Programmable polarization-independent spectral phase compensation and pulse shaping by use of a single-layer liquid-crystal modulator

C. G. Slater, D. E. Leaird, and A. M. Weiner

What we believe to be the first use of a single-layer liquid-crystal modulator array for spectral phase pulse shaping that operates independently of input polarization is reported. Polarization insensitivity is essential to optical-fiber-based applications such as dispersion compensation.

OCIS codes: 060.2330, 320.5540, 070.2580.

1. Introduction

Fourier transform pulse shapers[1] are widely applied to ultrafast optical waveform processing and have been used for applications ranging from quantum control[2] to dispersion compensation.[3–6] Programmable pulse shaping has been used to demonstrate the propagation of <500 fs pulses and up to 50 km of dispersion-compensated fiber links through the equalization of higher-order spectral phase components.[3,4] In addition, recent developments have led to pulse shaping technologies for dispersion slope compensation applicable to 40 Gbit/s fiber transmission.[5,6] In a similar vein, programmable pulse shaping is widely used to compensate higher-order phase terms arising from pulse stretcher–compressor pairs and accordingly improve pulse quality in femtosecond chirped-pulse amplifiers.[7,8] In most femtosecond laser applications the input to the pulse shaper has a stable and well-characterized linear polarization state. However, in fiber-optic applications, the input polarization state is usually not known and may vary with time. As a direct consequence, polarization-independent pulse shaping has significant relevance for fiber-based applications. Polarization-independent spectral phase compensation and pulse shaping have been demonstrated previously through the use of a two-layer liquid-crystal modulator (LCM) array technology.[9] This paper, for the first time to our knowledge, demonstrates polarization-independent spectral phase compensation by utilizing only a single-layer LCM. This idea was previously proposed in the patent literature[10] but prior to this work was not tested experimentally.

Fourier-transform pulse shaping is based on the masking of spatially dispersed optical frequency spectra.[1] Acousto-optics,[11] deformable mirrors,[8] and LCM arrays[12,13] have been used for such applications. The most widely utilized of these technologies is the LCM, which provides a large pixel count. In previous implementations, the one-layer LCM has been used to achieve phase control of a specific linear polarization, but the orthogonal polarization was uncontrollable.[12] In the two-layer case the two liquid-crystal layers are typically oriented at $\pm45°$ to the p plane.[13] The retardance of each of the two layers is voltage controlled on a pixel-by-pixel basis to manipulate the phase and output intensity (when used with a fixed polarizer) for linearly polarized input light. Spectral phase and partial spectral polarization control have been achieved in a similar setup by omitting the output polarizer, which led to pulses with a time-dependent polarization state.[14] Also in a previous system, based on a two-layer LCM, polarization-independent spectral phase control was achieved by driving the two layers of the LCM in common mode, in conjunction with a low polarization-dependent-loss diffraction grating.[9] In the current work, we replace the two-layer LCM previously required to achieve polarization independence with a combination of a single-layer LCM and a quarter-wave plate (QWP) arranged in a double-

The authors are with the School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Avenue, West Lafayette, Indiana 47907-2035. C. G. Slater's e-mail address is slatercg@purdue.edu.

Received 9 December 2005; accepted 19 January 2006; posted 9 February 2006 (Doc. ID 66495).

0003-6935/06/204858-06$15.00/0

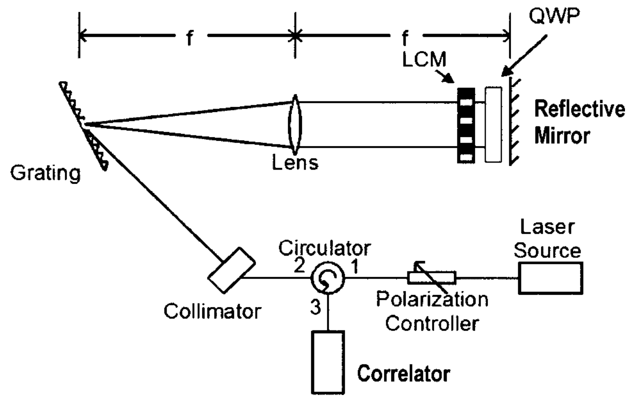

Fig. 1. Reflective Fourier-transform pulse shaper design. LCM, liquid-crystal modulator array; QWP, quarter-wave plate.

