

## APPLICATION NOTE

### Double Pulse Generation

#### Scope and Overview

High powered ultrashort laser pulses are used in many applications including high precision material ablation, laser induced breakdown spectroscopy, x-ray emission generation etc. It has been found that in many regimes that a double pulse configuration offers several advantages compared to a single pulse with equivalent power. This application note explores the application and creation of double pulses separated by 0 – 100 ps, i.e. those producible by the WaveShaper.

A step-by-step guide is provided to creating a double pulse \*.wsp filter using LabVIEW 8.5, however the guide can also be applied to other programming languages. The example vi provides control over the delay time between pulses and the intensity ratio of the first and second pulse. Experimental results demonstrate double pulses with varying delay time and intensity ratio.

#### Applicable Documents

- [WaveShaper Manual](#)
- [Latest LabVIEW Driver Set](#)

#### 1. Applications of Double Pulses

A major use for double pulses in lieu of single pulses can be found in laser ablation, where the presence of a pre-pulse can have a profound impact on the creation and dynamics of the generated plasma plume. The state of the plasma plume then greatly affects the absorption of the second pulse. This effect makes it valuable to researchers for its ability to produce noticeable enhancements in a number of important ultrashort pulse applications [1].

Double pulses have been shown to increase the ion yield and ion kinetic energy of ablated Si [2,3]; Al and B [4]. Such results are beneficial to thin film growth through the process of pulsed laser deposition (PLD) [5] and in ion implantation. Likewise, double pulses have been shown to intensify x-ray yield during ablation [6]. Improvements have

been found in  $K\alpha$  x-ray flashes from irradiated Cu and Ti [7]; and reported enhancement of X-ray pulse generation from irradiated distilled water jets [8]. Such improvements are applicable to laser induced breakdown spectroscopy (LIBS), and time-resolved x-ray diffraction. Interestingly, double pulses have led to an improved pump source for soft x-ray laser systems [9,10].

High-power ultrashort lasers used for micromachining have found significant enhancements in ablation yield, higher quality and/or smaller craters, etc from the use of double pulses. Pulse delay and intensity ratio provide tunable parameters in which to optimize a particular ablative process. Ultrashort double pulses separated by around 5 ps have been shown to significantly improve the ablation quality for Steel, Cu and Al, where higher ablation depths and smoother surfaces were observed [11]. Increased ablation efficiency for crystalline Si [12], as well as more efficient welding of glass substrates has been demonstrated [13]. Recently, numerical simulations have been carried out to investigate the complex plasma hydrodynamic mechanism behind the observed improvements, with results verifying experimental observation [14-16].

#### 2. Double Pulse Generation using the WaveShaper

With frequency dependent control over the attenuation and phase of an optical signal, the WaveShaper is capable of transforming a single input pulse into two output pulses. The delay time between these pulses can be up to 100 ps, and the relative intensities of each pulse can be arbitrarily specified.

Techniques taking advantage of double pulses often also require significantly high power beyond the maximum allowable power specification of the WaveShaper. For this reason, it may be necessary to apply the WaveShaper filtering before any optical signal amplification.

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The techniques outlined in the application note can be combined with a feedback loop designed to compensate linear and non-linear effects such as self-phase modulation that might arise as a result of amplification.

## 3. The Double Pulse Filter

With its fine control over attenuation and phase in the frequency domain, the WaveShaper is capable of performing pulse shaping.

### 3.1 Double Pulse Generating Filter Function

Consider an input pulse  $E_{in}(t)$  entering the WaveShaper. By choosing an appropriate filter, this pulse can be shaped to produce a desired output pulse  $E_{out}(t)$ . For prepulses, the desired output pulse is given by:

$$E_{out}(t) = \alpha\delta(t + \tau/2) + \beta\delta(t - \tau/2), \quad 1$$

where  $\tau$  is the duration between pulses, and  $\alpha$  and  $\beta$  are amplitude weightings. The WaveShaper performs filtering in the frequency domain, and can be described by the following:

$$\mathcal{F}\{E_{out}\} = F(f)\mathcal{F}\{E_{in}\}, \quad 2$$

where  $F(f)$  is the filter function. This function can be determined via a simple division:

$$F(f) = \frac{\mathcal{F}\{E_{out}\}}{\mathcal{F}\{E_{in}\}}. \quad 3$$

Most input pulses are sufficiently small enough that they can be approximated ideally as a delta input pulse i.e.  $E_{in}(t) = \delta(t)$  and  $\mathcal{F}\{E_{in}\} = 1$ , although using an experimental measurement of  $E_{in}(t)$  will produce more accurate results. The filter function is then simply the Fourier transform of the desired output pulse:

$$\begin{aligned} F(f) &= \mathcal{F}\{E_{out}\} \\ &= \mathcal{F}\{\alpha\delta(t + \tau/2) + \beta\delta(t - \tau/2)\} \\ &= \alpha\mathcal{F}\{\delta(t + \tau/2)\} + \beta\mathcal{F}\{\delta(t - \tau/2)\} \\ &= \alpha e^{i\pi f\tau} + \beta e^{-i\pi f\tau}. \end{aligned} \quad 4$$

An important double pulse parameter is the intensity ratio of the second pulse compared to the first pulse and is given by  $r = (\beta/\alpha)^2$ . Weightings  $\alpha$  and  $\beta$  can be set using Eq. 5 and Eq. 6 to produce this ratio with minimal loss:

$$\alpha = \frac{1}{\sqrt{r+1}}, \quad 5$$

$$\beta = 1 - \alpha. \quad 6$$

### 3.2 Converting to Attenuation and Phase

The filter function given by Eq. 4 must be converted to attenuation  $A(f)$  in dB and phase  $\phi(f)$  in radians, the units used in the WaveShaper Preset file (\*.wsp). This is done using the following equations:

$$A(f) = -20 \log_{10}(|F(f)|), \quad 7$$

$$\phi(f) = \arg(F(f)). \quad 8$$

## 4. Double Pulse Generation in LabVIEW

This example demonstrates how to use LabVIEW 8.5 and the WaveShaper driverset to create a \*.wsp double pulse generating filter.

The \*.wsp file format consists of 4 tab delimited columns: absolute frequency (THz), attenuation (dB), phase (Radians), and port number. More information about the \*.wsp file format can be found in the WaveShaper User Manual.

This instruction set makes use of the latest WaveShaper LabVIEW driver set which can be downloaded from the Finisar website (<http://www.finisar.com/waveshaper>). Make sure that this driver set has been downloaded and extracted into a convenient location. For more information about the driver set please consult the WaveShaper LabVIEW Driver Set Manual.

### 4.1 Step 1: Setting up LabVIEW

1. Open LabVIEW and create a new blank Virtual Instrument (VI).
2. Save your VI into a location of your choice.
3. Open up the WaveShaper LabVIEW driver set library file `wsapi.lvlib`. This library contains a set of VIs that provide

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access to all the functions available in the C API. While creating the double pulse WSP filter does not require using the API directly, it does make use of some additional VIs in the library used for writing the \*.wsp file to disk.

## 4.2 Step 2: Creating the Absolute Frequency Vector

This step creates the absolute frequency vector given by  $f$  in Eq. 4. In this example, the \*.wsp file is created for a C-band WaveShaper, and then is defined from 191.25 THz to 196.275 THz in 0.001 THz steps.

Navigate to the Block Diagram. One way to create the vector is with the use of a While loop. An example LabVIEW code is shown in Figure 1.

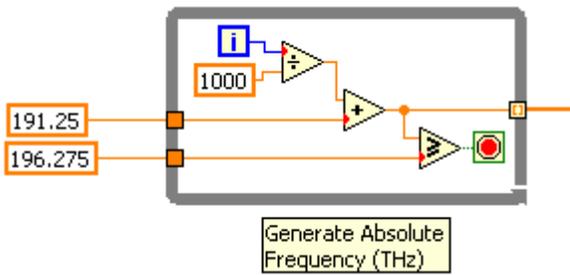


Figure 1: An example LabVIEW 'While Loop' used to create the Absolute Frequency vector.

