WHITE PAPER

Short Pulse Shaping using the WaveShaper 1000/SP

1. Scope and Overview

Pulse shaping is a powerful optical technique whereby the Fourier-domain of a pulse or sequence of pulses is manipulated in order to alter its properties. The WaveShaper 1000/SP series of Single-Polarization Programmable Filters has been optimized to deliver superior performance and flexibility in user operation for shaping of ultra-short laser pulses.

This application note provides an overview of the principles of pulse shaping, WaveShaper functionality, and applications in the field. This will cover the theoretical foundation of pulse shaping and its physical implementation in the WaveShaper, as well as providing several examples which illustrate the capability of this technology.

2. Why Shape A Pulse?

The ability to ‘shape’ a light pulse implies that one has arbitrary control over either one of, or both its amplitude and phase characteristics. Pulse shaping is therefore a powerful technique one can use for completely defining the temporal (or spectral) properties of a laser pulse.

A simple example of pulse shaping might be temporal expansion (or compression) of a pulse by application of a frequency dependent phase delay (Figure 1). In this instance the phase of each spectral component of the pulse is delayed independently in order to produce the desired result. More generally this type of approach can be used in either an open- or closed-loop configuration to compensate for dispersive effects in a medium which might diminish the quality of a narrow, shaped pulse.

Spectral processing capabilities also allow the user to reshape the temporal envelope of a pulse where it might be more advantageous, for instance, to go from a square pulse shape to something more parabolic. The user might even like to take individual pulses in a pulse-train and break them up into multi-pulse burst sequences where each pulse is individually shaped in a different way. All of these examples, and more, become trivial problems of the same class when the user has the ability to control the spectral phase and amplitude of the laser pulse.

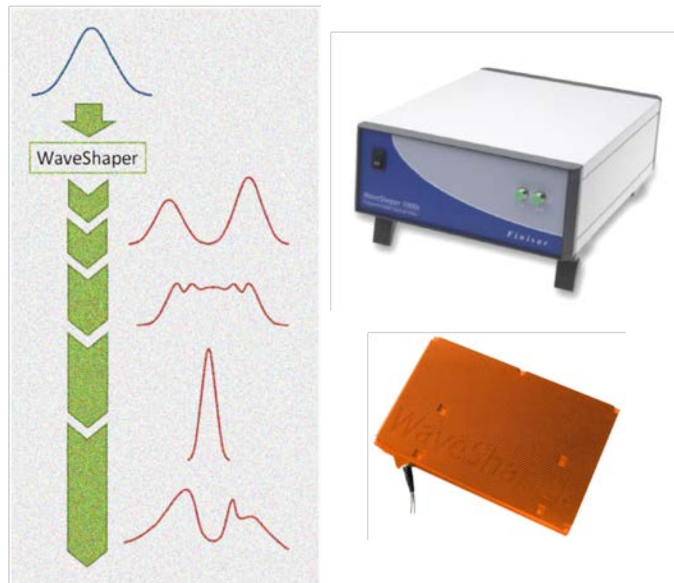

Figure 1: Top right: WaveShaper benchtop module. Bottom right: OEM version of the WaveShaper designed for embedding into third party equipment and instrumentation. Left: Representation of the range of possible output waveforms achievable with a WaveShaper.

The following are some typical examples of pulse shaping applications.

2.1 Material Processing

Material processing is one of the largest application areas for short pulsed lasers. Athermal ablation is achieved through the rapid delivery of energy from ultra-short pulses in the picosecond and femtosecond regime, which causes an exclusively non-linear process called optical breakdown [1]. This type of event is much more favorable than a diffuse, thermally driven one which causes unwanted collateral damage to the material under treatment. It has been shown that micromachining can be significantly improved by application of double pulses, where the temporal spacing and amplitude ratios of the two pulses can be optimized to significantly improve the ablation quality for Steel, Cu and Al [2].

2.2 Microscopy

Another example in biology and medicine is multi-photon optical microscopy, whereby nonlinear processes are harnessed to produce sharper images at greater physical depths and with less background scatter [3]. A crucial requirement of higher-order photon excitation processes is high intensity light for maximization of interaction rate. Here ultra-short laser pulses are favored due to high peak intensity and relatively low energy per pulse. Shorter pulses become increasingly susceptible to material dispersion in the imaging objects and so pulse shaping is used to compensate for this [4].

