# Control of filamentation induced by femtosecond laser pulses propagating in air

**Z. Jin, J. Zhang, M.H. Xu, X. Lu, Y.T. Li, Z.H. Wang, Z.Y. Wei**

*Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China*
jzhang@aphy.iphy.ac.cn

**X.H. Yuan**

*State Key Laboratory of Transient Optics Technology, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710068, China*

**W. Yu**

*Shanghai Institute of Optics and Fine Mechanics, P.O. Box 800-211, Shanghai 201800, China*

**Abstract:** Filamentation formed by self-focusing of intense laser pulses propagating in air is investigated. It is found that the position of filamentation can be controlled continuously by changing the laser power and divergence angle of the laser beam. An analytical model for the process is given.



**OCIS codes:** (190.3270) Kerr effect; (190.7110) Ultrafast nonlinear optics; (260.5950) Self-focusing; (320.2250) Femtosecond phenomena.

---

## References and links

1. J. Kasparian, M. Rodriguez, G. Méjean, J. Yu, E. Salmon, H. Wille, R. Bourayou, S. Frey, Y.-B. André, A. Mysyrowicz, R. Sauerbrey, J.-P. Wolf and L. Wöste, "White-Light Filaments for Atmospheric Analysis," Science **301**, 61 (2003).
2. A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, "Self-channeling of high-peak-power femtosecond laser pulses in air," Opt. Lett. **20**, 73 (1995).
3. L. Wöste, C. Wedekind, H. Wille, P. Rairoux, B. Stein, S. Nikolov, Ch. Werner, St. Niedermeier, F. Ronneberger, H. Schillinger, R. Sauerbrey, "Femtosecond Atmospheric Lamp," Laser Optoelektron **29**, 51 (1997).
4. R. Wagner, S.-Y. Chen, A. Maksimchuk, and D. Umstadter, "Electron Acceleration by a Laser Wakefield in a Relativistically Self-Guided Channel," Phys. Rev. Lett. **78**, 3125 (1997).
5. B. La Fontaine, , F. Vidal, Z. Jiang, C. Y. Chien, D. Comtois, A. Desparois, T. W. Johnson, J.-C. Kieffer, H. Pépin, and H. P. Mercure, "Filamentation of ultrashort pulse laser beams resulting from their propagation over long distances in air," Phys. Plasmas **6**, 1615 (1999).
6. M. Mlejnek, E. M. Wright, and J. V. Moloney, "Dynamic spatial replenishment of femtosecond pulses propagating in air," Opt. Lett. **23**, 382 (1998).
7. H. Yang, J. Zhang, W. Yu, Y. J. Li, and Z. Y. Wei, "Long plasma channels generated by femtosecond laser pulses," Phys. Rev. E, **65**, 016406 (2002)
8. H. Yang, J. Zhang, Y. J. Li, J. Zhang, Y. T. Li, Z. L. Chen, H. Teng, Z. Y. Wei, and Z. M. Sheng, "Characteristics of self-guided laser plasma channels generated by femtosecond laser pulses in air," Phys. Rev. E **66**, 016406 (2002)
9. H. Yang, J. Zhang, J. Zhang, L. Z. Zhao, Y. J. Li, H. Teng, Y. T. Li, Z.L. Chen, Z.H. Wang, Z.Y.Wei, J.X. Ma, W. Yu, and Z. M. Sheng, "Third-order harmonic generation by self-guided femtosecond pulses in air," Phys. Rev. E **67**, 015401 (2003)
10. V.P. Kandidov, N. Akozbek, M. Scalora, O.G. Kosareva, A.V. Nyakk, Q. Luo, S.A. Hosseini, and S.L. Chin, "Towards a control of multiple filamentation by spatial regularization of a high-power femtosecond laser pulse", Appl. Phys. B **80**, 267 (2005).
11. S.L. Chin, S. Petit, F. Borne, and K. Miyazaki, "The White Light Supercontinuum Is Indeed an Ultrafast White Light Laser," Jpn. J. Appl. Phys. **38**, L126 (1999)
12. J. Kasparian, R. Sauerbrey, D. Mondelain, S. Niedermeier, J. Yu, J.-P. Wolf, Y.-B. André, M. Franco, B. Prade, A. Mysyrowicz, S. Tzortzakis, M. Rodriguez, H. Wille and L. Wöste, "Infrared extension of the super

