Pulse shaping of incoherent light by use of a liquid-crystal modulator array

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Received June 14, 1996

We demonstrate the use of a femtosecond pulse-shaping apparatus for electronically programmable phase filtering of amplified spontaneous emission from an erbium-doped fiber amplifier. Pulse shaping applied to a broadband incoherent light (noise) input results in reshaped noise, with a specially tailored electric field correlation function. Our experiments clearly reveal that phase filtering can strongly affect the coherence properties of broadband, phase-incoherent light.

Femtosecond pulse-shaping technology,[1–5] based on filtering of spatially dispersed optical frequency components, is now finding applications ranging from optical communications to coherent control. In previous experiments the pulse shaper converted a coherent femtosecond input signal into an output waveform with a prespecified temporal intensity and phase profile. Here we apply femtosecond pulse-shaping techniques for electronically programmable phase filtering of broadband incoherent light. Instead of resulting in a reshaped pulse, pulse shaping applied to incoherent light results in reshaped noise, with a specially tailored electric field coherence function. Modulation and coding of the coherence properties of broadband light-wave signals have been proposed as the basis for time-division-multiplexed data transmission[6] or code-division networking[7] as well as for phase-encoded optical data storage in spectral hole-burning materials.[8] For such applications the simplicity of an incoherent light source may be an advantage over femtosecond-laser-based systems. Binary phase coding of incoherent light has been demonstrated by use of visible light sources with 2–3 nm of optical bandwidth.[7,8] This is, to our knowledge, the first demonstration of phase coding of incoherent light by use of gray-level phase control, with a bandwidth as large as 50 nm and with light in the 1.55-μm optical communications band. From a different perspective, our results show that incoherent light can be used to characterize the transfer function of a femtosecond pulse shaper, much as incoherent light and white-light interferometry have been used to characterize simple dispersive elements such as prisms and dielectric mirrors.[9,10]

Our experimental setup is shown schematically in Fig. 1. We use 1–2 mW of amplified spontaneous emission (ASE) from an angle-cleaved erbium-doped fiber amplifier pumped at 980 nm as our source of broadband incoherent light. A typical spectrum, showing spectral content from roughly 1520 to 1570 nm, is plotted in Fig. 2(a). The input light was split into two arms to form a Mach–Zehnder interferometer. A pulse shaper containing a 128-element liquid-crystal phase-modulator array[2] was placed in one arm (the signal arm) of the interferometer to program the coherence properties of the incoherent light. The other (reference) arm of the interferometer used a stepper-motor-driven translation stage with 0.1-μm step size to vary the relative delay. The output from the interferometer was directed to a photodiode connected to a lock-in amplifier (with the reference arm chopped) and a computer. Recording the photodiode signal as a function of delay yielded the electric field cross-correlation function between the shaped and the unshaped incoherent light. To aid in alignment, we also coupled the interferometer output through a single-mode optical fiber into an optical spectrum analyzer to measure the power spectrum, including the spectral interference between the two arms.

As in previous studies,[1–3] the pulse shaper consisted of a pair of gratings and lenses arranged in the zero-dispersion geometry [i.e., grating–lens and lens–liquid-crystal modulator (LCM) spacings equal to f, where f is the focal length of the two identical lenses]. The optical spectrum is spatially dispersed in the masking plane midway between the two lenses and can be manipulated by insertion of a spatially patterned amplitude and (or) a phase filter at this point. In the time domain the output waveform is given by the inverse Fourier transform of the complex input spectrum as modified by the pulse shaper. In the current implementation we used 830-line/mm gratings at a 23° input angle and 150-mm focal-length achromatic lenses. This dispersed the 50-nm optical bandwidth over a 12.8-mm spatial dimension, equal to the aperture of the LCM array that we use as a phase filter. The pulse shaper also includes a pair of half-wave plates placed on either side of the LCM to set the proper polarization state.[2] The input beam

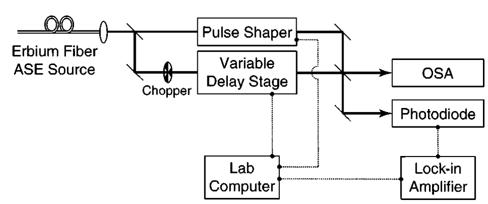

Fig. 1. Schematic experimental setup: OSA, optical spectrum analyzer.