2.3 Quantum Mechanical Systems

In quantum physics, photo-induced transitions between energy levels of a quantum system are used to probe dynamics and implement quantum coherent control. Here the spectral phase and amplitude distribution of the incident beam can be carefully tailored to optimize the interaction. Pulse shaping techniques have been used in atomic and solid state architectures to explore a variety of quantum control schemes [5,6].

2.4 Fiber-optic communication

Modern telecommunication relies heavily on fiber-optic technology for transmitting and processing signals over globally distributed networks. The creation and control of arbitrarily shaped optical waveforms is quickly gaining interest in all-optical signal processing applications [7]. The ever-increasing demand for higher transmission bandwidth is placing more stringent requirements on network optimization. Fast signal pulses require a greater deal of attention in regards to material dispersion effects in transmission fibers [8].

3. Fourier-domain Pulse Shaping

Fourier-domain processing is a powerful theoretical framework which allows one to transform a short optical input pulse to an extensive range of possible output waveforms. A whole class of pulse shaping problems can therefore be reduced to a simple, common workspace (Figure 2).

In general we can begin with an input temporal waveform E(t), which is ideally fully characterized in terms of phase and amplitude beforehand. The user can then formulate an expression for the desired output A(t). The question is that of how one would transform E(t) into A(t) without having to apply rapidly varying operations on the time scale of the short pulses themselves. The solution is to move into the spectral domain which is essentially static and apply a spectral filter there before moving back into the time domain. By calculating the Fourier-transforms E'(f) and A'(f) of the input and output waveforms respectively, we can determine the appropriate relation A'(f)=F(f)E'(f) where F(f) is the filter to be applied. Note that the transformation is linear, placing a restriction on the possible range of output forms. That is the output can only ever contain spectral components which were originally present in the input. We can then easily calculate the filter with the expression F(f)=A'(f)/E'(f). The final step is to apply the inverse Fourier-transform on A'(f) to recover A(t).

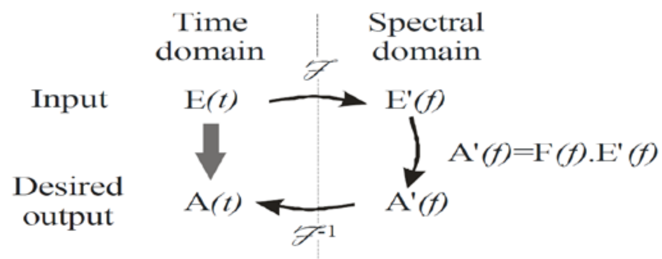

Figure 2: Diagrammatic representation of Fourier-domain pulse shaping.

Without loss of functionality, Fourier-domain Pulse Shaping reduces the complex task of applying a rapidly varying filter in the time domain, to using an essentially static filter in the spectral domain.

4. WaveShaper 1000/SP Operation

This section will explain how the WaveShaper 1000/SP family implements the core Liquid Crystal on Silicon (LCoS) Technology to bring the theory of the previous section into practice

The WaveShaper 1000/SP system essentially consists of the following components which are shown schematically in Figure 3:

- *Input/output fibers*. Polarization maintaining fibers are used in the WaveShaper/SP to ensure stable polarization states aligned with the principles axes of the optics. One fiber takes E(t) as input and the other A(t) as output.
- *Imaging optics* (not included in figure) *and conventional grating*. These are required to

perform the transformations from the time domain to the frequency domain and vice versa. Furthermore the imaging optics are configured to provide spatial divergence of the light in the vertical direction.
- *LCoS chip*. This is where the filter F(f) is implemented.
- A *cylindrical mirror* is used to relay the light between the different components listed above.

The LCoS chip consists of a reflective, two-dimensional array of pixels which can apply a controllable phase shift (modulo 2π) to incident light. The imaging optics and grating are arranged such that the input light is spectrally dispersed along the horizontal axis (spectral axis) of the LCoS array and spatially diverges along the vertical axis (deflection axis) (see Figure 3).

