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# Tailoring octave-spanning ultrashort laser pulses using multiple prisms

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**Abstract:** We demonstrate a novel pulse shaper in which an incident laser beam is angularly dispersed by a first prism, and then it is split into separate beams using multiple prisms. Since this new pulse shaper offers independent control of the amplitude and phase of the separate beams, it can produce pulses having desired temporal shapes. Furthermore, it imposes a significant amount of negative group delay dispersion (GDD) over an octave spectrum near visible, which can compensate for a positive GDD accumulated in the process of spectral broadening. Consequently, single-cycle or few-cycle laser pulses can be produced without the need for chirped mirrors.



## 1. Introduction

Tailoring the waveform of a laser pulse offers various ways to manipulate light-matter interactions. For example, a tailored femtosecond laser pulse enhances coherent control of chemical processes [1,2] and controls atomic excitation by manipulating the shape of quantum wavefunctions [3]. It can also manipulate the electron dynamics in strong field processes such as Raman transition, multi-photon transition, and high-harmonic generation [4–6]. As a result, tailoring the waveform of the laser pulse would open new opportunities for various research fields [7–12].

To shape ultrashort laser pulses spanning an octave, several approaches have been employed. An acousto-optic programmable dispersive filters (AOPDF) has become very popular due to easy co-linear alignment and simple configuration [13,14]. It has been successfully used to shape few-cycle pulses produced in a hollow-core fiber [15]. However, it has low throughput (<10%) for an octave-spanning bandwidth because the transmission efficiency of an acousto-optic device drops as the bandwidth increases [16].

There are other approaches, so-called 4-*f* pulse shapers, in which an incident laser beam is spatially separated due to angular dispersion imposed by gratings or prisms. Since its spectral components are separated in space, the amplitude and the phase of the spectral components can be manipulated using a spatial light modulator [17–20]. Then, the spectral components of the laser beam are combined back to form a tailored laser field. This method has been effectively applied to shape few- or single-cycle pulses [21–23]. However, it also has some limitations.

In the case of the grating-based pulse shaper, the transmission efficiencies are typically lower than 50% for an octave-spanning bandwidth due to the presence of grating pairs and spatial light modulators. Furthermore, it is challenging to be used for the bandwidth exceeding one octave due to the overlap of neighboring diffraction orders [24]. On the other hand, the prism-based pulse shaper has high transmittance in a broad spectral range [24–26]. However, it imposes a huge amount of positive group delay dispersion (GDD) when a broadband laser pulse is used. This is a serious problem because broadband laser pulses are commonly obtained through post-compression techniques in which a significant amount of positive GDD is accumulated. Thus, the use of the prism compressor worsens the dispersion condition.

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Recently, it has been demonstrated that an octave-spanning ultrashort laser pulse can be produced using a pulse shaper so-called 'waveform synthesizer' [27–29]. In this approach, a laser pulse that has an octave spectrum was obtained using a hollow-core fiber. The laser beam was split into multiple beams with different colors using dichroic beam splitters. Thus, it was possible to manipulate the amplitude and phase of the separate beams. Also, the use of the chirped mirrors that are specially designed compensated for the GDDs of the separate beams. The generation of an octave-spanning single-cycle laser pulse has been successfully demonstrated using the waveform synthesizer. However, this scheme requires specially designed optical elements (dichroic mirrors and chirped mirrors) with fixed parameters, and thus it is less flexible.

In this work, we introduce a novel prism-based pulse shaper that supports an octave-spanning spectrum. The pulse shaper consists of multiple prisms by which an input laser beam is split into four beams having different wavelengths. This four-channel pulse shaper is capable of tailoring pulses having desired temporal shapes by controlling the amplitude and phase of the four independent spectral components and the relative delays between them. The new pulse shaper inherently yields a huge amount of negative GDD, which can compensate for the positive GDD accumulated in the process of spectral broadening. Thus, it can be used as a broadband pulse compressor without using additional chirped mirrors. Our experiments confirm the generation of pulses having various temporal shapes, including a 3.5-fs near-single-cycle laser pulse and a double pulse.