## 4.3 Step 3: Creating the Double Pulse Filter

In this step, the double pulse filter from Eq. 4 is created. The LabVIEW Virtual Instrument in this example will use two numerical controls corresponding to the two double pulse parameters: the pulse delay  $\tau$ , and the intensity ratio  $r$ .

There are many ways to create the filter function, and an example LabVIEW code can be seen in Figure 2. In this example, the pulse delay is given in ps.

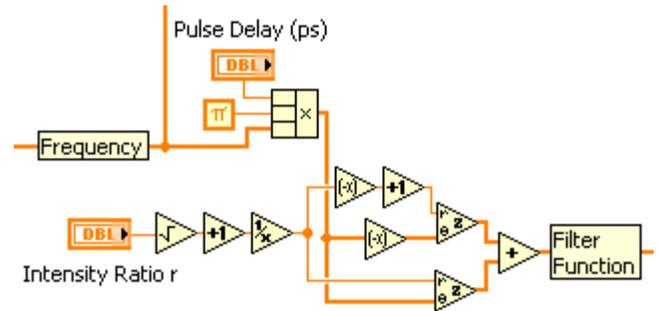


Figure 2: An example code to create the double pulse filter function.

## 4.4 Step 4: Converting to Attenuation and Phase

The filter function must be converted to attenuation and phase using Eq. 7 and Eq. 8 before the \*.wsp file can be created. In LabVIEW, this is best achieved by the code shown in Figure 3.

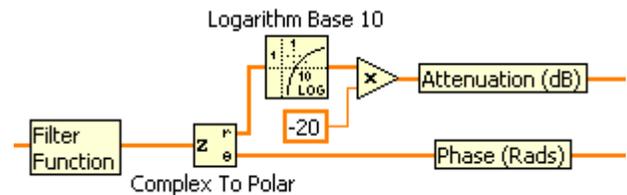


Figure 3: Converting the filter function to attenuation (dB) and phase (radians).

## 4.5 Step 5: Creating the \*.wsp File

The \*.wsp file is now ready to be constructed. Two VIs from the WaveShaper LabVIEW driver set, *BundleProfile.vi* and *CreateProfileString.vi* are used in this example to bundle and save the profile.

Firstly, *BundleProfile.vi* is used to combine the required profile data: absolute frequency, attenuation, phase and port number into a bundled profile, i.e. a single 2D array.

Secondly, the bundled profile is saved as a \*.wsp file using *CreateProfileString.vi* with a True Boolean wired to the 'Save File (False)' connector. A code snippet of these steps can be seen in Figure 4.

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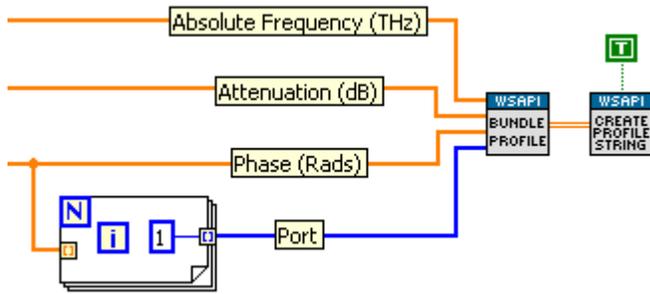


Figure 4: Bundling and saving the WSP profile into a \*.wsp file.

In this example, a port number of 1 is chosen for all frequencies.

## 4.6 Step 6: Running the VI

After saving the VI, select an appropriate delay time and intensity ratio. When the VI is executed, it will pop up a save \*.wsp file dialog window. Once this file is saved with a .wsp extension, it is ready to be loaded onto the WaveShaper using WaveManager.

## 5. Experimental Results

A WaveShaper 1000S was used to produce double pulses of various pulse delays and intensity ratios. The WaveShaper was filtered by an additional Gaussian envelope to simulate the input of 0.5 fs width laser pulses with a central frequency of 194 THz and the temporal response was measured using a LUNA Optical Vector Analyzer (OVA).