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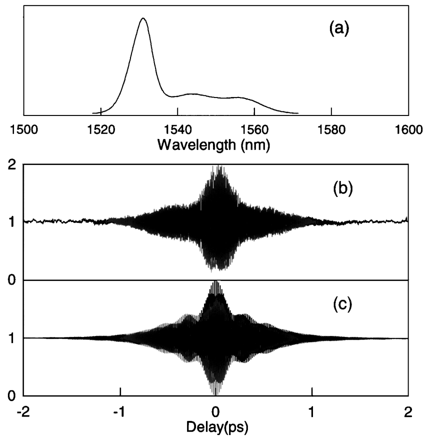

Fig. 2. (a) Power spectrum of ASE from the erbium-doped fiber amplifier. (b) Measured electric-field autocorrelation. (c) Calculated autocorrelation function, equal to the Fourier transform of the power spectrum.

radius was ~5 mm, resulting in a measured 75-μm beam radius at the masking plane of the same order as the 100-μm width of individual LCM pixels. The design of the LCM (Cambridge Research and Instrumentation) was similar to that reported in Ref. 2. The voltage applied to each modulator pixel could be controlled independently and continuously over 0–10 V through a menu-driven computer program developed in our laboratory, resulting in gray-level phase control between 0 and $>3\pi$, with a reprogramming time of the order of 10 ms. We calibrated the phase-versus-voltage response of the LCM outside the pulse shaper by measuring the polarization rotation of a 1.523-μm He–Ne laser.[2]

Because the incoherent light input to our experiments is a noise signal, the output from the pulse shaper is also noise. Therefore standard intensity cross-correlation techniques previously used to measure the output of coherent femtosecond pulse-shaping experiments are not useful here. Nevertheless, the phase pattern applied by the LCM array alters the coherence function of the incoming incoherent light, which one can observe by performing an electric field cross-correlation measurement. The average output power measured by the photodiode as a function of delay τ is given by the following equation,[11] where $H(\omega)$ represents the transfer function of the pulse shaper (approximately equal to the spatial phase pattern):

$$P_{\mathrm{av}}(\tau) = (1/2\pi) \int \{|E(\tilde{\omega})|^2 + |H(\tilde{\omega})E(\tilde{\omega})|^2 + [H(\tilde{\omega})|E(\tilde{\omega})|^2 \exp(-j\omega_0\tau) + \text{c.c.}]\} \times \exp(j\omega\tau)\mathrm{d}\omega\,. \tag{1}$$

Here ω_0 is the center frequency, $\tilde{\omega} = \omega - \omega_0$, and $E(\tilde{\omega})$ represents the input complex spectral amplitude. The first two terms, containing $|E(\tilde{\omega})|^2$ and $|H(\tilde{\omega})E(\tilde{\omega})|^2$, respectively, are independent of τ (only the first term, corresponding to the chopped reference arm, is detected by the lock-in amplifier). The remaining rapidly varying fringe terms, given by

$$P_{\mathrm{fringe}}(\tau) = (1/2\pi) \int [H(\tilde{\omega})|E(\tilde{\omega})|^2 \exp(-j\omega_0\tau) + \text{c.c.}] \times \exp(j\omega\tau)\mathrm{d}\omega\,, \tag{2}$$

yield the electric field cross-correlation function. It is easily shown that $P_{\mathrm{fringe}}(\tau)$ is equal to the input electric field autocorrelation convolved with $h(\tau)$, the impulse response of the pulse shaper obtained from the inverse Fourier transform of $H(\omega)$.

Figure 2(b) shows the data recorded with a uniform phase applied to the LCM, corresponding to $H(\omega) = 1$. In this case the experiment simply measures the electric field autocorrelation function. The narrow central peak has a width related to the inverse of the total optical bandwidth, whereas the lower-amplitude wings arise from the relatively narrow peak in the ASE spectrum near 1532 nm. The theoretical autocorrelation, equal to the inverse Fourier transform of the input power spectrum, is shown in Fig. 2(c). The excellent agreement between experimental and theoretical plots demonstrates that the pulse shaper is not introducing any significant dispersion. We note that similar traces (not shown) obtained when the final grating is moved either closer to or farther from the second lens exhibit an asymmetry that increases with increasing grating displacement, because such displacement leads to a net nonzero dispersion.

Figure 3(a) shows data obtained when the LCM imparts a binary phase modulation (shown in the inset) upon the spectrum. Unlike in Fig. 2(b), two symmetric peaks are observed, with a deep dip in the interference envelope at zero delay. Our data are in good agreement with the theoretical trace [Fig. 3(b)] calculated from Eq. (2) and can be understood if it is noted that the field cross-correlation value at zero delay is given by the net area under $H(\tilde{\omega})|E(\tilde{\omega})|^2$, which in this case is approximately zero because the applied phase profile, a step function between 0 and π, inverts roughly one half of the spectrum in the signal arm. In previous femtosecond pulse-shaping experiments, such a 0-to-π phase step was used to generate an odd pulse in which the electric field was an antisymmetric function of time.[1] We note that the degree of extinction in the interference envelope at $\tau = 0$ is much deeper