## 2. Pulse compressor using multiple prisms

In order to attain a pulse duration close to the transform limit, a laser pulse must have a linear spectral phase. The linear spectral phase over the entire spectrum is also a critical requirement for pulse shaping because it is achieved by slightly altering the linear spectral phase. However, a broadband laser pulse can have a huge amount of positive GDD that is accumulated in the process of spectral broadening. Unfortunately, the GDD of air and glass materials is also positive. The laser pulse gains an additional positive second-order phase as it propagates. Thus, special consideration is required to remove the second-order phase of the laser pulse.

There are a few approaches for compensation of the second-order phase of the laser pulse. One common method is to use chirped mirrors that can be designed to provide negative GDD [30–32]. They provide around a few ten or a few hundred $fs^2$ of negative GDD near visible wavelengths depending on the bandwidth of the laser pulse. Therefore, multiple chirped mirrors are often used to achieve a sufficient amount of negative GDD.

Grating pair and prism pair compressors can also be used, which enable continuous control of the amount of negative GDD by adjusting the separation distance of the grating or the prism pair. However, the grating pair compressor designed for a broad spectral range typically has low throughput. While the prism pair compressor offers higher throughput, they provide negative GDD only for a narrow spectral range.

It is worth investigating why the prism pair compressor yields negative GDD only for a limited spectral range. To address this issue, we calculated the amount of GDD introduced by a prism pair, as shown in Fig. 1(a). An incident laser beam is spread depending on its wavelength due to the angular dispersion imposed by the first prism. Thus, the laser beam takes a different optical path depending on the wavelength. The angular dispersion is compensated by the second prism. Then, the end mirror reflects back the laser beam along the same path. Since the optical path of the red component is shorter than that of the blue component, negative GDD can be achieved. Unfortunately, this simple estimation is not valid for a broad spectral range.

For broadband laser pulses, the second prism should be very large to accommodate the angularly dispersed laser beam. When the separation between the two prisms is 700 mm, the second prism with an apex angle of 69.1 degrees and a height of 29 mm is required. Then,

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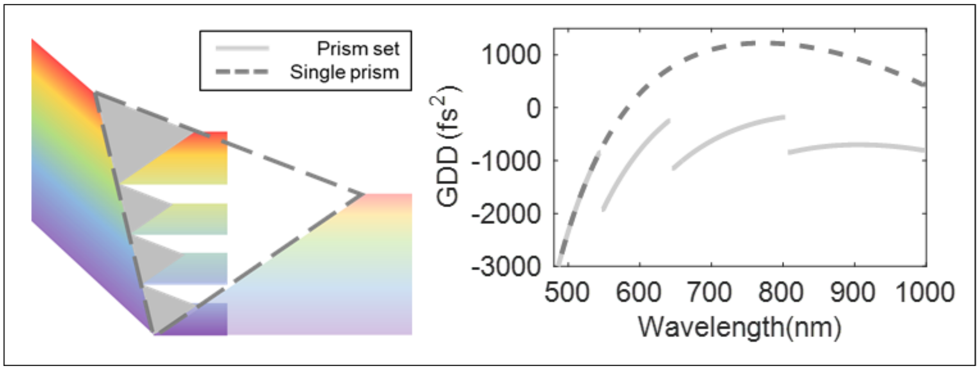


**Fig. 1.** Comparison of the multi-prism compressor with the conventional prism compressor. (a) a single second prism (dashed line) and multiple second prisms (gray triangles). (b) GDD of the conventional prism compressor that uses a pair of prisms (dashed line), and GDD of the multi-prism compressor (solid light gray line).

the long wavelength components pass through a thick part of the second prism, as shown in Fig. 1(a). As the spectral bandwidth of the laser pulse reaches an octave, this conventional prism compressor imposes a positive GDD for the wavelength longer than 582 nm, as shown in Fig. 1(b). Therefore, the conventional prism pair compressor cannot be used for a broadband laser pulse that already has a positive GDD accumulated in the process of spectral broadening.

