JP0050797

59. Femtosecond Time-resolved Optical Polarigraphy (FTOP)

S. Aoshima, M. Fujimoto, M. Hosoda, and Y. Tsuchiya

Central Research Laboratory, Hamamatsu Photonics K.K.
5000 Hirakuchi, Hamakita-city 434-8601, Japan

ABSTRACT

A novel time-resolved imaging technique named FTOP (Femtosecond Time-resolved Optical Polarigraphy) for visualizing the ultrafast propagation dynamics of intense light pulses in a medium has been proposed and demonstrated. Femtosecond snapshot images can be created with a high spatial resolution by imaging only the polarization components of the probe pulse; these polarization components change due to the instantaneous birefringence induced by the pump pulse in the medium. Ultrafast temporal changes in the two-dimensional spatial distribution of the optical pulse intensity were clearly visualized in consecutive images by changing the delay between the pump and probe. We observe that several filaments appear and then come together before the vacuum focus due to nonlinear effects in air. We also prove that filamentation dynamics such as the formation position and the propagation behavior are complex and are strongly affected by the pump energy. The results collected clearly show that this method FTOP succeeds for the first time in directly visualizing the ultrafast dynamics of the self-modulated nonlinear propagation of light.

Keywords: Ultrafast Measurement, Femtosecond Pulses, Kerr effect, Polarization, Birefringence, Propagation, Laser Plasma, Nonlinear Effect, Filamentation, Ultrafast Dynamics.

1. INTRODUCTION

Over the past three decades, the propagation of intense laser pulses has attracted much interest due to its self-modulating nonlinear effect.[1] In recent papers, the propagation of intense femtosecond laser pulses in under-dense plasma has been actively studied because of its importance to laser fusion, particle acceleration, and the high-field physics of laser plasma interactions.[2-4] It is very important in laser ablation to monitor the beam quality such as the spatial- and time-distribution. To observe this propagation behavior, indirect techniques such as the Schlieren method have been used.[5] However, these methods cannot take an instantaneous image of the laser pulse interaction with the material, because only the long-lived gradient in the refractive index is measured after the excitation.

We propose a novel time-resolved imaging technique called FTOP (Femtosecond Time-resolved Optical Polarigraphy) for visualizing the ultrafast propagation dynamics of intense light pulses in a medium.[6] The method probes the instantaneous birefringence induced by the laser's electric field in the atmosphere. Since the induced birefringence has an ultrafast response in air, an instantaneous image of the laser pulse in the interaction region can be visualized. By using FTOP, we are able to observe the ultrafast temporal evolution in the two-dimensional spatial distribution of the optical pulse intensity through consecutive femtosecond snapshot images. Information about the propagation dynamics is useful for laser ablation.

2. PRINCIPLE OF FTOP MEASUREMENT

2.1. Experimental setup and an obtained image

Figure 1 shows the experimental setup of FTOP. Horizontally linear polarized intense optical pulses (100-fs, 7.0-mJ, 10-Hz, 800-nm) from a Ti:Sapphire amplifier system are split into a pump and a probe. The pump beam carries most of the incident beam's energy.

After the beam passes through the variable optical delay, the $\lambda/2$ plate makes the polarization of the pump

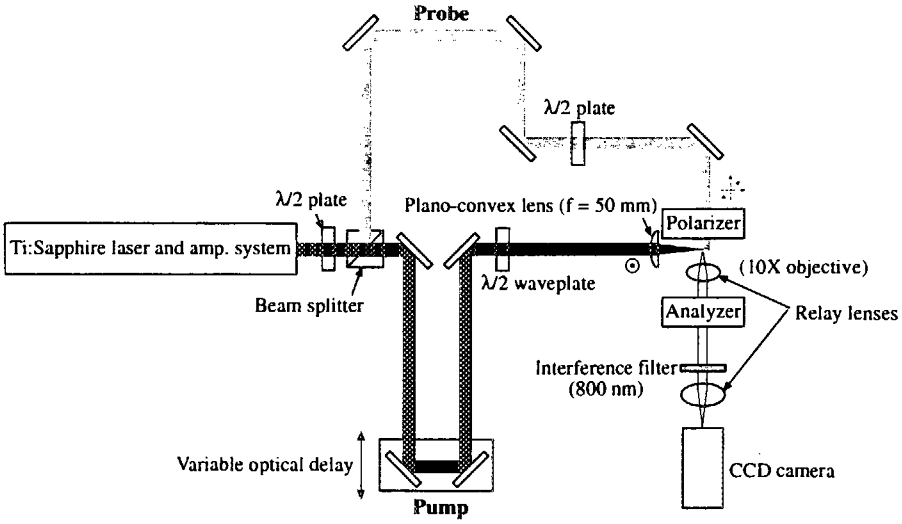

Figure 1 Experimental setup of Femtosecond Time-resolved Optical Polarigraphy (FTOP).

