Circular phase mask for control and stabilization of single optical filaments

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Received February 21, 2006; revised May 17, 2006; accepted May 18, 2006;
posted May 22, 2006 (Doc. ID 68241); published July 10, 2006

We experimentally demonstrate an efficient way to control and stabilize single optical filaments initiated by ultrashort laser pulses in a rare gas medium. This is done by the application of a stationary two-dimensional phase mask to the laser beam prior to focusing. Simple circular phase-step patterns of a given radius and relative phase are sufficient to stabilize the pointing of the filament output and to optimize the spectral bandwidth of the light without any resulting loss of input laser power. © 2006 Optical Society of America

OCIS codes: 190.2620, 190.7110, 320.5540.

It has been shown recently that the output of single optical filaments can be used for femtosecond pulse compression below 6 fs for 800 nm laser light, well into the few-cycle regime.[1,2] Optical filamentation occurs when high-intensity laser pulses are focused into a medium exhibiting a positive nonlinear refractive index. If the intensity is high enough, a steady-state propagation can be obtained where the diameter of the laser beam stays approximately constant over a large number of Rayleigh lengths.[3,4] This steady-state condition is the result of a dynamical balance between diffraction and ionization-induced defocusing on the one hand and refocusing by a positive nonlinear refractive index of the material (optical Kerr effect) on the other hand.

Diffraction (divergence), ionization-induced defocusing, and the Kerr-effect-induced self-focusing depend on the laser beam size and the spatially varying laser intensity. The nonlinear effects involved in the filamentation process make it susceptible to variations of the local intensity in the laser focus. Ionization is mainly produced in the most intense part of the laser field, whereas the change of the refractive index due to the Kerr effect depends linearly on laser intensity. Therefore both of these processes amplify existing aberration effects in the laser beam due to any spatial distortion that is initially present in the focus. Since minor fluctuations of the spatial mode are always present in amplified laser systems, it is important to find ways to stabilize the filamentation process, especially if the output of the filament is to be used for other experiments in the lab. In addition, laser-based atmospheric analysis techniques such as femtosecond lidar[5,6] also benefit from methods of stabilizing and controlling the filamentation process, and in this case (where the laser pulse power is much higher), the breakup into multiple filaments has been controlled.[7]

Earlier work reported control of single filamentation by using an iris in the incident laser beam.[8] The resulting diffraction pattern along the optical axis of the laser beam leads to the onset of filamentation. Since a certain amount of laser light is sacrificed for this technique to work, it would be more attractive if a similar means of control could be found where power loss is circumvented.

In this Letter, a circular spatial phase mask in the laser beam prior to focusing is used to stabilize the pointing fluctuations of a single optical filament and to control and enhance the bandwidth of the coherent supercontinuum light that is generated from femtosecond laser pulses. Since only the phase of the laser light is changed, the total power of the input laser pulse is unaffected by the phase mask, as opposed to using an amplitude mask such as an iris. In our experiment, the phase mask is provided by a two-dimensional liquid-crystal-based spatial light modulator. In general, however, the phase mask can be imprinted by a stationary phase plate that is designed to match the established optimal parameters (radius and phase difference). Thus the method represents a straightforward approach to stabilizing and enhancing the optical nonlinear filamentation process for the case of single optical filaments, which will be applied in femtosecond laser pulse compression of the few-cycle regime[1,2] and enable advanced schemes for future implementations of pump- probe supercontinuum probing[9] of ultrafast condensed phase dynamics.

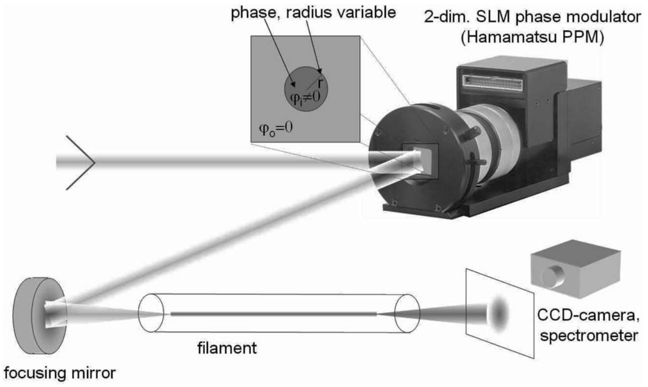

Fig. 1. Experimental setup. The spatial phase of the laser pulse is modified by a circular phase mask created with a two-dimensional spatial light modulator before being focused into the gas cell for optical filamentation. The output characteristics of the laser after filamentation (beam stability and pulse spectrum) are recorded.