pass geometry. This solution potentially reduces cost, both because one-layer LCMs are less complex to assemble than two-layer LCMs and because the associated electronics need to control only half the aggregate number of LCM pixels compared to the two-layer case. An additional benefit is that this solution, in principle also allows the realization of a pulse shaper with zero polarization-dependent loss (PDL), even if a grating with nonzero PDL is used in its construction. A drawback is that the insertion of the QWP requires that the LCM be displaced from the reflecting mirror, which may degrade spectral resolution.

2. Theory

A simple qualitative description of polarization-independent pulse shaping by using a single-layer LCM and a QWP in a reflection geometry, as shown in Fig. 1, is given in this section. This configuration provides voltage-dependent phase-only control independently of input polarization. For the sake of discussion we will assume that the liquid-crystal molecules are aligned along the y direction (P polarization). Now consider any general input polarization state to be represented by a superposition of orthogonal S and P states. On the first pass through the LCM, only the P component experiences a voltage-dependent phase shift for our assumed liquid-crystal alignment. The QWP is oriented with axes at $\pm 45°$ so that in double pass it acts as a half-wave plate effectively rotating the polarization state reference frame by 90°. Then, on the second pass through the LCM, again only one component (the one orthogonal to the input case) experiences a voltage-dependent phase shift. As a result, in double passing through the LCM, both the S and P states have experienced the same net phase shift. For completeness, a more quantitative argument follows.

The mathematics behind polarization-insensitive operation is best understood by means of Jones calculus. The Jones matrix for any distinct pixel in the single-layer LCM and QWP design can be combined to form the overall effective Jones matrix of the system, J_{LCM}, which can be written as follows:

$$J_{\text{LCM}} = \begin{bmatrix} g_x & 0 \\ 0 & g_y \end{bmatrix} \begin{bmatrix} \exp(-j\zeta_x) & 0 \\ 0 & \exp(-j\zeta_y(V)) \end{bmatrix} \begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix} \times \begin{bmatrix} \exp(-j\zeta_x) & 0 \\ 0 & \exp(-j\zeta_y(V)) \end{bmatrix} \begin{bmatrix} g_x & 0 \\ 0 & g_y \end{bmatrix}. \quad (1)$$

Here, $\zeta_x = \omega n_o(L_{\text{LCM}}/c)$ and $\zeta_y(V) = \omega n_e(V) \times (L_{\text{LCM}}/c)$ refer to the optical phase corresponding to light propagation through the liquid-crystal layer, where L_{LCM} is the propagation length through an LCM pixel, ω is the angular frequency of the wave, $n_e(V)$ and n_o are the refractive indices along the extraordinary and ordinary axes, respectively, of the liquid-crystal array, and c is the velocity of light in vacuum. Also, g_x and g_y are complex numbers characterizing the amplitude and phase of the electric field after diffracting from the grating. The application of a voltage (V) to a LCM pixel produces a longitudinal electric field, which rotates the molecules of the liquid crystal toward the direction of the applied field. As a result, the phase for light polarized along the initial liquid-crystal orientation, $\zeta_y(V)$, is a function of the voltage applied to that pixel of the LCM. The phase for light polarized perpendicular to this direction, ζ_x, is usually voltage independent. Note, however, that our analysis would hold even if both ζ_x and $\zeta_y(V)$ are voltage dependent. Equation (1) can be simplified to yield

$$J_{\text{LCM}} = jg_x g_y \exp\{-j[\zeta_x + \zeta_y(V)]\} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}. \quad (2)$$

