Ultrafast control of multiple filamentation by ultrafast laser pulses

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Control of multiple filamentation by laser-induced microlens effect due to a nonlinear interaction of two overlapping laser beams inside a glass plate was demonstrated. Individual or multiple spots on the white light pattern which is a product of multiple filamentation through a mesh can be switched on and off with a very high contrast ratio on a femtosecond time scale. This phenomenon can find applications such as ultrafast optical switch and high-speed sampling. © 2005 American Institute of Physics. [DOI: 10.1063/1.2106022]

Filamentation and white light production from the nonlinear propagation of ultrashort laser pulses in transparent media is a universal phenomenon and is still of major interest since many applications have been found\textsuperscript{1,2} or will become possible. Filamentation is normally observed in early experiments by softly focusing a laser beam into optical media or observed when an ultrashort laser pulse propagates over a long distance in air or solids. When the laser power is much higher than the critical power for strong self-focusing, multiple filamentation occurs. Multiple filamentation originates from local random inhomogeneities in the medium or irregularities of the beam profile and is unavoidable normally.\textsuperscript{3,4} Moreover, such multiple filaments will undergo competition for energy.\textsuperscript{5} However, by inducing strong intensity gradients or phase distortion in the input beam profile, the multiple filamentation effect of the irregularities can be overcome and controlled.\textsuperscript{3,6–9} By inserting a slit or mesh into the beam to produce highly structured diffraction patterns, we have shown partially and fully controlled multiple filamentation in liquids.\textsuperscript{3,6} However, until now all of these multiple filamentation processes are controlled by using passive diffractive optical elements. In this letter we demonstrate that multiple filamentation can be controlled by another femtosecond laser beam. The white light spot patterns as a product of multiple filamentation through a mesh can be switched on and off with a very high contrast ratio on a femtosecond time scale. This phenomenon can find applications such as ultrafast optical switch and high-speed sampling.

Our experimental setup is shown in Fig. 1. A Ti:sapphire laser beam (1.9 mJ, 60 fs, 1 kHz) is divided by a beam splitter into two. One beam (pump laser) which has 80% of the total energy is launched through a metallic wire mesh (5 × 5 meshes, unit cell 497 × 497 µm, wire width 54 µm) into a 10-mm-thick cell filled with ethanol. A 2-mm-thick BK7 glass plate which is used as the optical medium for the interaction of the two beams is placed in the beam between the cell and the mesh. The wire mesh creates on the surface of the cell a symmetric diffraction pattern which can be controlled by changing the distance from the mesh to the cell. Although the generated diffraction patterns appear to be very rich and complicated, only those peaks whose intensities are higher than the threshold for strong self-focusing can develop into mature filaments and produce white light.\textsuperscript{6} The output white light patterns are imaged onto a charge coupled device camera by using a green filter (transmission is high only for λ < 500 nm). The other beam (switching laser), which has 20% of the total energy, is focused by a lens before it passes through the glass plate. The centers of the two laser beams overlap on the surface of the glass plate at a small angle of 4.5° and the time delay between them can be changed by a computer-controlled optical delay line.

The pump laser beam before the mesh has a Gaussian profile with a radius of 4 mm and the intensity is about 6 × 10\textsuperscript{10} W cm\textsuperscript{2}. The distance from the mesh to the cell is selected as 170 mm. The glass plate is inserted in the beam 8 cm away from the cell. The maximum intensity of the pump laser inside the glass plate increases by a factor of ~4 at the

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FIG. 1. Experimental setup for the control of multiple filamentation in ethanol by using a switching femtosecond laser pulse.
self-focusing within 1 cm can transfer into mature filaments pattern. There are mainly 8 peaks in the diffraction pattern. The measured diffraction pattern is shown in Fig. 2(b). By the diffraction of the wire mesh uniform beam profile is transformed into a very rich and complicated pattern. There are actually 8 × 8 peaks symmetrically distributed inside the beam together with a lot of secondary peaks with lower intensities. The line profile along one row of peaks shown in Fig. 2(a) is shown in Fig. 2(c). Since the self-focusing effect strongly depends on the radial gradient, filamentation preferably happens around each peak and this structure of electric field will be maintained except for the increase of the contrast ratio. The evolution of the beam profile will not abide by the Talbot effect of diffraction any more during propagation in ethanol since self-focusing will be dominant. The consequence is that the main diffraction pattern is likely to be “frozen” by the nonlinear effect during its propagation. Only those peaks whose intensities are higher than the threshold (~1 × 10^11 W cm^-2) for strong self-focusing within 1 cm can transfer into mature filaments and produce white light.36 Figure 2(d) shows the experimental result of the propagation of the corresponding patterns shown in Figs. 2(a) and 2(b) through the ethanol cell. The output white light patterns show a one to one correspondence to the input patterns. No random hot spot can be detected.

In Fig. 3 we only show the four typical white light patterns when the switching laser overlaps with the pump laser inside the glass plate at different time delays. Since the two laser beams overlap at a small angle, the time delay between the two pulses at different spatial positions is different even if the delay between the two is fixed. The zero time delay in Fig. 3 is thus defined as the time t_0 when the switching effect could be clearly observed while reducing the relative delay between the two pulses from “infinity.” At the beginning (t = t_0), as shown in Fig. 3(a), the left two columns of white light spots have been switched off and some spots have shifted positions a little bit from the original position to the right or the left compared to the white light patterns shown in Fig. 2(d) when the switching laser beam is off. When the switching laser is delayed by 9 fs, it is shown in Fig. 3(b) that a new column of spots appears which comes from the filamentation of the weaker peaks between the third and fourth columns of main peaks as shown in Figs. 2(a)–2(c). In fact, this new column of spots appeared when we increased the delay from 9 to 40 fs, and another new column of “secondary” peaks (between the fifth and sixth columns of main peaks) can also appear when we increased the delay from 100 to 130 fs. This kind of result indicates that mature filamentation can be switched on and off by a laser beam on a femtosecond scale. Different columns of white light spots can be switched on and off as shown in Figs. 3(c) and 3(d) when the switching laser is delayed by 61 and 82 fs, respectively. The switching is very stable from shot to shot. The switched pattern changes only when the time delay between the two laser pulses is changed.

Generally, the column of “suppressed” peaks (switched off) moved from left to right when we increased the delay from 0 to 150 fs since the overlapping zone of the two beams moves from left to right. However, some columns of suppressed peaks moved from right to left as shown in Fig. 3(d). This kind of phenomenon is mainly caused by our experimental arrangement where two laser beams overlap inside a glass plate which is placed between a mesh and ethanol cell. After interaction with the switching laser, the pattern of the pump laser will change due to the diffraction in free space before it arrives at the ethanol cell, which will not guarantee that changes of the pattern only take place at the overlapping zone. That is why we have observed that some columns of suppressed peaks move from right to left as shown in Fig. 3(d).

The physics lying behind this switch on and off experiment of white light production can be explained as follows:
The phase shift \( \Delta \phi(x) \) experienced by the pump laser due to the nonlinear interaction of two laser beams is
\[
\Delta \phi(x) = 4m_2 \int_0^{2\pi n_2} \left[ E_{01} + E_{02}\exp\left(-\frac{(d_1 - d_2)^2}{T^2 c_n^2}\right)\right]^2 dz.
\]

In conclusion, we have demonstrated that multilayerfilamentation and white light production can be controlled optically at ultrafast speed. The overlap of two femtosecond laser beams in an optical medium can reorganize multilayer filaments on a femtosecond scale. The white light patterns can be switched on and off and also shifted by controlling the second laser pulse. This new phenomena might be very useful in optical communications.