continuum generated by femtosecond terawatt laser pulses propagating in the atmosphere," Opt. Lett. **25**, 1397 (2000).
13. Z. Jin, J. Zhang, Y. Q. Liu, K. Li, X. H. Yuan, Z. Q. Hao, X. Lu, Y. T. Li, Z. H. Wang, W. J. Ling, Z. Y. Wei, "Coherence measurement of white light emission from fs laser propagation in air," Chin. Phys. Lett. **22**, 2608 (2005)
14. J. Kasparian, R. Bourayou, V. Boutou1, C. Favre, G. Méjean, D. Mondelain, A. Mysyrowicz, M. Rodriguez, E. Salmon, R. Sauerbrey, H. Wille, J.P. Wolf, L. Wöste, J. Yu, L. Klingbeil, K. Rethmeier, W. Kalkner, A. Hartzes, H. Lehman, J. Eislöffel, B. Stecklum, J. Winkler, U. Laux, S. Hönger, Y. Pan, R. K. Chang, and S. C. Hill, 12th SQE, (2002).
15. G. Méchain, C. D'Amico, Y.-B. André, S. Tzortzakis, M. Franco, B. Prade, A. Mysyrowicz, A. Couairon, E. Salmon, R. Sauerbrey, to be published in Opt. Commun.
16. W. Yu, M. Y. Yu, J. Zhang, L. J. Qian, X. Yuan, P. X. Lu, R. X. Li, Z. M. Sheng, J. R. Liu, and Z. Z. Xu, "Long-distance propagation of intense short laser pulse in air," Phys. Plasmas **11**, 5360 (2004)

## 1. Introduction

In recent years, a femtosecond laser beam has been found to be able to propagate in the air for long distances as self-guided filaments [1-10]. When the laser power exceeds critical power $P_N$, nonlinear Kerr response of air occurs and focuses the laser beam, resulting in an increase of the laser intensity. When the laser intensity exceeds the threshold of multiphoton ionization (MPI), the plasma produced will defocus the beam. Dynamic balance between the Kerr focusing and MPI defocusing allows the laser beam to propagate for a distance of hundreds of meters, forming a plasmas filament with a nearly constant diameter during the propagation. A supercontinuum white light emission is also observed from the filaments, having a wavelength range from the near-infrared to the ultraviolet [1, 3, 11-13].

Such a long distance propagation of laser pulses is useful in many applications, such as laser triggered lightening, remote diagnostics, LIDAR, etc. Most of these applications require long and continuous filaments. The spatial position where the filaments start to form is also an important parameter and should be controllable. By changing group velocity dispersion (GVD), Kasparian *et al*. succeeded in controling the filamentation distance from several meters to over one hundred meters [14]. Méchai *et al*. also obtained the filamentation distance over 300 m by changing the pulse duration of initial laser beam [15].

In our experiment, we studied the effects of the energy and divergence angle of femtosecond laser pulses on laser self-focusing and filamentation. It is shown that by controlling the laser energy and divergence angle, one can realise a long-distance propagation of filaments starting at precise position.

## 2. Experiment and discussion

The experiment was conducted using the Extreme Light (XL) -II Ti:sapphire laser system operating at 800 nm with a repetition at 10 Hz. The laser system can provide 640 mJ in 30 fs pulses. In our experiment, the energy per pulse was limited to around 10-50 mJ and the pulse duration was 60 fs. The laser beam diameter is about 30 mm.

The experimental setup is shown in Fig. 1. An optoelectronic diode was placed after a 97% reflecting mirror to monitor the laser energy. An imaging system on a carrier was setup to measure the beam profile. A white screen was placed at the edge of the carrier. A CCD camera (NTE/CCD-512-TK) was installed in front of the screen at about 15° to the propagation axis. The carrier was moved in a range from 3 to 50 meter (the limit of our laboratory) along the propagation direction.