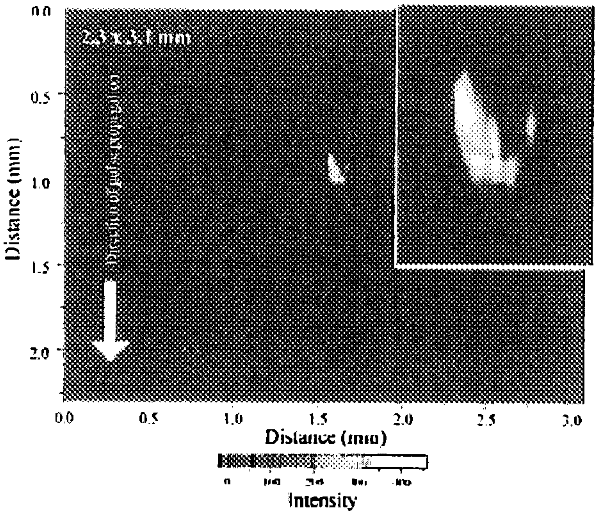

Figure 2 Image taken by FTOP

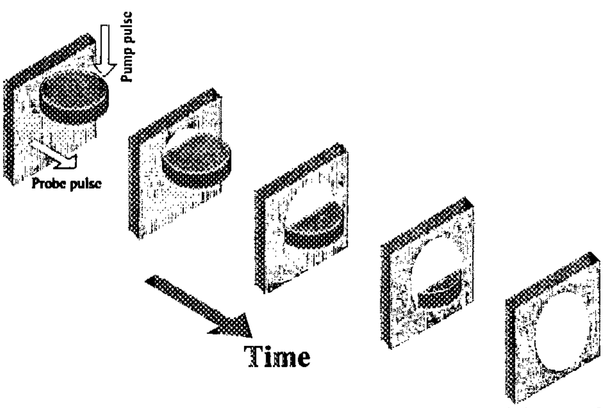

Figure 3 Diagram of relations between positions of pump and probe pulses in interaction region

vertical, before it is focused in the air by a 30-mm diameter plano-convex lens (f = 50 mm). The lens diameter is larger than the cross section of the pump pulse, which has a diameter of 20 mm and a 1/e diameter of 12.8 mm. Meanwhile, the collimated probe pulse synchronously irradiates the area around the focal point. The polarizer is used after the λ/2 plate, and the linear polarization angle of the probe is set to exactly 45 degrees with respect to the horizontal plane of the optical bench. After the beam passes through the interaction region, the analyzer only extracts the components perpendicular to the polarizer. The relay lenses magnify the image, which is then detected by the CCD camera. The CCD camera is rotated 90 degrees to improve the recognition in the perpendicular direction to the light pulse propagation, because the CCD has an insensitive area between the horizontal scan lines.

Figure 2 shows an example of FTOP images. The direction of pulse propagation is from top to bottom as indicated by the white arrow. The bright area is magnified and inset. The observed area is 2.3 mm x 3.1 mm at the interaction region. The CCD camera has 480 x 640 pixels, and the corresponding spatial resolution is 4.8 μm/pixel.

2.2 Vertical axis in FTOP image

Figure 3 is a diagram of relating the position of the pump and probe pulses in the interaction region at five different moments. In the figure, the pump and the probe pulses propagate from top to bottom and from left to right, respectively. Since the speed of both light pulses are the same, the spatial distribution of the pump pulse intensity is detected as the spatial intensity distribution of the probe pulse. Therefore, the FTOP image is created like a top view as shown in the right side figure, despite the fact that the probe pulse passes across the interaction region horizontally.

Furthermore, the vertical length of the image corresponds to the pulse duration (shown as the thickness of the pulses) and the response time of the optical Kerr effect. Then, the vertical axis of the FTOP image relates to both the time- and space-axis, because the interaction time upon the spatial distribution of the pump pulse provides this information.

3. ULTRAFAST DYNAMICS OF LASER PULSE PROPAGATION IN ATMOSPHERE

The FTOP image changes according to time, which is determined by different arrival times at the pump pulse and the probe pulse interaction region. We can vary this timing by changing the optical path length of one of those pulses to another one by using a "variable optical delay" (Fig. 1). The experimental condition is the same as that described in the section 2.1. The energy of the pump pulse in front of the focusing lens is 3.5 mJ.

