Generation of extended filaments of femtosecond pulses in air by use of a single-step phase plate

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We experimentally demonstrate that by use of a phase plate that is placed between an adjustable aperture and a focusing lens, the length of the filament can be dramatically extended in air with a femtosecond laser pulse. In addition, the far-field beam profile captured after the filament indicates that the supercontinuum is strongly confined on axis, and a single filament appears to be attainable at relatively high input pulse power when the phase plate is used.

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Since its discovery by Braun et al. [1], femtosecond laser filamentation in gas has attracted a lot of interest for its potential application in remote sensing [2], lightning control [3–5], generation of few-cycle pulses [6], coherent light conversion such as third-harmonic generation [7, 8], and so on. From the fundamental point of view, the physical mechanism of femtosecond filamentation is understood as a dynamic balance between the self-focusing given rise by the optical Kerr effect and the diffraction as well as the plasma defocusing [9–12]. As the pulse propagates, an energy reservoir, which contains the majority of the pulse energy, surrounds and continuously supplies energy to the filament core, compensating for the energy loss due to diffraction and heating inside the filament. For this reason, the intense ultrafast pulses can be transferred to a remote place without significantly losing its peak intensity. For many practical applications, such as the lightning control and remote sensing, generation of long filaments is of great importance [2–5, 13]. One simple and intuitive way to extend the filament length seems to be the employment of a loosely focused input beam; however, multiple filaments, which are initiated by hot spots inside the beam, can be easily produced before the pulse reaches its geometric focal spot [14]. Recently, another promising method to extend the filament with a Bessel beam has been reported that could impressively increase the length of filament by around 2.5 times [14, 15]. In this Letter, we demonstrate that by use of a phase plate for modifying the input pulse wave front, we successfully increase the length of the filament. In addition, we find that this technique may be useful for suppressing multiple filamentation at a relatively high input-pulse power, promoting the formation of a single filament.

The experiment was carried out with an ~40 fs (FWHM), ~795 nm Ti:sapphire laser (Legend Elite-Duo, Coherent, Inc.) operated at a repetition rate of 1 kHz and a pulse energy of ~6.0 mJ. The beam diameter was measured to be ~9.7 mm (1/e2). After passing through an adjustable annular aperture, the beam is focused by a fused-silica lens with a focal length of 0.5 m, which is placed ~50 mm after the aperture. To modify the waveform of the beam, a phase plate is employed that is placed ~5 mm before the lens. The size of the phase plate, which is made of BK7 glass, is 16 × 16 × 1.8 mm3. In particular, the center part of the phase plate is thinned by wet etching to produce a π-phase shift of the 800 nm wave. The phase-shifted area has a circular shape with a diameter of 5 mm. With this phase plate, it is possible to create a dark field at the geometric focus because of the destructive interference between the beams passing through the inner circle and the outer ring parts. For an ideal Gaussian beam, when the aperture opening is 8 mm in our experiment, the designed phase plate can ensure a full attenuation of the laser intensity at the geometric focus. On the other hand, we have made comparative study on the filamentation with and without phase plate, respectively. In the latter case, we used a piece of BK7 glass substrate with the same thickness as the phase plate to balance the waveform distortion induced by the nonlinear optical propagation taking place inside the phase plate. Images of both the plasma channel and the far-field beam profiles of the filaments are captured by a digital camera (Nikon, D40) and the colors are real.