The output signal is dependent on a fixed polarization-independent amplitude factor ($g_x g_y$) and a voltage-dependent phase term $j \exp\{-j[\zeta_x + \zeta_y(V)]\}$. The matrix expression in the final result is simply a fixed polarization transformation. This means that when the extraordinary and ordinary axes of the QWP are aligned at angles of $\pm 45°$, as previously assumed, the polarization transformation is independent of the phase applied. Stated more simply, the QWP performs the operation of swapping the x and y components of the signal polarization state but otherwise supports polarization-independent spectral phase pulse shaping. As noted above, common-mode programming of a two-layer LCM has been shown to yield a phase-only polarization-independent response.[9] Equation (2) shows that the same phase-only response applies to an arbitrary input polarization state using a single-layer LCM and QWP for a reflection-mode pulse shaper. Furthermore, in Ref. 9 the PDL of the overall system directly reflects the PDL of the grating, therefore the selection of a low-PDL grating is required. In the current setup, overall zero PDL can be obtained independently of the grating PDL. The grating PDL will, however, contribute to an isotropic insertion loss, so a relatively low PDL is still desirable.

3. Setup

The source laser used in these experiments was a passively mode-locked erbium fiber laser operating at a 50 MHz repetition rate, a nominal pulse width of 70 fs, and a spectral FWHM of 60 nm centered at 1578 nm.[15] A reflection geometry Fourier-transform pulse shaper design was used,[9] which simplified the alignment as compared to transmission geometry, especially for fiber-coupled systems. Figure 1 shows the design of the experimental setup. To avoid significant power loss due to spectral windowing, the pulse shaper was designed to accommodate a spectral range of twice the FWHM of the spectrum (120 nm). A polarization-insensitive fiber circulator separated the input pulses from the output waveform. The circulator allowed the light to enter and leave the pulse shaping system through a single terminal. In the shaper, pulses left the fiber and entered free space through a 1.9 mm beam diameter collimator. A diffraction grating with 1100 lines/mm aligned at an incident angle of approximately 60° angularly dispersed (and recombined on the second pass) the collimated beam. No special care was taken to select a low-PDL grating. A 145 mm achromatic lens placed one focal length from the grating and one focal length from the mirror focused the spatially separated light into a series of discrete spots at the mirror. A standard single-layer 128-element LCM (CRI, Inc., SLM-128-P-NM) was programmed to impart a polarization-independent phase pattern onto the spectrum, as described above. Each pixel on the LCM was 98 μm wide and 5 mm tall, with a separation of ~2 μm between each of the pixels. The pulse spectrum of 120 nm was spread across the 12.8 mm aperture. A 1 in. (2.54 cm) diameter, zero-order QWP 2.5 mm thick (ThorLabs WPQ05M-1550) was placed between the LCM and the retroreflecting gold mirror.

The LCM was displaced from the focal plane in the pulse-shaping apparatus because of the requirement that the QWP be placed between the LCM and the retroreflecting mirror. This had the potential to degrade resolution. In the current experiments the displacement between the active LCM plane and the mirror was roughly 24 mm, much larger than the minimum value corresponding to the 2.5 mm QWP thickness. The 24 mm displacement consists of the ~10 mm distance between the active LCM plane and the outside edge of its mechanical package and the ~14 mm thickness of the QWP mount. The measured resolution for the experimental setup is 400 μm, corresponding to 4 LCM pixels, which was obtained by turning on one pixel of the LCM at a time and observing the peak spectral amplitude out of the setup on an optical spectrum analyzer (OSA). The effective resolution was determined at the point where turning on one more LCM pixel did not increase the peak spectral amplitude but only broadened the observed spectral width. The measured resolution was consistent with that expected based on Gaussian beam propagation for a beam waist at the retroreflecting mirror. It is important to note, however, that much better resolution should be possible in an optimized setup. To this end, one should use a LCM manufactured so that the active LCM plane is aligned with the outside of its package (pulse-shaping LCMs with such packages are now commercially available). One should also fabricate a QWP mount with a thickness not exceeding the thickness of the QWP itself. With these precautions it should be possible to achieve an active LCM plane to retroreflecting mirror displacement of the order of 3–4 mm. Considering that a Gaussian beam focused to a diameter of 100 μm intensity FWHM, equal to the width of one LCM pixel, spreads by less than 10% in propagating 4 mm, it should be possible to maintain a resolution close to one pixel in an optimized setup.