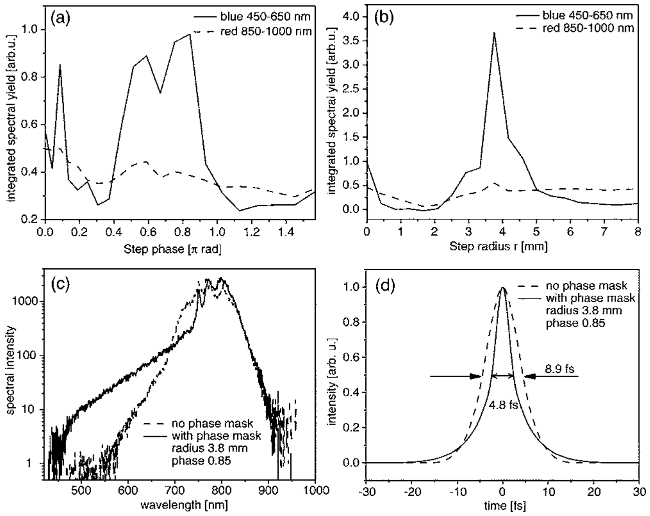

Fig. 2. Controlling the supercontinuum spectrum after filamentation by a circular phase mask. (a) Variation of the phase for a constant radius $r=2.9$ mm. The integrated spectrum in the blue (450–650 nm) (solid curve) and the red spectral region (850–1000 nm) (dashed curve) are plotted versus the phase step. (b) Blue (solid) and red (dashed) integrated spectral content versus radius of the phase step for a constant phase of 0.85π. An optimum occurs near a phase and radius of 0.85π and $r=3.9$ mm, respectively. (c) The spectrum obtained without (dashed line) and with application of the optimal phase mask (solid line). (d) Predicted bandwidth-limited laser-pulse shapes and FWHM durations for the spectra shown in (c).

The experimental setup (see Fig. 1) employs a 1 kHz Ti:sapphire multipass amplifier operating at a 780 nm central wavelength and a pulse energy of 0.6 mJ. The pulse duration is 30 fs. The pulses are directed onto the surface of a two-dimensional spatial light modulator from Hamamatsu Photonics, operating in reflective mode. The phase of the reflected light can be controlled by means of a video signal on a monitor output of a computer, resulting in a controllable array of 480 × 480 pixels. After reflection by the spatial light modulator, a near normal incidence concave spherical mirror is used (focal length $f=1$ m) to focus the light into a tubular cell filled with argon gas at an absolute pressure of 2.1 bars. After propagation through the cell, the beam profile of the filamentation output is detected on a viewing screen and stored in the computer by means of a CCD camera. For all the experiments shown, we chose a circular phase mask of a given fixed phase value φ within a selected radius r and 0 outside. The circular phase mask was always centered on the laser beam, which was measured to have a $1/e^2$ radius of 4.0 mm.

We first consider the control of the supercontinuum spectrum produced after optical filamentation. We varied the phase value φ for a constant radius r of the phase mask and varied the radius r for a fixed value of φ. Results are shown in Fig. 2. After analyzing the integrated content in the red and the blue spectral regions (red, 850–1000 nm; blue, 450–650 nm), a maximum is observed for the variation of φ that is particularly pronounced for the blue spectral part. A maximum is also observed for the variation in r. The spectrum of the laser pulse after the filamentation is shown in Fig. 2(c), both before and after applying an optimal circular phase mask of $r=3.9$ mm and $\varphi=0.85\ \pi$. The amount of light produced in the blue part of the spectrum is significantly increased; the enhancement is almost one order of magnitude for a substantial part of the blue spectral region. The blue part of the spectrum is particularly sensitive to improved filament conditions since in optical filamentation a blueshift is produced both by the effect of the nonlinear refractive index at the trailing edge of the pulse and the refractive index change due to laser-induced plasma buildup. The total bandwidth of the optimized laser pulse after the filament covers one optical octave. Techniques to stabilize the absolute phase of lasers[10] most commonly require the laser pulse to cover an octave-wide spectrum to perform interferometry with an upconverted- or downconverted sample of the same pulse; the filament output satisfies this desirable criterion. Moreover, the bandwidth-limited FWHM pulse duration of the coherent supercontinuum is much shorter for the controlled case [Fig. 2(d)]. The circular phase mask can thus be employed to enable further compression of femtosecond pulses undergoing filamentation, which could be particularly interesting if the presented control technique is applied to filaments already delivering very broadband spectra.[1]

The circular phase mask also significantly improves the pointing stability of the filament output. The output profile of the laser ~1 m after the filament is recorded and analyzed to obtain the beam position (intensity centroid) for 50 subsequently acquired images over a time scale of 10 s (we did not observe any significant additional fluctuations on a longer time scale). The result is shown in Fig. 3. The case of no applied phase mask is compared with two cases of phase masks with a phase difference of 0.85π and two radii of $r=2.7$ mm and $r=2.9$ mm. The pronounced reduction of the pointing fluctuation is apparent for both phase masks applied. Calculating the standard deviation of the x and y positions for the beam, we can quantify the improvement of pointing stability by factors of 4 and 3 for phase-mask radii of 2.7 and 2.9 mm, respectively.