First, as shown in Fig. 1, we compare the plasma channels and the corresponding far-field laser spots...
after filamentation under different aperture sizes with and without the use of the phase plate. The propagation direction of the femtosecond pulses is from left to right in Fig. 1. When no phase plate is employed, increase of the aperture size enhances the visible brightness of the filament and the filament length, while the starting point of the filament changes. When the aperture size is 4 mm, the formed filament reaches its maximal length of around 120 mm and the plasma channel starts much earlier as compared with the case when the aperture size is adjusted to 12 mm, as can be seen in Figs. 1(a) and 1(b). Also, it can be seen from Fig. 1(b) that the plasma channel is quite bright but the filament length is only around 60 mm when the aperture size is 12 mm with an input pulse energy of 5.96 mJ. Similar results have been observed recently by Daigle et al. [16]. After the phase plate is employed, the plasma channel is nearly the same when the aperture size is smaller than or equal to 5 mm, which is the diameter of the phase-shifted circular area, as evidenced by Fig. 1(c). However, the length of the filament reaches ~190 mm when the aperture is 12 mm, as shown in Fig. 1(d). As compared with the case of without using the phase plate, the filament length is increased by more than three times. This might be understood that as the wavefront on the phase plate is split into two parts with different phases, namely, the central and the peripheral parts, which are of different radii of curvature after propagating nonlinearly (because of the high peak power/intensity) through the phase plate and the lens, they will naturally self-focus into two filaments along the axis. Consequently, the filament is significantly extended as compared to the case without the use of the phase plate. In addition, far-field beam profiles of the filaments captured with a digital camera (Nikon, D40) are also shown in Fig. 1. Apparently, when no phase plate is used and the input energy is high, the super-continuum in Fig. 1(b) shows a weak central beam spot surrounded by an intense ring structure. On the contrary, after the phase plate is employed, the super-continuum is still well confined axially, even when the full energy is injected. In addition, as observed in the experiment, the beam-pointing fluctuation is greatly improved when the phase plate is used, which is consistent with the report by Pfeifer et al. [17].

Next, we build a simple imaging system mounted on a motorized translation stage to observe the beam profiles in the filaments formed at different pulse energies, as shown in Fig. 2. The beam spot close to the first wedge on the motorized translation stage is clearly imaged onto a CCD. After capturing each frame of image, we carefully examine the front surface of the wedge to make sure it is not damaged by the filament. To exclude the influence of reflected light (the reflected incident beam and the weak white light generated inside W3) by the back (not polished) surface of the wedge, we use dampers and slits to make sure only the reflected light by the front surface can pass through. To avoid the average effect of pulse-to-pulse fluctuation, the exposure time of the CCD is fixed at ~1 ms to ensure a single-shot image. The laser spots at ~2 cm before the geometrical focal position, where the strongest fluorescence can be observed without the phase plate, are captured with and without the phase plate, respectively, as shown in Figs. 3(a) and 3(b). It can be clearly seen that multiple filaments start to appear when the aperture size is 6 mm with input pulse energy of 3.76 mJ in Fig. 3(a). Further increase of the aperture size results in an increased number of the filaments. This may be explained as the fact that the number of filaments almost linearly increases with the ratio between the input power and threshold power of filamentation [10,18]. However, when the phase plate is employed, the beam profile of the filament always appears to be a single filament, even with the injection of the full pulse energy, as shown by Fig. 3(b). Therefore, the use of the phase plate can not only increase the length of the filament but also effectively increase the energy threshold for multiple filamentation.

Fig. 1. (Color online) Filament profiles and the corresponding far-field laser spots. (a), (b) without the phase plate and (c), (d) with the phase plate when the aperture sizes are 4 mm and 12 mm, respectively. The exposure time of the digital camera for capturing plasma channels and far-field beam spots are 15 s and 1/250 s, respectively. The zero of the longitudinal axis represents the position of geometrical focal spot of the lens.

Fig. 2. (Color online) Experimental setup for measuring the beam-spot profiles inside the filaments. W1, W2, and W3 are three wedges made of BK7 glass.
In conclusion, we demonstrated the extension of filamentation in air with a phase plate placed before the focal lens, which will be important for applications such as remote sensing and lightning control and so on. In addition, single filamentation can be obtained at large input laser energies by use of the phase plate.

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Fig. 3. (Color online) Beam-spot profiles captured 2 cm before the geometrical focus inside the filaments with different aperture sizes (a) without and (b) with the phase plate. Aperture sizes and the corresponding pulse energies after the aperture are given in each frame.

References