Visualization of optical pulse filamentation by femtosecond time-resolved optical polarigraphy

Martin Centurion, Ye Pu, Demetri Psaltis

Martin Centurion, Ye Pu, Demetri Psaltis, "Visualization of optical pulse filamentation by femtosecond time-resolved optical polarigraphy," Proc. SPIE 5580, 26th International Congress on High-Speed Photography and Photonics, (17 March 2005); doi: 10.1117/12.584170

SPIE.

Event: 26th International Congress on High-Speed Photography and Photonics, 2004, Alexandria, Virginia, United States

Visualization of optical pulse filamentation by femtosecond time-resolved optical polarigraphy.

Martin Centurion, Ye Pu and Demetri Psaltis
California Institute of Technology, MS 136-93, Pasadena, CA 91125

ABSTRACT

We have observed the filamentation of optical pulses in carbon disulfide(CS_2) using femtosecond time-resolved optical polarigraphy(FTOP)[1]. A pump-probe setup is used to capture the propagation of a 150 femtosecond laser pulse in CS_2. The probe pulse propagates in a direction perpendicular to the pump. The high intensity of the pump pulse causes a transient index change in the material through the Kerr effect. The induced birefringence is proportional to the intensity of the pump and can be captured by monitoring the polarization of the probe. The probe pulse is imaged on a CCD camera to recover the intensity profile of the pump pulse. We have used this technique to observe the spatial evolution of the pulse as a function of power and propagation distance. Initially, the pulse propagation causes a coarse redistribution of the intensity. The beam then breaks up into stable light filaments which propagate for several millimeters, and finally the beam profile becomes unstable to small fluctuations in the input power.

Keywords: femtosecond, polarigraphy, pulse propagation, filamentation, optical instability.

1. INTRODUCTION

A light pulse propagating in a nonlinear Kerr medium will experience self focusing if its power is above a critical value which depends on the material properties. If the pulse power is much higher than the critical power then the optical beam will break up into filaments. Each filament is expected to carry approximately the critical power, defined as[2]:

$$P_{cr} = \frac{\pi(0.61)^2 \lambda}{8 n_0 n_2}$$

Where λ is the wavelength of the light in vacuum, n_0 is the refractive index of the material and n_2 is a constant which gives the strength of the Kerr nonlinearity and has units of inverse intensity. The critical power for carbon disulfide with our experimental parameters is 190KW. Multiple filamentation is a very rich subject and has attracted a lot of interest[3-6].

We studied the pulse propagation as a function of power and propagation length using femtosecond time-resolved optical polarigraphy(FTOP)[1]. This method is a valuable tool for the observation of femtosecond pulse propagation[7]. A weak probe pulse is used to capture the nonlinear index change induced in the material by a strong pump pulse. The probe pulse propagates at an angle with respect to the pump. The pump pulse interacts with the material and induces a transient change in the index of refraction through the third order nonlinearity. The index change experienced by the probe is proportional to the intensity of the pulse. The magnitude of the index change depends also on the polarization vector of the probe because the third order susceptibility tensor($\chi^{(3)}$) has different strengths for the response parallel and perpendicular to the pump polarization. This nonlinear induced birefringence can be captured by monitoring the polarization state of the probe pulse. The probe is polarized at an angle of 45 degrees with respect to the polarization vector of the pump pulse and imaged through a crossed polarizer after traversing the nonlinear material.

If the Kerr response of the material is instantaneous, or much shorter than the duration of the pulse, the material will be birefringent only while the pump pulse is present. In this case the probe will capture an instantaneous intensity profile of the pump pulse. If the material response time is much longer than the duration of the pulses then probing the material after the pump pulse has gone through will reveal the trajectory of the pulse propagation. In the intermediate regime, the time resolution of the intensity profile will be limited by the response time of the material. In our case the response time is similar to the pulse duration, but there is a longer decay time of about 2 picoseconds.

26th International Congress on High-Speed Photography and Photonics, edited by D. L. Paisley, S. Kleinfelder, D. R. Snyder, B. J. Thompson, Proc. of SPIE Vol. 5580 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.584170

2. SETUP

We launched 150 femtosecond pulses form a Ti:Sapphire laser amplifier system through a 10mm glass cell filled with carbon disulfide(CS_2). Figure 1 shows a diagram of the experimental setup. A cylindrical lens was used to focus the beam into a line inside the medium and generate a single column of filaments. This allowed us to observe the filamentation process from the output of the glass cell and also from a transverse direction. The beam profile at the output of the cell was imaged on a CCD camera(End CCD). A side view of the optical beam profile inside the material was obtained using FTOP. The probe pulse propagates in a direction perpendicular to the pump and is polarized at 45 degrees with respect to the polarization of the pump. After the probe traverses the nonlinear medium it goes through an analyzer (polarizer at -45 degrees) and is imaged on a CCD camera(Side CCD). The images from the end CCD capture the beam profile of the pump after traversing the nonlinear material. The images from the side capture the spatial evolution of the beam profile. A delay line in the probe beam is used to observe the pump pulse at different positions inside the material.