The consecutive time-resolved images for propagation in the atmosphere are taken at 91 temporal points with a 66.7-fs delay step. The images are quite stable on a shot-to-shot basis. In order to improve the signal-to-noise ratio, we integrate 10 shot profiles to produce data for one image. The background, such as the emission from the breakdown plasma, is subtracted. Figure 4 shows 48 typical continuous snapshots. The same areas of CCD images are extracted in the figure. The spatial distribution of the pump pulses are clearly measured and move from top to bottom according to the change of time.

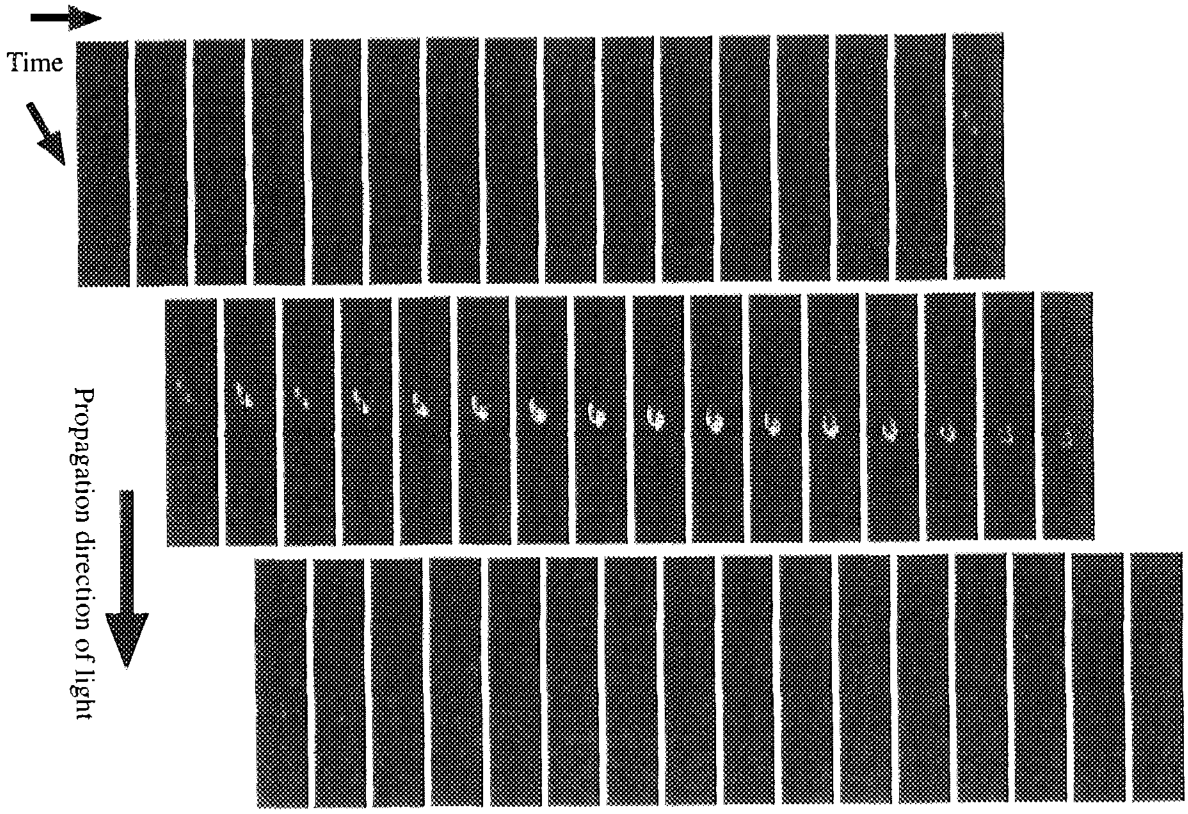

Figure 4 Typical FTOP images of 48 continuous snapshots with a 66.7-fs delay step.

4. CAPABILITY OF SINGLE-SHOT PULSEWIDTH MEASUREMENT BY FTOP

As mentioned in section 2.2, the vertical axis of the FTOP image simultaneously represents the time and distance, and the time depends on the pulse duration and the response time of the media. When the spatial distribution is suppressed, the vertical axis of the FTOP image becomes the time-axis. As an example, we analyzed the right image of Fig. 5 (a) ,which is suitable for the condition. The intensity profile data was created by adding data in the horizontal axis direction from the data in the image. Figure 6 shows the profile data. The right side corresponds to the bottom of the image.