Figure 5 shows the temporal profiles of double pulses with  $r = 1$ , and various pulse delays. The intensity of the pulse corresponding to 0 ps delay time has been reduced by a factor of 4 in order to be comparable with the other results. The reasons behind this are discussed in Section 6.2. Figure 6 shows the temporal profiles of double pulses with  $\tau = 25$  ps and various intensity ratios. This set of results demonstrate that double pulses can be produced using the WaveShaper 1000S with fine control over the pulse delay time from 0 to 100 ps and control over the relative intensities of the first and second pulse.

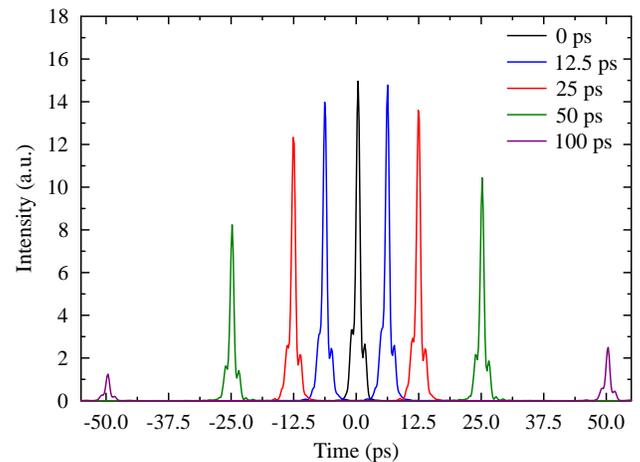


Figure 5: Experimental results showing the effect of varying delay time.  $r = 1$  for each measurement. The intensity of the central pulse has been reduced by a factor of 4.

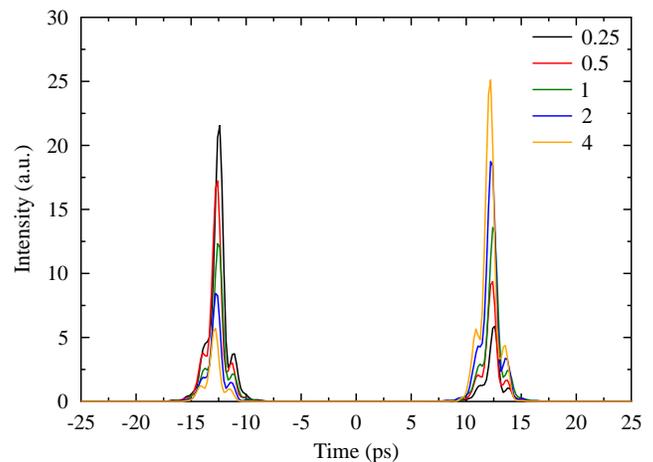


Figure 6: Experimental results showing the effect of varying intensity ratio.  $\tau = 25$  ps for each measurement.

## 6. Discussion

### 6.1 Attenuation due to Group Delay

The intensities of the peaks depicted in Figure 5 appear to follow a Gaussian envelope. This is caused by group delay induced attenuation, and illustrates the delay time limitations of the WaveShaper. In general, a WaveShaper inducing group delay on a signal also introduces an additional attenuation. Inducing a delay of more than

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$\pm 50$  ps is unpractical due to limitations inherently related to the internal optics of the WaveShaper.

## 6.2 Attenuation due to Splitting

Ideally, a double pulse filter should produce two pulses with intensities equal to half the power of the input pulse. However, when considering that the attenuation profile  $A(f)$  is greater than zero in some regions, some loss of power is expected. The double pulses depicted in Figure 5 show intensities of a quarter that of the input pulse, indicating half the power has been attenuated. Consider  $\alpha$  and  $\beta$  in Eq. 1. The following condition,  $\alpha^2 + \beta^2 = 1$ , must hold in order to conserve energy. However, maintaining this condition leads to negative attenuation for certain frequencies.

## 7. References

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1389 Moffett Park Drive  
Sunnyvale, CA 94089  
Tel.: +1-408-548-1000  
Fax: +1-408-541-6138  
wvashaper@finisar.com  
<http://www.finisar.com/optical-instrumentation>