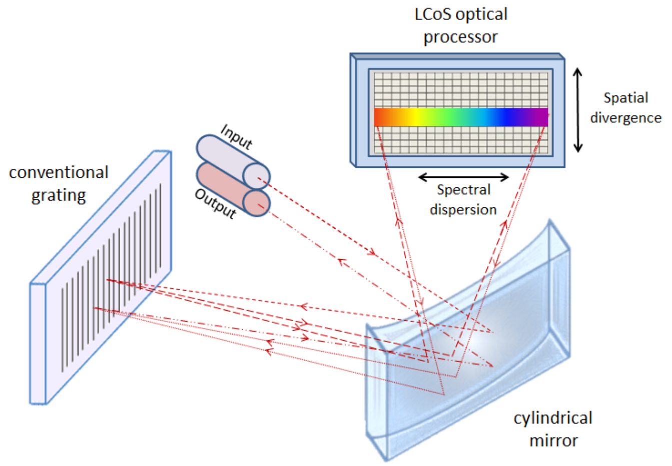

Figure 3: Schematic layout of the WaveShaper 1000/SP. Beam path is as follows (in order of causality): short dashed line is input and is relayed to the grating by the cylindrical mirror; long dashed line is the spectrally-dispersed light and is relayed to the LCoS chip; dotted line has been processed by the LCoS chip and is reconverging as it is relayed back to the grating; dotted-dashed line is the output and is relayed back to the output fiber. Note that the imaging optics which produce the vertical spatial dispersion have been omitted from this schematic.

The spectral axis is arranged such that each frequency component of the light can be addressed independently by individual columns of pixels. These columns have several functions. The first is to apply a phase ramp to shape the wave front of the reflected light, effectively controlling the vertical angle of the reflected light such that it is directed towards the output fiber. The phase ramp can have a constant phase added to it effectively producing a phase delay at the frequency of interest. Another function is to intentionally produce attenuation of amplitude by finely tuning the angle of reflection to partially decrease the strength of the coupling to the output fiber. In this way each column of pixels can be thought of as an element which can operate on a spectral component in two parameters: phase retardation, and amplitude attenuation.

A non-zero group delay is then introduced by having a non-constant spectral-phase relationship. This effectively alters the beam path length, as a function of wavelength, on its way to the output fiber. A consequent effect is a small degree of misalignment with the output fiber in the horizontal direction which will also cause some amplitude attenuation. This effect limits the maximum possible group delay.

The extent to which the technology accurately implements the principles of Fourier-domain pulse shaping is determined by several key system specifications. The temporal length of shaped pulses has a fundamental lower bound due to the maximum optical bandwidth of the system. A transform-limited pulse is one which has the *shortest* possible temporal length as limited by the available spectral bandwidth. On the other hand the *longest* workable pulse will be limited by the WaveShaper's optical transfer function (OTF). The OTF is essentially an expression of the narrowest feature addressable in the spectral domain. In the case of the WaveShaper/SP family of products this is approximately 0.1 nm, meaning that a pulse with spectral features comparable to (or smaller than) this width cannot be 'shaped' in the sense that it cannot be subdivided into independently workable spectral components.

Given the above constraints the WaveShaper will operate reliably and accurately in the femtosecond to picosecond pulse length regime.

5. Experimental Demonstrations

5.1 Double Pulse Burst Generation

Pulse shaping can be used to take a single pulse train and filter out a train of closely spaced double pulses. In an experiment a WaveShaper 1000S/SP 1.5 µm Single-Polarization Programmable Filter was used to achieve this by applying the double pulse filter to single pulses with a central frequency of 1545 nm and a width of 0.5 fs [9]. By tuning the parameters of the filter function the double pulse temporal spacing τ and relative amplitude ratio R could be varied. Figure 4 and Figure 5 show measurements, under variation of parameters τ and R respectively, of the temporal response. Note that the amplitudes of the pulses in Figure 5 show an approximate Gaussian decay centered around τ=0. This is due to the previously mentioned output fiber misalignment associated with applying a group delay.