#9209 - $15.00 USD Received 19 October 2005; revised 25 November 2005; accepted 26 November 2005

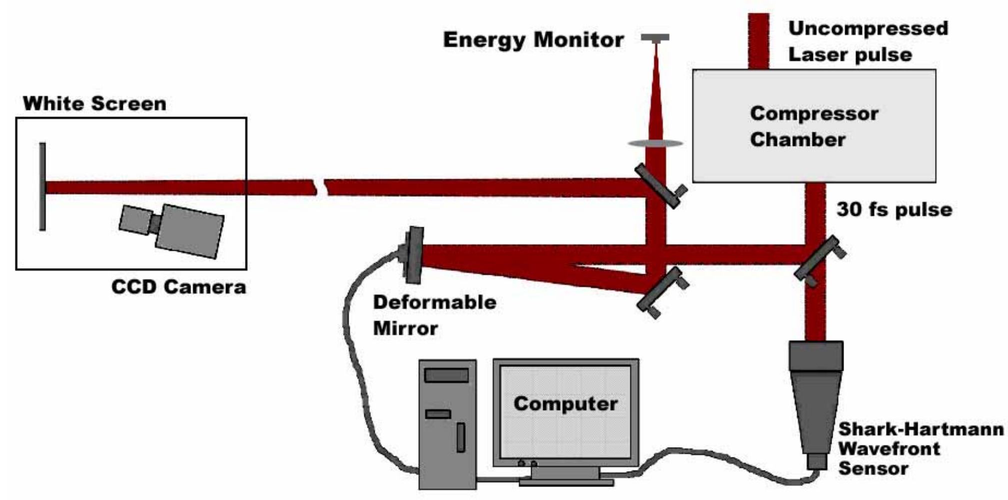


Fig. 1. The experimental setup. An adaptive optical system is placed after the laser compressor chamber. We use the deformable mirror to change the divergence angle of the laser beam. An imaging system was setup on a carrier.

A deformable mirror was used to control the divergence angle of the laser beam. The deformable mirror is a multilayer round disc. The first disc, which was polished and has a highly reflective coating, was made from optical glass. It is followed by two discs made from piezoceramic material. The discs are firmly glued to each other. Deformation of the surface of the mirror is achieved via the reverse piezoelectrical effect when there is an electric field E across the piezo-disc layer.

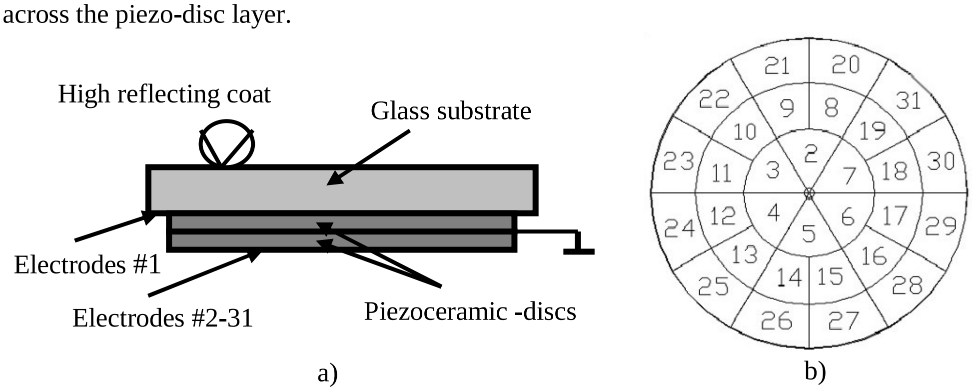


Fig. 2. (a) Multilayer setup of the deformable mirror. (b) Configuration of control electrodes.

Figure 2 shows the setup of the deformable mirror. The first piezoceramic disc has two round electrodes used for general curvature control. The second disk was controlled by 30 electrodes for controlling the individual parts of the mirror surface. In this experiment, we change the voltage applied on the first disk to obtain a continuously adjustable divergence angle of the laser beam. The relationship between the voltage and the divergence angle was shown in Fig. 3.

#9209 - $15.00 USD Received 19 October 2005; revised 25 November 2005; accepted 26 November 2005