4. Experiment

Output waveforms are measured via second-harmonic generation (SHG) intensity cross correlation with a reference pulse directly from the laser. The reference pulse and the pulse shaper output pulse are connected to the cross correlator through dispersion-compensated links constructed from an appropriate combination of standard single-mode

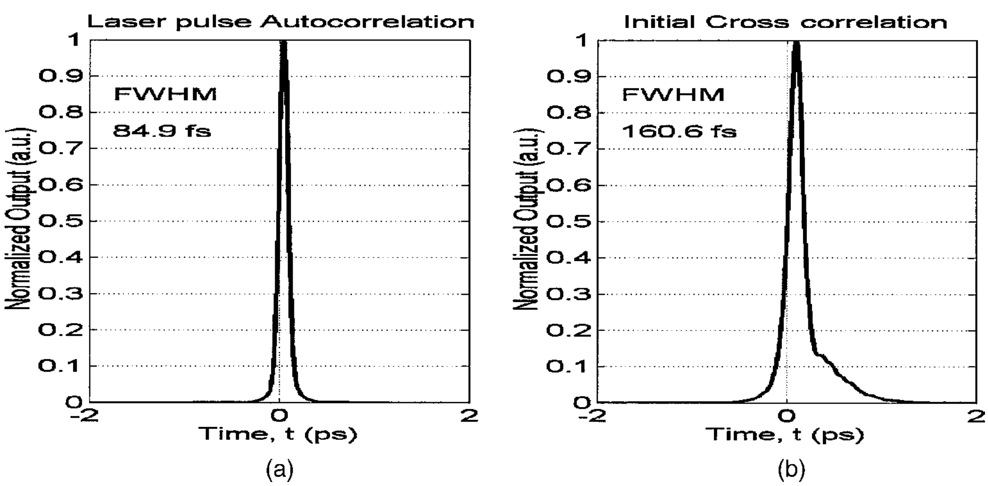

Fig. 2. Autocorrelation of pulse emitted by the laser and initial cross correlation of shaper output pulse with the pulse shaper in a quiescent state (constant spectral phase).