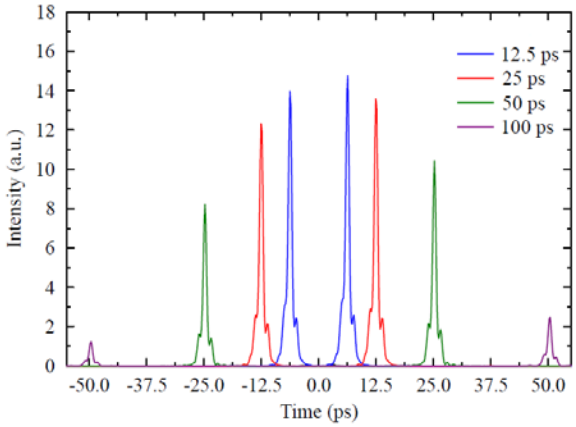

Figure 4: Experimental results showing the effect of varying delay time. R= 1 for each measurement.

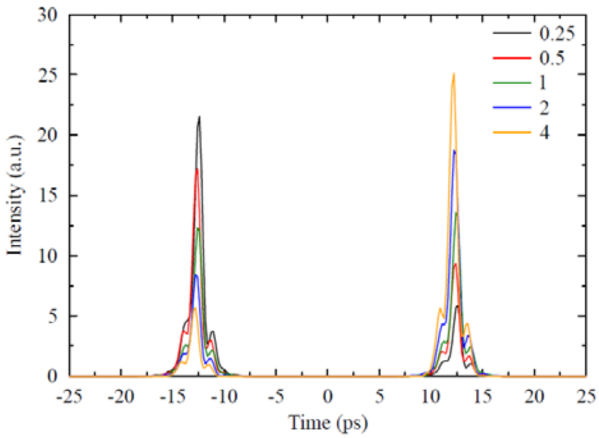

Figure 5: *Experimental results showing the effect of varying intensity ratio.* τ *= 25 ps for each measurement.*

5.2 Dispersion Compensation

The phase shifting functionality of the WaveShaper can be used to compensate for material dispersion by application of an equal and opposite group delay. In a proof of concept experiment a pulse train with 10 GHz repetition rate and 6.4 ps pulses, at 1550 nm, was sent through 1.2 km of standard single mode fiber (ITU-T G.654, resulting in a total dispersion of 20 ps/nm), before being input to the WaveShaper [8]. In separate trials the WaveShaper was configured to apply 0, -4, -8, -20 and -40 ps/nm dispersion to the pulse train. For each dispersion setting the temporal envelopes of the output pulses were measured with an optical autocorrelator (Figure 6). It can be seen that the pulse is optimally recompressed with the -20 ps/nm setting and further compressed with the -40 ps/nm setting.

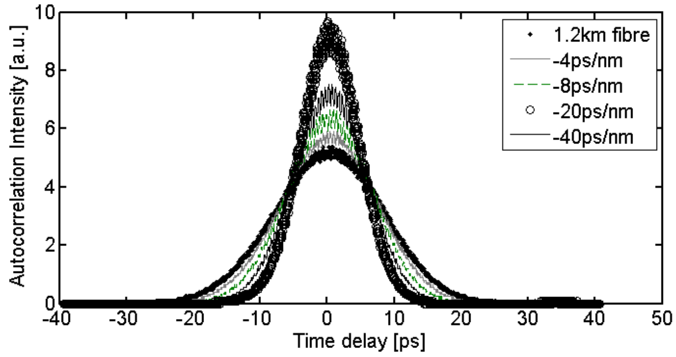

Figure 6: Autocorrelation traces of pulses after propagation over 1.2km of single mode fiber (producing a total of 20 ps/nm dispersion) and respective compensation by the WaveShaper with settings of -4, -8, -20 and -40 ps/nm.

5.3 Pulse Envelope Shaping

Optical pulses with a parabolic temporal intensity profiles are known to be attractive candidates for chirped pulse amplification (CPA) due to their enhanced linearity in chirp and ability to retain their intensity profile during propagation in gain media. It is therefore useful to produce high quality, transform limited parabolic pulses.