Our multi-prism pulse shaper can provide negative GDD for a broad spectral range. We used a set of small prisms instead of a single big prism at the position of the second prism. We found that four small prisms are sufficient to support an octave-spanning spectrum that can produce a near-single-cycle pulse. This new approach can impose negative GDD for a broad spectral range, as shown in Fig. 1(b). The amount of the GDD of the four channels can be adjusted by changing the distance between the first prism and the multiple second prisms. The size of the second prisms can also be adjusted so that they have a similar amount of GDD over the spectral region of interest. We assumed that all prisms are made of fused silica. The height of the first channel (807–995 nm) prism is 12 mm. The height of the second (645–803 nm), third (547–643 nm), and fourth (482–545 nm) prism is 7 mm. Therefore, the positive GDD over a broad spectral range can be compensated using the multi-prism compressor.

## 3. Setup of the pulse shaper and measurement using TIPTOE technique

A schematic diagram of the new prism pulse shaper is shown in Fig. 2. For experimental demonstration, we used a Ti:sapphire laser (Femtolasers, Femtopower X CEP4) that produces laser pulses with a duration of 30 fs at the repetition rate of 1 kHz. The laser beam with an energy of 1.3 mJ at the central wavelength of 800 nm was used. The spectrum of the laser pulse was broadened using a stretched hollow core fiber. One side of the fiber was under vacuum, and the other side of the fiber was filled with neon gas (3.7 bar). A broad spectrum that covers from 500 nm to 950 nm was obtained, as shown in Fig. 3(a), which can support a near single-cycle pulse.

The broadband laser beam was guided to the multi-prism pulse shaper. In the multi-prism pulse shaper, the laser beam was focused using a cylindrical focusing mirror with a focal length of $f$ = 1.15 m which corresponds to the distance between the spherical focusing mirror and the end mirrors placed at the Fourier plane, as shown in Fig. 2. The first fused silica prism imposes an angular dispersion on the incident laser beam. Then, the laser beam was separated by multiple fused silica prisms, as shown in Fig. 1(b). The amplitude and phase of the laser beam in each

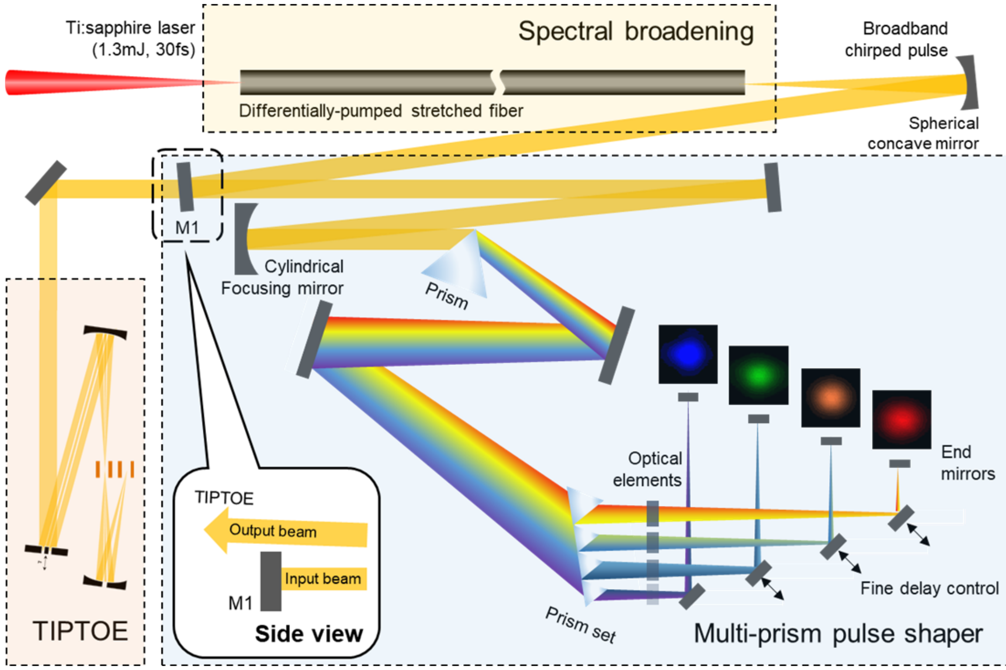


**Fig. 2.** Experiment setup for pulse shaping experiments. Laser pulses are generated using a Ti:sapphire laser. The laser pulses propagate through the spectral broadening system (yellow area), the multi-prism pulse shaper (blue area), and the pulse characterization device (TIPTOE) setup (red area). The beam profiles of the focused beam after passing through each channel are shown above the end mirrors. The side view of the mirror M1 is shown in the inset. The output beam tilted by the end mirrors passes over the mirror M1 and is guided to the TIPTOE setup.