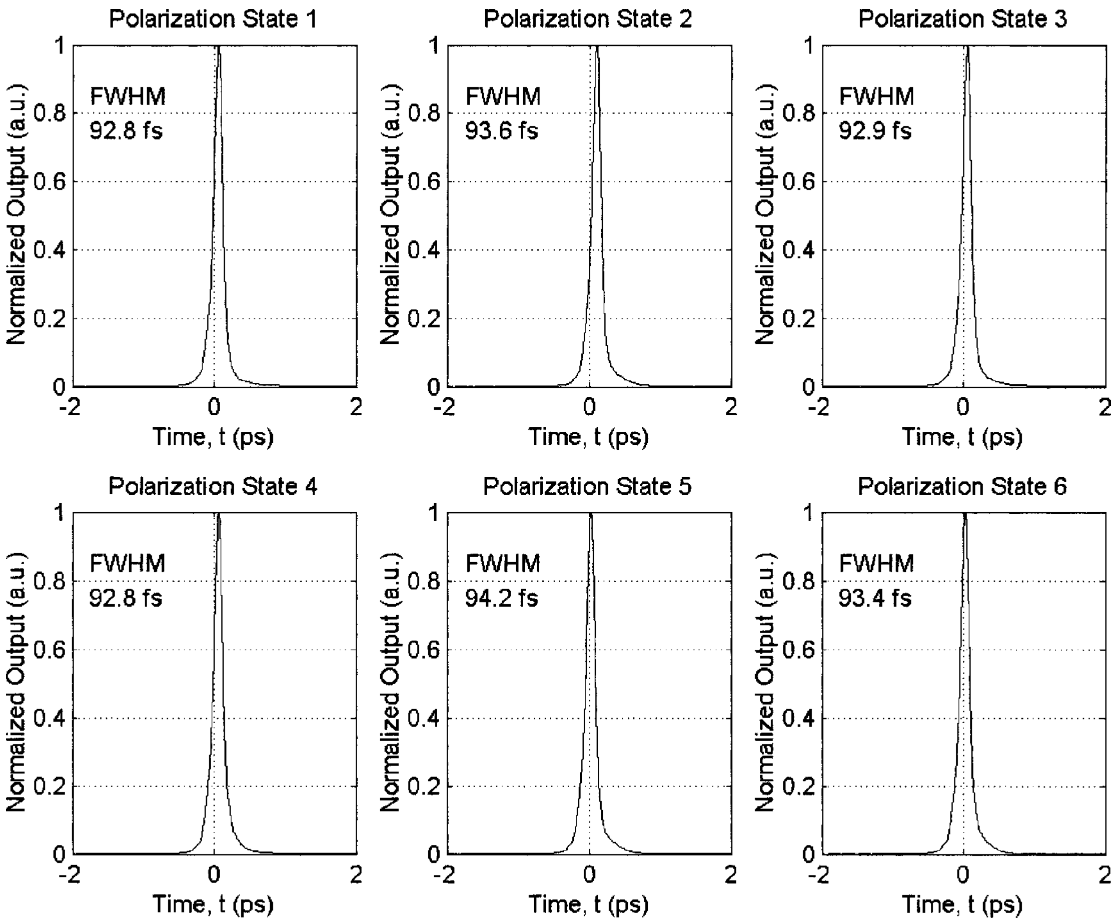

Fig. 3. Intensity cross correlation after spectral phase compensation for six different input polarizations. Correlation traces are essentially identical, confirming polarization independence.

and dispersion-compensating fibers. Because the SHG crystal works only for a single polarization state, polarization controllers are used in both reference and pulse shaper links to properly align the polarization states into the correlator before each measurement. An autocorrelation measurement of the reference waveform from the laser and the initial cross-correlation measurement with the pulse shaper in a quiescent state (constant spectral phase) are shown in Fig. 2.

The pulse broadening and distortion present in the initial cross correlation shown in Fig. 2(b) is due to residual cubic spectral phase in the fiber link connecting the pulse shaper to the cross correlator, which arises because the higher-order dispersion of single-mode and dispersion-compensating fibers is imperfectly matched. After programming the LCM in the pulse shaper with an opposite cubic spectral phase to cancel the distortion, and assuming a secant hyperbolic pulse shape, a pulse with a deconvolved width of approximately 90 fs can be obtained, as shown in Fig. 3.

To demonstrate that the pulse shaper is polarization insensitive, a fiber polarization controller was used at the input to the circulator to send several different input polarization states to the pulse shaper

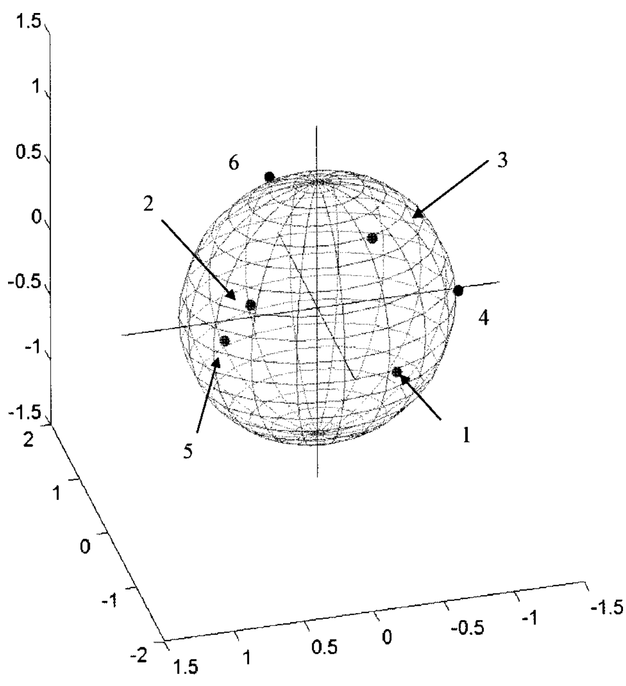

Fig. 4. Polarization states used to demonstrate polarization insensitivity.