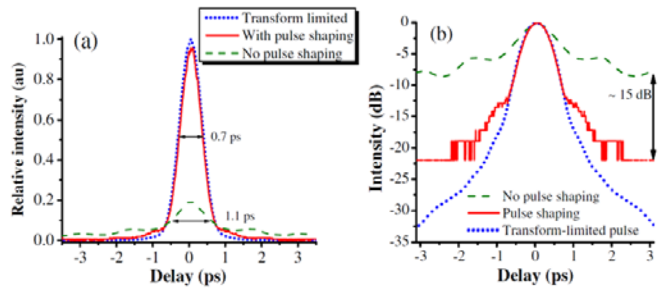

Figure 7: *Calculated and measured temporal intensity profiles on a (a) linear and (b) logarithmic scale of parabolic CPA pulses. The blue trace is a calculated transform limited parabolic pulse whereas the red and green traces are*

autocorrelation measurements in the presence and absence (respectively) of the WaveShaper pulse shaping scheme. These figures have been borrowed from [10].

In an experiment the WaveShaper was implemented in a feedback loop, along with a fiber based amplifier and frequency-resolved optical gating (FROG) for detection, in order to produce high quality, nearly-transform-limited, amplified parabolic pulses [10]. Figure 7 shows comparisons of the resulting temporal pulse profiles with and without pulse shaping, to the calculated profile for a transform limited version of the pulse. The results show a significant improvement for the scheme in which the pulse shaping was implemented using the WaveShaper.

6. Summary

Pulse shaping implies arbitrary control over the spectral amplitude and phase characteristics of a short optical pulse, and has a growing range and depth of application in industry and research. The WaveShaper 1000/SP series implements the principles of fourier-domain pulse shaping using LCoS technology as its core element. The WaveShaper 1000/SP is engineered to provide superior pulse shaping performance in the femtosecond to picosecond pulse length regime.

The Finisar range of single polarization WaveShapers comprises the WaveShaper 1000/SP 1.5 µm Single-Polarization Programmable Filter and the WaveShaper 1000/SP 1 µm Single-Polarization Programmable Filter (for 1 µm operation). For more information please contact your local WaveShaper sales representative or visit http://www.finisar.com/instruments.

7. References

[1] X. Liu, D. Du, G. Mourou, "Laser Ablation and Micromachining with Ultrashort Laser Pulses", Quantum Electronics, IEEE Journal of, Vol. 33, Issue 10 (1997) pp. 1706-1716

[2] R. Le Harzic, D. Breitling, S. Sommer, C. Föhl, K. Köhnig, F. Dausinger, E. Audouard, "Processing of Metals by Double Pulses with Short Laser Pulses", Biological and Medical Physics, Biomedical Engineering (2008) pp. 29-51

[3] A. Nimmerjahn, P. Theer, F. Helmchen, "Two-Photon Laser Scanning Microscopy", Optics Communications 188, 25 (2001) pp. 25-29

[4] D. Pestov, B. Xu, H. Li, M. Dantus, "Two-Photon Microscopy with Sub-8 fs Laser Pulses", in Frontiers in Optics, OSA Technical Digest (CD) (Optical Society of America, 2010), PDPA4

[5] D. Meschulach, Y. Silberberg, "Coherent Quantum Control of Multiphoton Transitions by Shaped Ultrashort Optical Pulses", Phys. Rev. A, Vol. 60, 2 (1999) pp.1287-1292

[6] A.P Heberle, J.J Baumberg, T. Kuhn, K. Köhler, "Femtosecond Pulse Shaping for Coherent Carrier Control", Physica B: Condense Matter, Vol. 272, Issues 1-4 (1999) pp. 360-362

[7] Finisar white paper: http://bit.ly/1GfbWSH

[8] Finisar white paper: http://bit.ly/13a1Swt

[9] Finisar white paper: http://bit.ly/1x4bC7W

[10] D. Nguyen, M. U. Piracha, P. J. Delfyett, "Transform-limited pulses for chirped-pulse amplification systems utilizing an active feedback pulse shaping technique enabling five time increase in peak power", Opt. Lett. 23, 4913-4915 (2012)

Finisar

1389 Moffett Park Drive
Sunnyvale, CA 94089
Tel.: +1-408-548-1000
Fax: +1-408-541-6138
waveshaper@finisar.com
http://www.finisar.com/instruments