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. 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 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, 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. 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. 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. 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
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.\(^1\)

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.

We propose that frequency-domain phase coding of coherent ultrashort pulses could form the basis for an...
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. Other CDMA systems have traditionally been based on time-domain encoding, and optical implementations have relied on incoherent processing. The proposed ultrashort-pulse CDMA system could be configured as shown in Fig. 5. N subscriber stations are connected via a passive N x 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 threshold. 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 threshold and account for interference that is due to 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^-5, assuming 1-O-bit/sec individual data rates and 80-fsec input pulses. Three hundred subscriber pairs could be supported at a BER of 10^-8. 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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References