In addition, a pronounced correlation between the x and y directions is visible in the data for the case where no phase mask is applied. This correlation seems to completely vanish for the stabilized cases in which a circular phase mask is applied. A possible explanation for this effect could lie in the circular symmetry of the phase mask that becomes imprinted on the laser beam prior to filamentation. Just as in the case with a solid circular aperture,[8] a circularly symmetric interference pattern is created in the focus where filamentation is initiated. Imprinting a circular symmetry on the laser beam prior to focusing appears to reduce the significance of asymmetric beam shape fluctuations at the critical (nonlinear) filament onset, such as thermal lensing in the amplifier or turbulence in the beam path. In the absence of the phase mask, these fluctuations can lead to a deterioration of the pointing stability of the filament beyond the

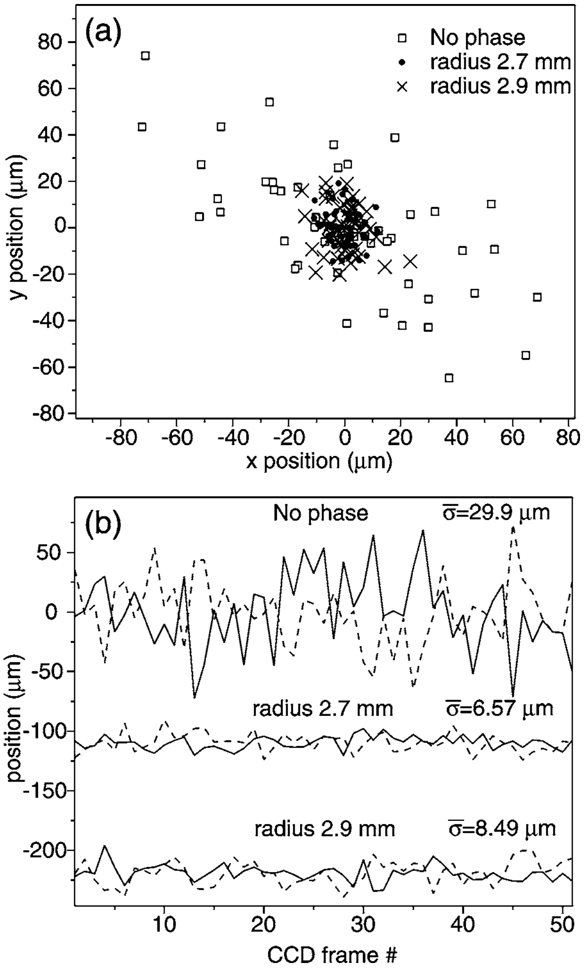

Fig. 3. Stabilization of pointing fluctuations in the laser beam after filamentation. (a) Position of the beam after the filament for the case of no phase mask applied (open squares), and phase mask of 0.85π applied with a radius of 2.7 mm (solid dots) and 2.9 mm (crosses). (b) Position of x (solid curve) and y positions (dashed curves) versus frame number of image acquired with CCD camera after filamentation. The curves are offset along the vertical axis. The mean standard deviation $\bar{\sigma}$ of the x and y positions is decreased by factors of 4 and 3 for the case of radii of 2.7 and 2.9 mm, respectively.

one given by the laser. The circular phase mask is one possible way to remove the pointing instability caused at the nonlinear filament onset. The pointing stabilization of the filamentation process is of particular importance for experiments that use coherent radiation from the filament output. If this output is used for nonlinear optical applications, focusing to a stable and stationary waist position is desirable if not imperative. In the regime of much higher laser pulse powers, where typically multiple filaments are produced, an asymmetric continuous spatial phase (aberration) produced by tilting the focusing lens was recently used to create a more stable filament[11] with potential applications in atmospheric remote sensing.

The presented method of filamentation control with circular phase masks can be easily carried out with a corresponding circularly shaped flat and thin layer of index-matching material on a transparent substrate such as fused silica. The layer thickness and radius can be made to match the optimal values. Thus the electronically controlled SLM can be eliminated in routine applications of the technique. However, more complex phase masks may be found by applying an evolutionary algorithm in a closed-loop control experiment[12] to obtain further enhancements of the filament output quality.

The authors acknowledge financial support of a MURI program from the Air Force Office of Scientific Research, contract FA9550-04-1-0242. Construction of the laboratory and some personnel were supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under contract DE-AC02-05CH11231. T. Pfeifer acknowledges support from a Feodor Lynen grant of the Alexander von Humboldt Foundation. His e-mail address is tpfeifer@lbl.gov.

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