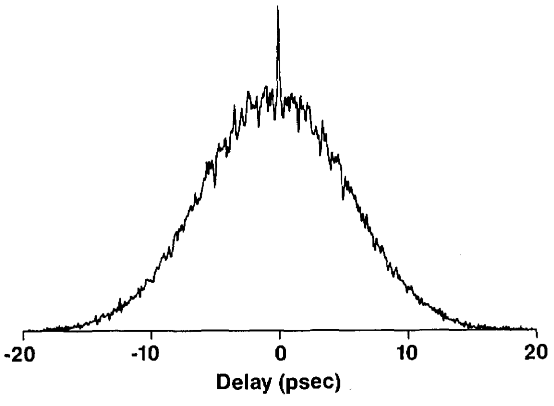

Fig. 4. Autocorrelation of 127-element M-sequence code.

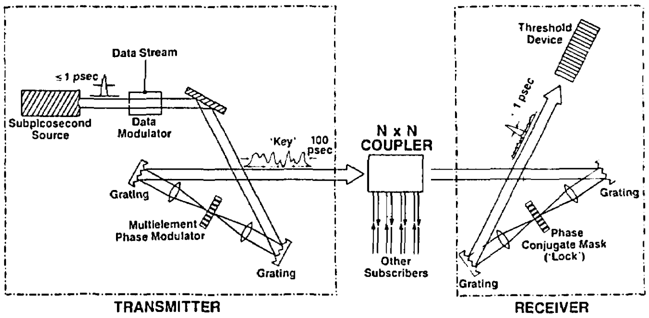

Fig. 5. Proposed ultrashort pulse, CDMA communications network.

ultrahigh-speed, CDMA optical communications network. CDMA is a type of spread-spectrum communication in which multiple pairs of subscribers, each assigned different, minimally interfering code sequences, communicate simultaneously and asynchronously over a common fiber channel.[4] Other CDMA systems have traditionally been based on time-domain encoding, and optical implementations have relied on incoherent processing.[11,12]

The proposed ultrashort-pulse CDMA system could be configured as shown in Fig. 5. N subscriber stations are connected via a passive $N \times N$ directional coupler. Each transmitter station is equipped with a picosecond or femtosecond source and an encoder that contains a multielement phase modulator; each receiver is equipped with a decoder, which contains a similar phase modulator, and an optical threshold device. Each receiving station is assigned a unique lock, or access code, which it imposes on its phase modulator. A given subscriber pair can communicate only if the transmitter encodes by using a key that is phase conjugate to the receiver's lock. In that case the decoder will reassemble the transmitted signal into an intense ultrashort pulse that can be detected by the thresholder. Signals encoded by using the wrong key will not be decoded and will be rejected.

The number of users N that the network could accommodate depends on the length and the properties of the code sequences. The code length in turn depends on the spectral resolution that the optical system can provide. As discussed in Ref. 3, the number of distinct spectral features that can be imposed within a given bandwidth is related to the divergence of the input beam and to the angular dispersion of the grating. In the present work, with a 3-mm input beam, we achieve a resolution sufficient to generate a code sequence of length 127; for a 1-cm beam diameter, the resolution would approach 500. Provided that the code length does not exceed the available spectral resolution, coding and decoding can successfully be achieved.

We have performed bit-error-rate (BER) calculations for the proposed femtosecond CDMA network, in which we model the codes as binary random sequences. The calculations assume an ideal thresholder and account for interference that is due to the other users but do not include power-budget considerations. Our analysis will be described in detail elsewhere. As a particular example, we estimate that a free-space network utilizing 128-element random codes could support simultaneous communication by 30 subscriber pairs at a BER of 10^{-9}, assuming 1-Gbit/sec individual data rates and 80-fsec input pulses. Three hundred subscriber pairs could be supported at a BER of 10^{-5}. For a fixed BER, the number of users who could be accommodated increases with increasing code length and with decreasing individual bit rates and shorter input pulses.

In summary, we have demonstrated encoding and decoding of femtosecond pulses and have suggested that this technology could be utilized for a high-capacity, optical CDMA communications network. Real-time encoding and decoding could be achieved by replacing the prefabricated masks used in the current work with multielement modulators. Ultrashort-pulse CDMA could then serve as a novel architecture for a rapidly reconfigurable optical crossbar switch, in which any transmitter station could connect to any receiver station. Our results should contribute to a new class of communications techniques based on frequency-domain manipulation of ultrashort light pulses.

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