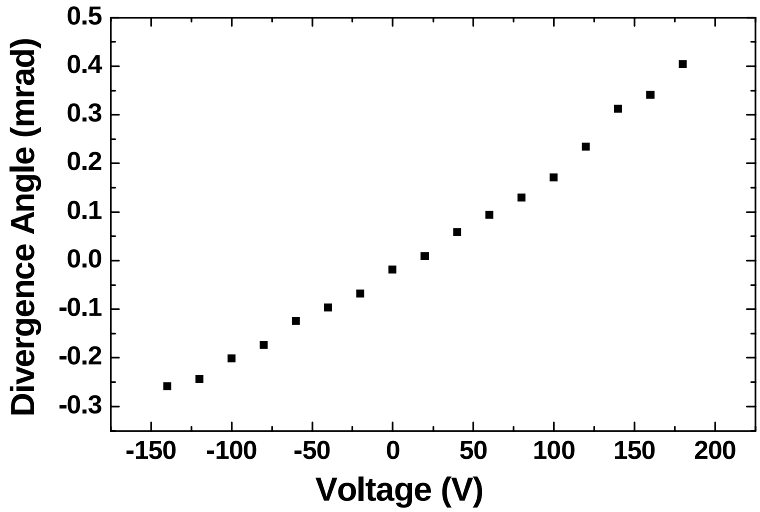


Fig. 3. Dependence of the divergence angle on the voltage applied on the deformable mirror. We obtain an adjustable divergence angle by change the voltage of the deformable mirror.

Figure 4 shows the typical evolution of a laser beam propagating in air during self-focusing and filamentation. The divergence angle of the beam was -0.02 mrad. The laser power was 500 GW. After propagating in air for about 7 meters, a filament appeared. This filament then separated into several filaments at a distance of about 9 meters. At a position over 20 m, the beam broke up with an irregular intensity distribution and more filaments appeared.

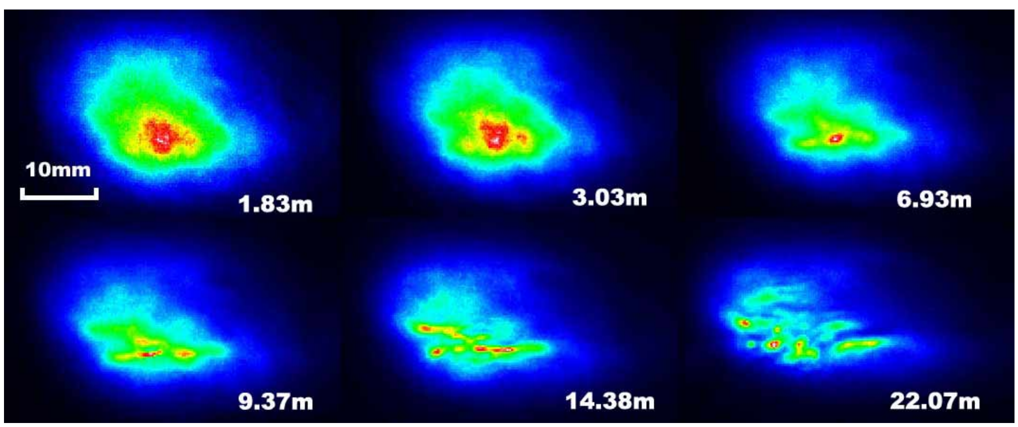


Fig. 4. A typical evolution for a 500 GW laser beam propagating in the air. The number at the right bottom of each frame shows the position where the image was taken.

Figure 5 shows the evolutions of the beam profile with different laser power. The divergence angle was 0.32 mrad. When the laser power was 300 GW, no filament was observed even after 20 meters. With a laser power of 420 GW, we could obtain a single filament. When we increased the laser power to 550 GW, multi-filaments were observed. Thus it is possible to control the position and number of filamentation by adjusting the laser power and divergence angle.

#9209 - $15.00 USD Received 19 October 2005; revised 25 November 2005; accepted 26 November 2005