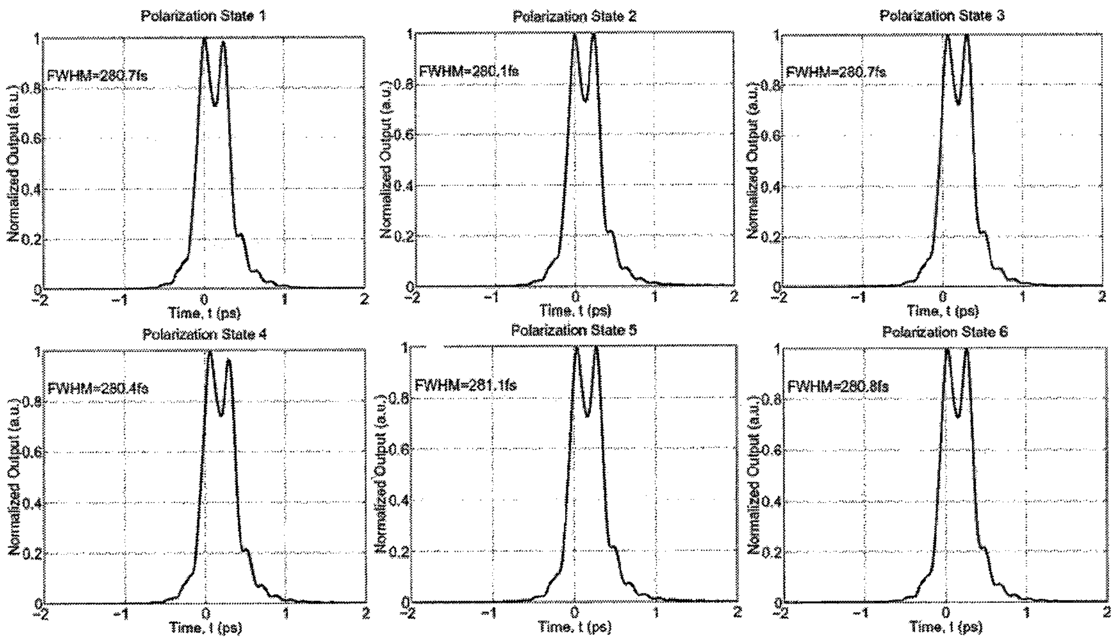

Fig. 5. Cross-correlation measurement of odd pulses for six different input polarizations. Pulse shapes are essentially identical, confirming polarization independence.