channel were individually controlled by adjusting the length of the beam path after the second prism using the piezo actuators, as shown in Fig. 2. When the laser beams was reflected on the end mirrors, the laser beam was slightly tilted up. The reflected laser beams went back through the prisms, but it passed over the mirror M1, as shown in the inset of Fig. 2. Finally, the combined laser pulse was sent to a pulse characterization device called tunneling ionization with a perturbation of the time-domain observation of an electric field (TIPTOE).

The distance between the first prism and a group of the second prisms was set to 70 cm, which yielded an average negative GDD of 700 $fs^2$. The far-field image of each laser beam was individually measured after passing through the pulse shaper. They exhibit symmetrical Gaussian shapes, as shown in Fig. 2. The throughput of the setup was 49.6%. The energy loss in this setup is mainly due to the low reflectance of the aluminum (85.0%) and the silver (95.5%) mirrors. These mirrors can easily be replaced by broadband dielectric mirrors. Then, the throughput would be increased to 86.1%. This is a significantly higher transmittance than that of a grating compressor which typically yields less than 50%, even for a narrower bandwidth [33–35].

The temporal profiles of the laser pulses were measured using the TIPTOE technique. TIPTOE is a temporal characterization method that utilizes the extreme nonlinearity of ionization [36,37]. Sub-cycle ionization of an intense laser field is used as a fast temporal gate, enabling temporal characterization in the time domain. When a weak replica pulse of the input pulse is superposed at the focus, the ionization yield is modulated. The temporal profile of the laser pulse is found from the ionization yield modulation measured as a function of the time delay between the two laser pulses (incident and replica pulses) [38]. It has been successfully applied for various laser

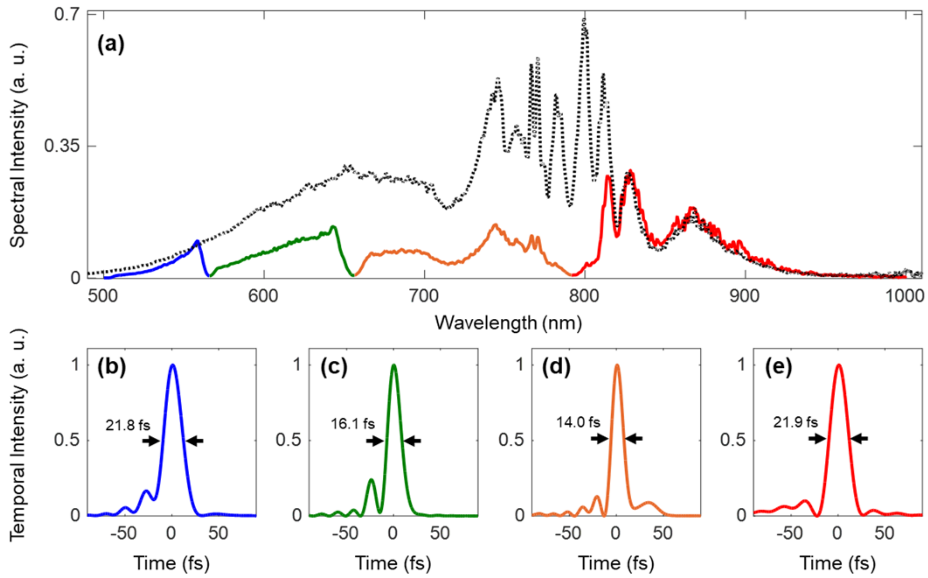


**Fig. 3.** Spectral and temporal intensity profiles of the laser pulse in individual channels. (a) A spectrum measured before the pulse shaper (dotted line) and spectra of Ch. 1 (red), Ch. 2 (orange), Ch. 3 (green), and Ch. 4 (blue) laser beams measured by a grating-based spectrometer (Ocean Optics, USB4000). (b-e) Intensity profiles of Ch. 4 (b), Ch. 3 (c), Ch. 2 (d), and Ch. 1 (e) laser beams measured by the TIPTOE technique. The full width at half-maximum (FWHM) pulse durations are shown in the figure.

pulses such as single-cycle, few-cycle, and long pulses for a broad wavelength range from UV to IR, and even for two-color laser pulses [39–41].