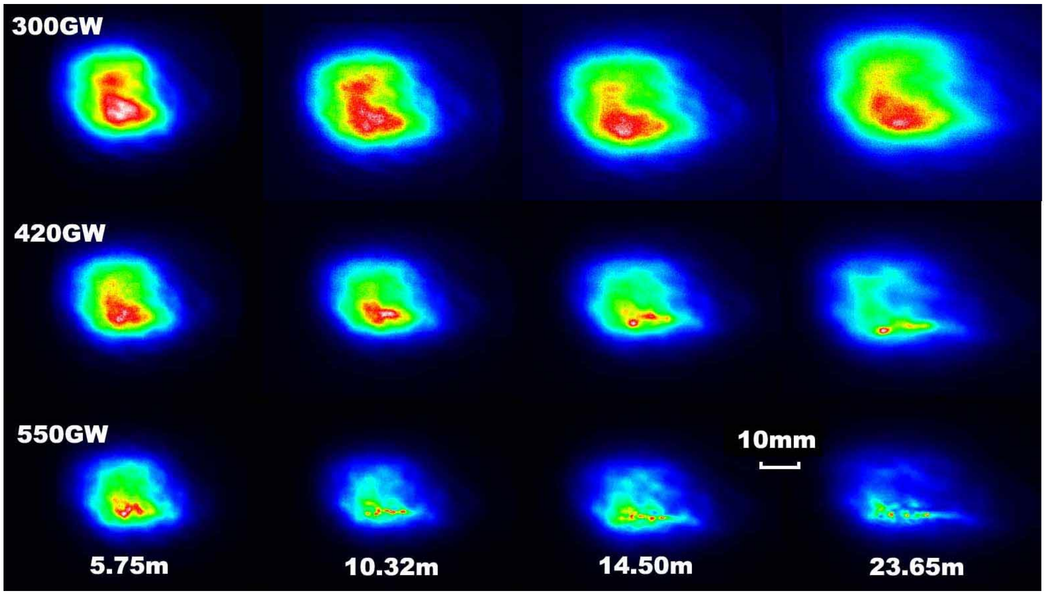


Fig. 5. Evolution of the beam profile at different laser powers. The numbers at the bottom are the propagation distance. Different filamentation positions are obtained by changing the laser power.

We measured the positions ($z_f$) where the filaments were formed for different laser power and divergence angle, as shown in Fig. 6. A rapid increase of $z_f$ was observed when we increased the divergence of the laser beam. One can control the position of the filamentation by adjusting the laser divergence angle and the laser power since $z_f$ is very sensitive to the laser divergence angle and laser power, especially when the former is positive.

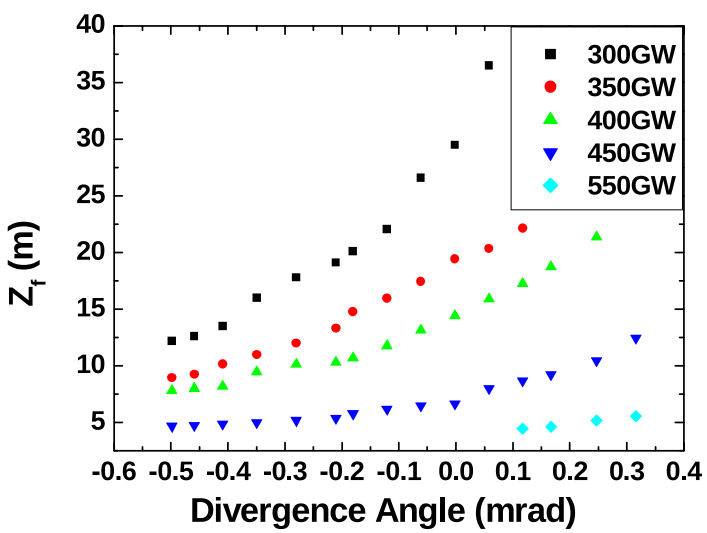


Fig. 6. Filamentation positions for different laser powers and divergence angles.

We now present a theoretical model for the observed behavior [16]. Considering a Gaussian laser beam propagating in air, we obtain the focusing distance

$$z_m \sim -\left(gb_0 + \sqrt{g^2 b_m^2 - 2\alpha_1}\right)/\left(g^2 + 2\alpha_1 b_0{}^2\right) \tag{1}$$

where g(=tanθ) is the divergence of the beam, $b_0$ is initial beam size, $b_m$ is the focal spot size, $\alpha_1$=1-$P_0/P_N$, $P_0$ is the laser power and $P_N$ is the critical power for self-focusing (~2 GW at 800 nm). The space is normalized by $\lambda_0$, where $\lambda_0$ is the laser central wavelength. Detail discussion about this model can be found in Ref. 16. Assuming that the position where the filaments appeared was at the self-focusing position, we can compare the calculation results with the experiment.

Experimentally, the local self-focusing usually occurs as a result of inhomogeneity of the initial laser intensity distribution. A part of the laser energy is then focused at some specific position of the beam section. We compared the vertical beam profiles at a propagation distance of 183 cm and 693 cm, as shown in Fig. 7. The laser power was 300 GW. We found that the self-focusing occurred for a spot of 2.4 mm diameter. The integrated laser power in this area was about 40 GW. So a beam size of 2.4 mm and power of 40GW was chosen in our analytic calculation.