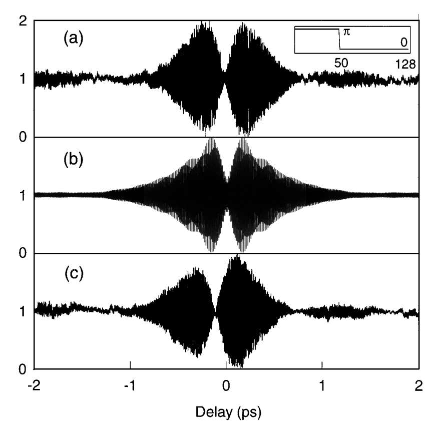

Fig. 3. (a) Electric field cross-correlation measurement of incoherent light spectrally filtered by use of a binary $(0, \pi)$ phase step. The applied phase pattern is shown in the inset. The horizontal scale on the inset indicates the modulator pixel number. (b) Calculated cross correlation corresponding to (a). (c) Cross correlation measured for a phase function similar to that in (a) but with a phase step going from 0 to $\sim 0.8\pi$.

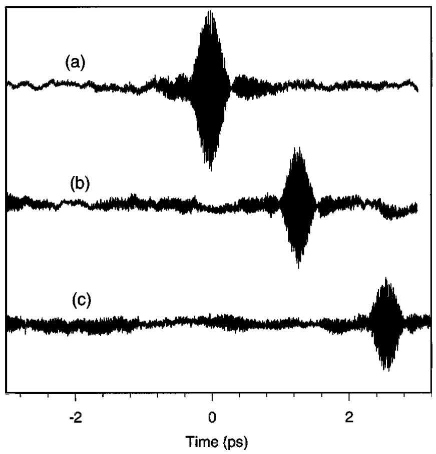

Fig. 4. Electric field cross-correlation measurements for gray-level phase patterns corresponding to a linear spectral phase sweep (modulo 2π). (a) Constant phase. (b) $\pi/8$ phase change per pixel. (c) $\pi/4$ phase change per pixel.

in Fig. 3 than that observed in the previous coherent pulse-shaping experiments. We attribute this difference to the use of electric field correlation measurements here rather than to intensity cross-correlation measurements, which washed out the null previously. Figure 3(c) shows data from another interesting measurement, in which the π phase step used for Fig. 3(a) was decreased to $\sim 0.8\pi$. The resulting dip in the interference envelope now comes very close to complete extinction. At the same time, the fact that $H(\omega)$ is no longer real introduces an asymmetry into the data.

We also used the LCM to place gray-level phase modulations on the incoherent light spectrum. The experiments reported here are based on the fact that, if $f(\tau)$ and $F(\omega)$ are a Fourier transform pair, then the delayed signal $f(t - \tau)$ has the Fourier transform $F(\omega)\exp(-i\omega\tau)$. Thus a linear spectral phase sweep corresponds in the time domain to a net delay. In previous coherent pulse-shaping experiments, this relation was exploited to achieve femtosecond pulse position modulation.[2,12,13] Here we demonstrate that a linear spectral phase sweep can also be used to adjust the time position of broadband incoherent light. Figure 4 shows data measured for three different linear phase sweeps. In curve (a) of Fig. 4 the phase is kept constant; as a result the correlation peak is detected at $\tau = 0$. The difference in the shape of the correlation peak compared with that shown in Fig. 2 arises because the power spectrum is somewhat different from that in the previous experiments. In curves (b) and (c) of Fig. 4 the phase varies in steps of $\pi/8$ and $\pi/4$, respectively, from one LCM pixel to the next (modulo 2π). The correlation peaks in curves (b) and (c) are delayed by 1.25 and 2.5 ps, respectively, in good agreement with theory. The maximum delay attainable with this scheme is limited by the requirement that the phase step per pixel must remain $\lesssim \pm 3\pi/4$ to avoid aliasing effects.[2] In our experiments $\tau_{\max} \lesssim \pm 7.7$ ps.

Note that in these experiments we cannot directly determine the applied phase mask from the cross-correlation data because of the possibility of phase errors in our interferometry measurements. By using the method of Ref. 10 to track the interferometer motion, one could obtain dependable phase measurements and hence derive the phase function applied by the LCM through Fourier analysis of the correlation data. An alternative approach is to determine the phase function through spectral interferometry, an approach that we are currently pursuing.

In summary we have demonstrated the use of an electronically programmable pulse-shaping apparatus to modify the coherence function of ASE from an erbium-doped fiber amplifier. Our experiments clearly reveal that phase filtering can strongly affect broadband, phase-incoherent light.

This study was supported by National Science Foundation grant ECS-9312256 and by the U.S. Air Force Office of Scientific Research under contract F49620-95-1-0533.

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