## 4. Results and discussions

We measured the laser pulses produced through the individual beam paths. Their spectrum and temporal intensity profiles are plotted in Fig. 3. The full width at half-maximum (FWHM) temporal durations of the pulses are 21.9 fs (Ch. 1, red), 14.0 fs (Ch. 2, orange), 16.1 fs (Ch. 3, green), and 21.8 fs (Ch. 4, blue). All the pulses have weak pre-pulses due to the remaining third-order dispersion (TOD), as shown in Fig. 1(b). The slopes shown in the GDD plot correspond to TOD. Therefore, precise control over the relative phase of the pulses is essential to minimize the formation of the pre and post pulses.

Different temporal profiles of the laser pulse were achieved by carefully selecting the appropriate relative phase of the four distinct laser pulses. Figure 4 displays examples of the tailored pulse profiles. A double pulse with a delay of 46 fs is shown in Fig. 4(a). The delay of the double pulse could be continuously controlled. Therefore, it will be useful for pump-probe experiments. A near single-cycle pulse is also shown in Fig. 4(b), which is made by adding all four laser beams with the minimum phase deviation. The FWHM temporal duration of the pulse is 3.56 fs, which corresponds to 1.5 optical cycles, while the transform-limited duration is 3.55 fs. Therefore, our multi-prism compressor offers an efficient way to achieve the near-transform-limited duration pulse. The intensity of the pre-and post-pulses is only 9.7% of the main pulse intensity. The main pulse contains approximately 80% of the total pulse energy.

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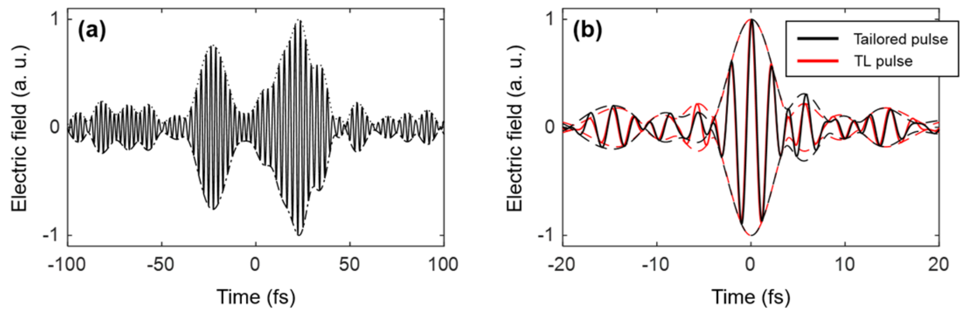


**Fig. 4.** Laser pulses produced using the multi-prism pulse shaper. The tailored laser pulses, such as (a) a double pulse and (b) a compressed pulse are shown. The compressed one (black line) is compared with the transform-limited one (red line). The FWHM duration of the compressed one is 3.56 fs (1.5 optical cycles), which is close to that of transform-limited one, 3.55 fs.

## 5. Conclusion

We demonstrated that broadband laser pulses could be tailored using the multi-prism pulse shaper. The new pulse shaper consists of multiple prisms which split an incident beam into multiple channels. Furthermore, this arrangement yields a huge amount (700 $fs^2$) of negative GDD, enabling the formation of a near-single-cycle laser pulse without having chirped mirrors. We showed that pulses having desired temporal shapes such as double pulses and a near single-cycle pulse can be generated.

The conventional pulse shapers that use grating or prism pair could be applied only for a limited bandwidth due to their low efficiency and unwanted positive GDD [16,24–26]. The waveform synthesizers can be successfully applied for a broadband laser pulse, but it requires a complicated design of chirped mirrors for different channels [27–29,42,43]. Our approach is more flexible because the amount of negative GDD can be adjusted by changing the distance between the first and the second set of prisms. Thus, the multi-prism compressor will be useful not only for compensating the positive GDD developed through spectral broadening but also for tailoring the temporal profile of the laser pulse.

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**Data Availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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