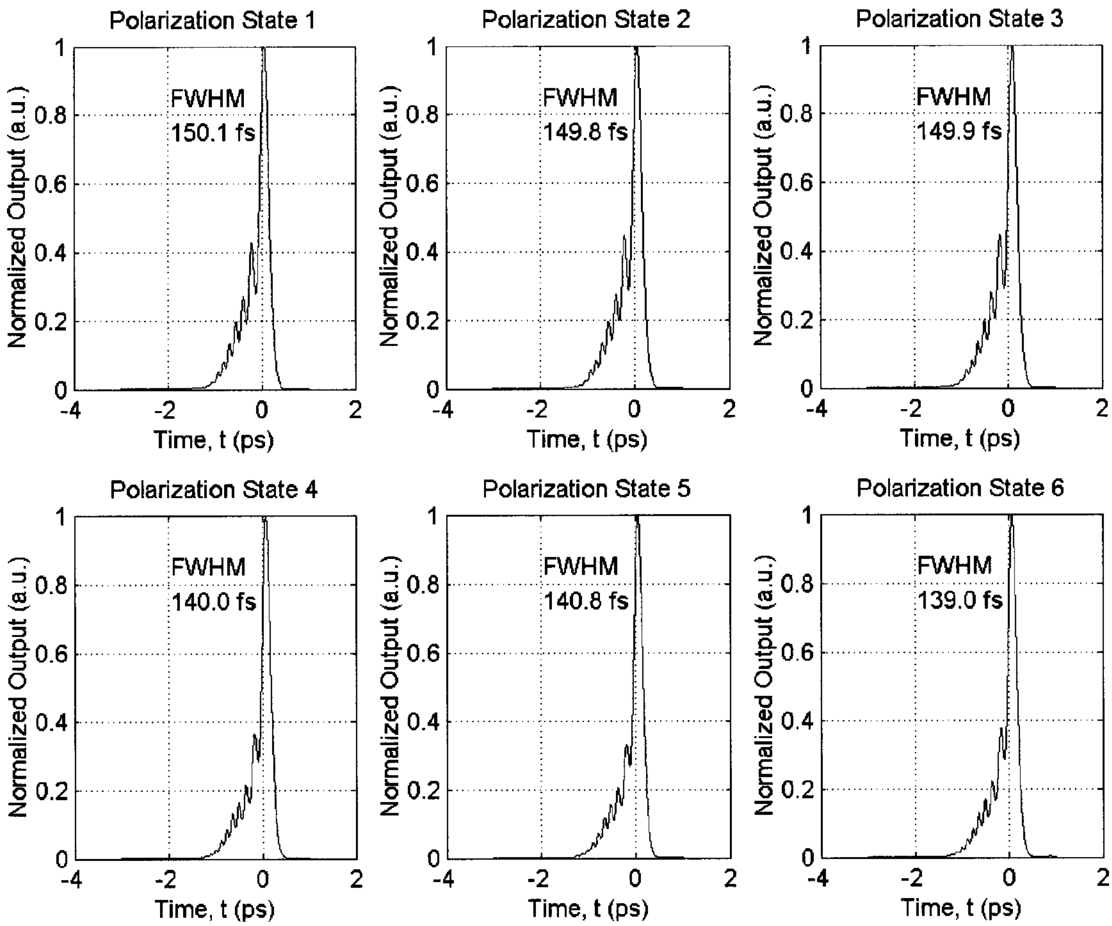

Fig. 6. Dispersion-compensated cubic pulses for six different input polarizations. Pulse shapes are essentially identical, confirming polarization independence.

with the time-domain output recorded for each input state. A wavelength-parallel polarimeter[16] was used to obtain an indication of the input polarization orientation. Six different input polarization states were selected and then investigated for several different pulse shapes. The same six polarization states were used for all pulse shapes shown. The median wavelength input polarization states are shown in Fig. 4 by using a Poincaré sphere representation. The cubic phase compensation experiment was repeated for all six input polarization states, in each case with identical voltage drive levels applied to the LCM. The cross correlations of the compensated pulses, shown in Fig. 3, are indistinguishable for all the input polarization states tested. The pulse widths are identical to within 2 fs. This result clearly shows polarization-insensitive phase-only pulse shaping.

As another example, the LCM was programmed with a single π phase shift placed symmetrically in the spectrum. This is known to produce an odd pulse, an antisymmetric electric field waveform corresponding to a double pulse intensity profile spaced symmetrically at approximately $t = 0$.[17,18] The cross-correlation measurements plotted in Fig. 5 show the expected pulse doublet, again essentially identical for all polarization states tested without changing the settings of the LCM. The small shoulder evident in all the traces for positive delays at approximately 0.5 ps arises because in this example the residual cubic phase of the setup is not compensated.

As a final test of this setup, a cubic spectral phase large enough to overcompensate the cubic phase from the fiber link itself was applied to the LCM. The result is a broadening of the pulse with an oscillatory tail now preceding the pulse, rather than following it as in Fig. 3. Again the waveform remains essentially constant for all the input polarizations, as illustrated in Fig. 6.

In summary, these results demonstrate spectral phase pulse shaping with a functionality that is independent of input polarization through the use of a single-layer LCM array and a QWP in a double-pass pulse-shaping geometry.

