# Experimental demonstration of an all-diffractive quasi-direct space-to-time pulse shaper by frequency-resolved optical gating


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**Abstract:** We experimentally characterized the pulse sequences generated by an all-diffractive quasi-direct space-to-time pulse shaper for the first time. This technique is promising in generating user-defined XUV and x-ray pulses.



**OCIS codes:** (320.5540) Pulse shaping; (320.7100) Ultrafast measurements; (050.1965) Diffractive lenses.


## 1. Introduction

The ability to synthesize user-defined optical waveforms is crucial in applications of biosciences, femtochemistry, and high-field physics. In a Fourier-transform (FT) pulse shaper, the output temporal waveform is associated with the spatial pattern on the Fourier plane via a Fourier-transform operation [1]. In contrast, a direct space-to-time (DST) pulse shaper directly maps the spatial pattern to the output temporal waveform, which is more appropriate in optical packet generation [2]. However, the strong absorption of refractive optics in XUV and x-ray range seriously limits the applications of typical FT and DST shapers in these spectral regions. We have proposed an all-diffractive quasi-DST (QDST) pulse shaper to solve this problem [3,4]. The optical setup consists of a circularly symmetric mask and a kinoform diffractive lens (DL) facing with each other [5]. The output optical waveform is colleted by a pinhole located at the focal point of the DL (for the carrier frequency of the pulse). The resulting temporal waveform is given by the convolution of an incident short pulse with the mask transmittance function expressed in the squared radial coordinate $r^2$ (thus a "quasi" DST process). Though the QDST pulse shaper has been used to realize fixed [6] and dynamic [7] spectral filtering, its shaping functionality in the time domain has not been experimentally demonstrated yet. In this letter, we report on second-harmonic generation frequency-resolved optical gating (SHG FROG) measurement of bursts of pulses generated by the aforementioned QDST shaper for the first time.

## 2. Theory

In the QDST pulse shaper, a circularly symmetric mask with complex transmittance $t(r)=q(\mu)$ is aligned in contact with a kinoform DL, where $\mu=r^2$ is the squared radial variable. The frequency-dependent focal length of the DL is given by $Z(\omega)=Z_0\omega/\omega_0$, where $\omega_0$ represents the carrier frequency of the input pulse. When an input plane wave of electric field $e_0(t)=\mathrm{Re}\{u_0(t)\exp(j\omega_0 t)\}$ impinges on the mask, the output temporal envelope collected by a small pinhole at an axial distance $z=Z(\omega_1)$ from the DL can be formulated by [3]:

$$u_{out}(t) = u_0(t) \otimes \left[q(t/\beta)\exp(j\delta\omega t)\right], \tag{1}$$

where $\beta=(2cZ_0)^{-1}$ is the conversion constant, and $\delta\omega=\omega_1-\omega_0$ is the frequency shift due the deviation of the pinhole position from $Z_0$. The output temporal window is $\Delta t\approx a^2\beta$, which can be tuned by changing the mask radius $a$ or the DL focal length $Z_0$. In the limit of very short input pulse, $u_0(t)\approx\delta_{Dirac}(t)$, the temporal waveform of the output pulse is simply a scaled version of the mask transmittance function in the squared radial variable $\mu$. In practice, the finite extension of pinhole, the spatially nonuniform input irradiance upon the mask, and the observable dependence of the DL efficiency on the phase steps in the radial direction can distort the output temporal waveform (say introducing a roll-off envelope for the generated burst of pulses). This problem can be mitigated by expanding the input beam size and substituting the binary amplitude mask by an optimized Fresnel phase hologram [4].

## 3. Experimental results

The experimental setup consists of a femtosecond laser, the QDST pulse shaper, and the SHG FROG system. The laser system is a Ti:Sapphire multi-pass amplifier (femtopower pro, femtolasers), producing 1 kHz, 30 fs (FWHM), pulses centered at 795 nm wavelength. The beam diameter (full width at $e^{-2}$) of the laser amplifier was ~15 mm, and was expanded by a factor of 4 via a reflective beam expander. The QDST pulse shaper is composed of a circularly symmetric binary amplitude mask attached to a DL. Each mask used in our experiments was made by photolithography with direct laser writing on a chrome photomask. Mask M3 and mask M4 were designed to produce three and four isolated pulses with unequal and equal temporal spacing, respectively. The DL with $Z_0$=150 mm ($\beta$=111 fs/mm$^2$) was supported by the ONT team of the Fern Universität Hagen in Germany by means of a lithography procedure. The home-made SHG FROG system consists of a non-collinear Michelson interferometer, a 10-μm-thick BBO crystal, and a spectrometer (USB 2000+, Ocean Optics). The FROG traces were obtained by recording a series of second-harmonic (SH) power spectra at different delays, then processed by a commercial software (FROG3, Femtosoft) to retrieve the complex fields.