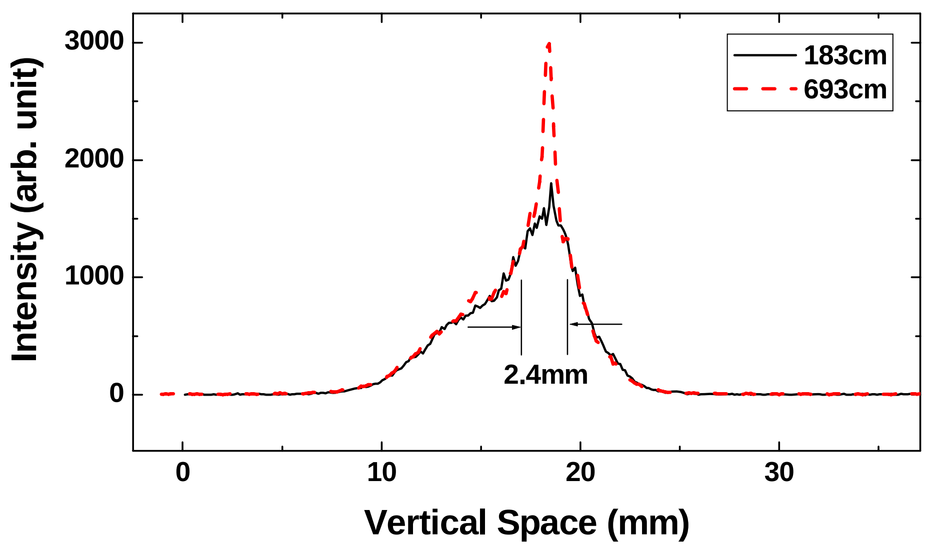


Fig. 7. Comparison of the vertical beam profiles at a propagation distance of 183 cm and 693 cm. A 2.4 mm diameter local self-focusing was observed. The solid line in Fig. 8 shows the calculated $z_m$ when for $P_0$=40 GW and $z_0$=2.4 mm. The squares are the filamentation positions of the 300 GW laser at different divergences. The calculation well fits the experimental results.

#9209 - $15.00 USD Received 19 October 2005; revised 25 November 2005; accepted 26 November 2005

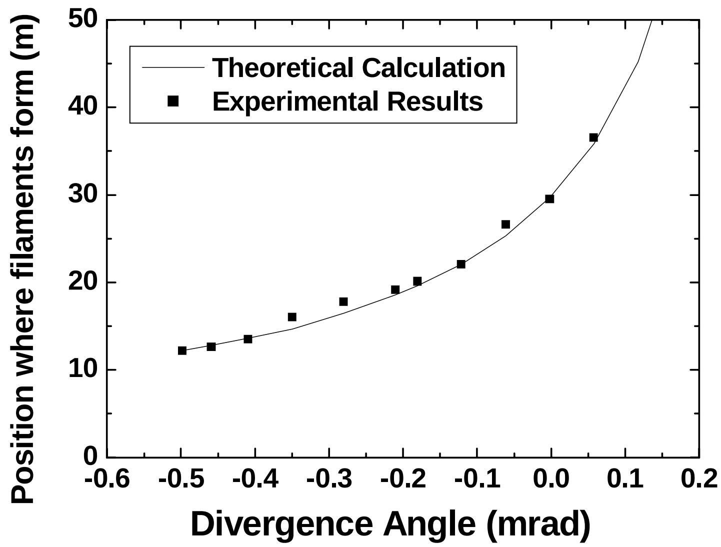


Fig. 8 Comparison of the calculation and experimental results. The solid line shows the calculated result for $P_0$=40 GW and $z_0$=2.4 mm. The squares are the measured filamentation position of a 300 GW laser beam.

## 3. Conclusion

We have observed the formation and separation of filaments when an intense femtosecond laser beam propagates in air. The dynamic balance between the Kerr focusing and MPI defocusing allows the laser beam to propagate for a long distance. By changing the laser power and divergence angle, we have demonstrated a new way to control the positions of the filaments besides GVD and pulse duration control. A much longer filamentation is possible by simultaneous control of spatial and temporal characteristics of the laser beam. A simple analytical model was presented and it agrees well with our experimental results.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant Nos 60321003, 10374116 and 60478047.

#9209 - $15.00 USD Received 19 October 2005; revised 25 November 2005; accepted 26 November 2005