We found that the profile has 13 FWHM pixels, and our calculation shows that the measured width is 208 fs using the spatial resolution of 4.8 μm/pixel and a refractive index of air at 1.0. There are two important points regarding an optical pulse duration of 100 fs. First, we can experimentally confirm that the response time of the Kerr effect of air is ultrafast in the order of 100 fs. Second, this method can be used to non-invasively monitor the pulse duration. In principle, single shot monitoring can be performed. In addition, phase matching such as in the SHG autocorrelator or SHG-FROG[8] is unnecessary when using this simple measurement method. Therefore, FTOP can be one of the suitable methods for measuring atto-second pulses with a very wide spectrum. In addition, there is the possibility that the response time of the Kerr effect in the medium can be accurately measured by FTOP.

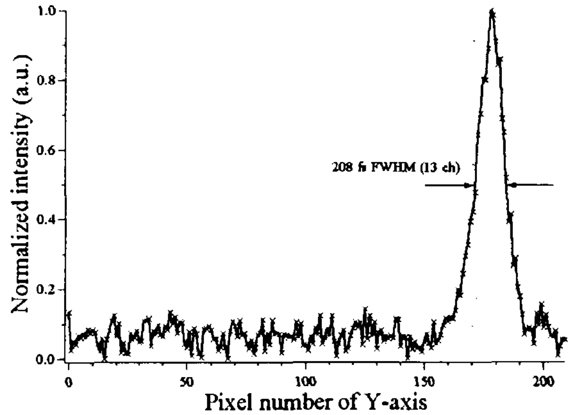

Figure 5 Intensity profile using right image of Fig. 8 (a) and measured pulsewidth (FWHM).

5. CONCLUSION

We have proposed a novel time-resolved imaging technique named FTOP (Femtosecond Time-resolved Optical Polarigraphy) for visualizing ultrafast propagation dynamics of intense light pulses in a medium. By using the optical Kerr effect, we have observed two-dimensional images of intense femtosecond laser pulse propagation in air with femtosecond time resolution and clearly captured phenomena such as the ultrafast temporal dynamics of filamentation. This information including the two-dimensional spatial distribution is very useful for laser processing and laser ablation. This method can be applied to measurements of pulsewidth, the optical Kerr constant and its decay time, and high-power pulse monitoring for space and time. Moreover, a single shot record of the pump pulse propagation can be obtained by using a pulse train as a probe beam. This will ensure precise observations even with shot-to-shot instability.

ACKNOWLEDGMENT

The authors would like to thank Y. Suzuki and T. Hiruma for their encouragement, and K. Kaufmann for his helpful discussion. A part of this study was funded by the Special Coordination Funds for promoting Science and Technology from the Science and Technology Agency of the Japanese Government.

REFERENCES

1. Y. R. Shen, Prog. Quant. Electr. **4** , 1 (1975); A. Braun, G. Kohn, X. Liu, D. Du, J. Squier, and G. Mourou, Opt. Lett. **20** , 73 (1995).
2. J. Fuchs, G. Malka, J. C. Adam, F. Amiranofi, S. D. Baton, N. Blanchot, A. Héron, G. Laval, J. L. Miquel, P. Mora, H. Pépin, and C. Rousseaux, Phys. Rev. Lett. **80** , 1658 (1998).
3. M. Borghesi, A. J. Mackinnon, R. Gaillard, and O. Willi, Phys. Rev. Lett. **80** , 5137 (1998).
4. A. Pukhov and J. Meyer-ter-Vehn, Phys. Rev. Lett. **76** , 3975 (1996).
5. C. E. Clayton, K. C. Tzeng, D. Gordon, P. Muggli, W. B. Mori, C. Joshi, V. Malka, Z. Najmudin, A. Modena, D. Neely, and A. E. Dangor, Phys. Rev. Lett. **81** , 100 (1998).
6. M. Fujimoto, S. Aoshima, M. Hosoda, and Y. Tsuchiya, Opt. Lett. **24** , 850 (1999).
7. For example, P. Chessa, E. De Wispelaere, F. Dorchies, V. Malka, J. R. Marquès, G. Hamoniaux, P. Mora, and F. Amiranofi, Phys. Rev. Lett. **82** , 552 (1999), and references therein.
8 K. W. DeLong, R. Trebino, J. Hunter, and W. E. White, J. Opt. Soc. Am. B **11**, 2206 (1994).