Fig. 1a and 1b illustrate the measured and retrieved FROG traces with a FROG error of 1.37%, respectively; when mask M4 and a pinhole of 50 μm in diameter were used. The traces exhibit clear modulation along delay and wavelength axes, which is the signature of pulse sequences. The retrieved temporal intensity (Fig. 1c, solid) exhibits four pulses centered at [0, 298, 490, 723] (fs), consistent with the simulated result (Fig. 1c, dashed). The stronger decay of the retrieved pulse amplitudes is mainly attributed to the spatially nonuniform irradiance across the mask. The retrieved power spectrum (Fig. 1d, solid) also agrees well with the simulation (Fig. 1d, dashed) in terms of the positions of the spectral peaks. The retrieved phases (Fig. 1c and 1d, dash-dot) are subject to higher error, for SHG FROG is unable to uniquely determine the relative phases of well-separated pulses [8]. The measurement results of another pulse sequence produced by mask M3 and a pinhole of 20 μm in diameter are shown in Fig. 2. The retrieved temporal intensity (Fig. 2a, solid) correctly shows three isolated pulses, while the unequal spacing between adjacent pulses results in more complicated spectrum and higher measurement error.

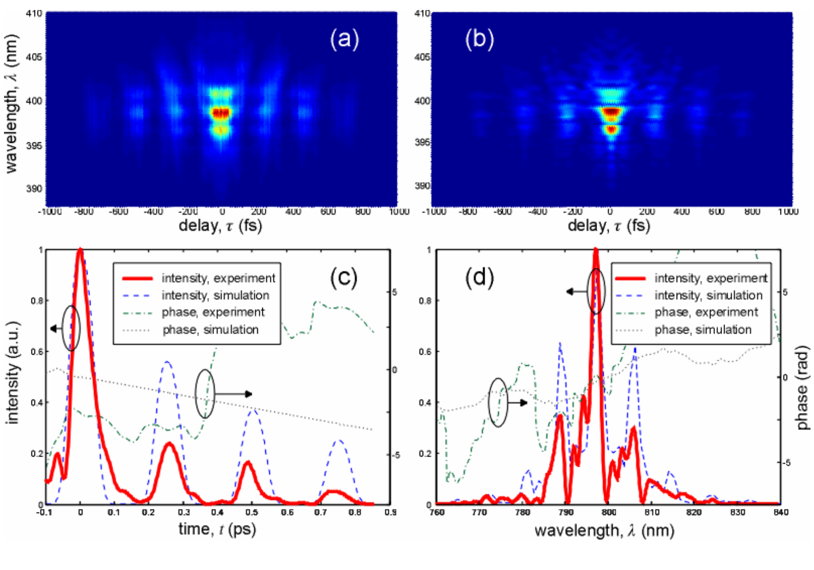


Fig. 1. (a) Measured, and (b) retrieved FROG traces when using mask M4 and a pinhole of 50 μm in diameter. The measured and simulated intensity and phase curves in the (c) time, and (d) frequency domains, respectively.

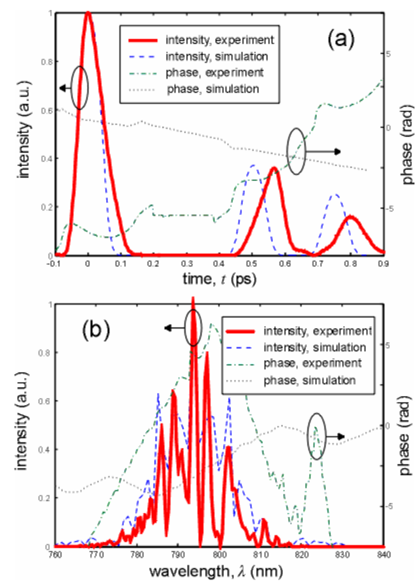


Fig. 2. The measured and simulated intensity and phase curves in the (a) time, and (b) frequency domains, respectively; when using mask M3 and a pinhole of 20 μm in diameter.

## 4. Conclusions

We experimentally measured the complex fields of pulse sequences generated by an all-diffractive DQST pulse shaper for the first time. This technique is promising in generating user-defined temporal waveforms in XUV and x-ray ranges. This work was supported by the Spanish Ministerio de Educación y Ciencia (MEC) through Consolider Programme SAUUL CSD2007-00013 and the project FIS2010-15746. It was also supported by "Convenio UJI-Bancaixa" under grant INV-2010-42 and National Science Council of Taiwan under grant 97-2221-E-007-028-MY3.

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