This work was supported by the National Science Foundation under grants 0140682-ECS and 0501366-ECS. The authors thank S. X. Wang for help with the polarization measurements.

References

1. A. M. Weiner, "Femtosecond pulse shaping using spatial light modulators," Rev. Sci. Instrum. **71,** 1929–1960 (2000).
2. R. J. Levis, G. M. Menkir, and H. Rabitz, "Selective bond dissociation and rearrangement with optimally tailored, strong-field laser pulses," Science **292,** 709–713 (2001).
3. C.-C. Chang, H. P. Sardesai, and A. M. Weiner, "Dispersion-free fiber transmission for femtosecond pulses using a dispersion-compensating fiber and a programmable pulse shaper," Opt. Lett. **23,** 283–285 (1998).
4. Z. Jiang, S.-D. Yang, D. E. Leaird, and A. M. Weiner, "Fully dispersion compensated ~500 fs pulse transmission over 50 km single mode fiber," Opt. Lett. **30,** 1449–1451 (2005).
5. H. Takenouchi, T. Goh, and T. Ishii, "8 THz bandwidth dispersion-slope compensator module for multiband 40 Gbit/s WDM transmission systems using an AWG and spatial phase filter," Electron. Lett. **37,** 777–778 (2001).
6. T. Sano, T. Iwashima, M. Katayama, T. Kanie, M. Harumoto, M. Shigehara, H. Suganuma, and M. Nishimura, "Novel multichannel tunable chromatic dispersion compensator based on MEMS and diffraction grating," IEEE Photon. Technol. Lett. **15,** 1109–1100 (2003).
7. T. Brixner, M. Strehle, and G. Gerber, "Feedback-controlled optimization of amplified femtosecond laser pulses," Appl. Phys. B **68,** 281–284 (1999).
8. E. Zeek, R. Bartels, M. Murnane, H. Kapteyn, S. Backus, and G. Vdovin, "Adaptive pulse compression for transform-limited 15-fs high-energy pulse generation," Opt. Lett. **25,** 587–589 (2000).
9. R. D. Nelson, D. E. Leaird, and A. M. Weiner, "Programmable polarization-independent spectral phase compensation and pulse shaping," Opt. Express **11,** 1764–1769 (2003).
10. A. M. Weiner, "System of method for programmable polarization-independent phase compensation of optical signals," U.S. patent 6,879,426 (12 April 2005).
11. J. X. Tull, M. A. Dugan, and W. S. Warren, "High Resolution, ultrafast laser pulse shaping and its applications," Adv. Magn. Opt. Reson. **20,** 1–56 (1997).
12. A. M. Weiner, D. E. Leaird, J. S. Patel, and J. R. Wullert, "Programmable shaping of femtosecond pulses by use of a 128-element liquid-crystal phase modulator," IEEE J. Quantum Electron. **28,** 908–920 (1992).
13. M. M. Wefers and K. A. Nelson, "Generation of high-fidelity programmable ultrafast optical waveforms," Opt. Lett. **20,** 1047–1049 (1995).
14. T. Brixner and G. Gerber, "Femtosecond polarization pulse shaping," Opt. Lett. **26,** 557–559 (2001).
15. K. Tamura, H. A. Haus, and E. P. Ippen, "Self-starting additive pulse mode-locked erbium fibre ring laser," Electron. Lett. **28,** 2226–2228 (1992).
16. S. X. Wang and A. M. Weiner, "Fast wavelength-parallel polarimeter for broadband optical networks," Opt. Lett. **29,** 923–925 (2004).
17. J. P. Heritage, A. M. Weiner, and R. N. Thurston, "Picosecond pulse shaping by spectral phase and amplitude manipulation," Opt. Lett. **10,** 609–611 (1985).
18. A. M. Weiner, J. P. Heritage, and E. M. Kirschner, "High resolution femtosecond pulse shaping," J. Opt. Soc. Am. B **5,** 1563–1572 (1988).