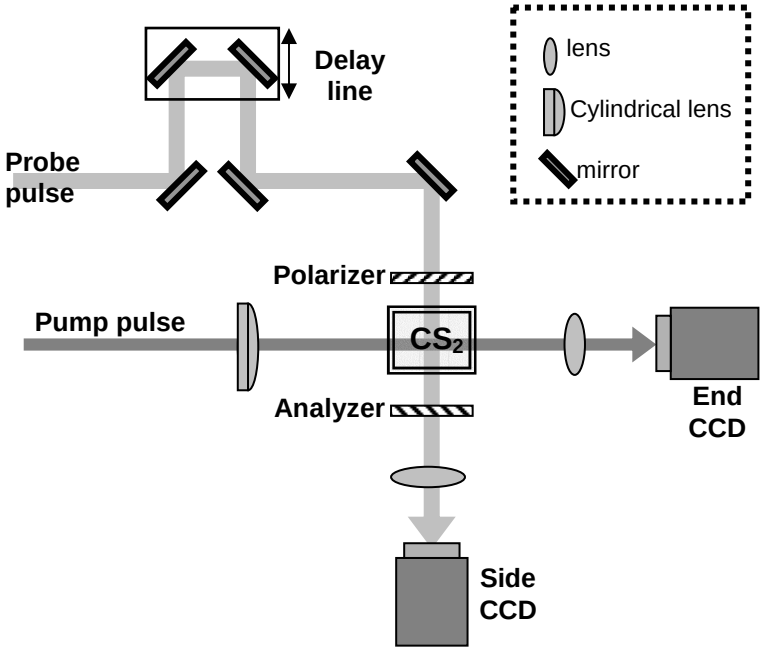

Figure 1: Experimental Setup. The pump pulse is imaged at the output of the CS_2 cell. A side view is captured using FTOP.

3. RESULTS

We have observed three different phases in the filamentation process as a function of input pulse power. In the first phase the beam self focuses into a line with a coarse redistribution of the intensity(Fig. 2.a-c). A beam that is not collimated will self focus if the self focusing angle is greater than the diffraction angle. For $P = 12P_{cr}$(Fig .2.a), self focusing and diffraction just balance each other and the output beam size is approximately the same as the input. For higher power the beam self focuses into a thin line. The minimum width of the focused line is 16μm for $P = 80P_{cr}$. In the second phase ($P > 100\ P_{cr}$) the beam breaks up into individual filaments which appear at the local maxima of the intensity distribution(Fig. 2.d-e). The filaments are seeded by small variations in the input beam and are not sensitive to small variations in the input energy. The pattern of filaments is repeatable from shot to shot as long as the beam profile is not changed and the power variation is only a few percent. The number of filaments is seen to increase with power. The filament size is 10μm FWHM and does not change when the energy is increased. The third phase, at $P > 300P_{cr}$, is characterized by the output beam profile becoming unrepeatable(Fig 2.f-h). As the power increases the filaments start to appear closer to each other, which allows them to interact more strongly. Part of the energy is scattered out of the

central maximum into side lobes. As the input power increases the fraction of energy in the central maximum decreases and filaments start to appear on the side lobes. In fact for P = 1200P_{cr}(Fig 2.h) there are more filaments on the side lobes than in the central maximum.

The FTOP setup was used to obtain a side view of the filamentation process inside the CS_2 cell as function of propagation distance. The transverse beam profile at different positions was obtained by changing the delay of the probe pulses. The full trajectory of the beam was reconstructed by adding multiple frames of the pulse at different positions. We have observed the propagation of pulses with P = 390P_{cr} and 1200P_{cr}. Figure 3 shows the propagation of the pulses for 5mm, starting just inside the glass cell. The pulse with higher power(Fig 3.b) breaks up into filaments earlier, at about 1.2mm into the material, while the lower power pulse(Fig 3.a) starts to break up 2.9mm into the material. The nonlinear phase change will be larger for higher intensity, thus the shorter self focusing distance. The lower power pulse initially breaks up into 14 filaments, while the higher power breaks up into 33 filaments.

For P = 390Pcr the number of filaments increases with propagation distance. The spacing between filaments is initially large enough that each filament propagates without interacting with its neighbors. In the spaces between the filaments the light continues to self-focus, generating new filaments. For the higher power the number of filaments initially increases, but after propagating for about 4mm the number of filaments decreases. In this case the density of filaments is higher and the evolution is much more dynamic. As the pulse continues to propagate the number of filaments continues to decrease, until the output at 10mm where we see almost a continuous line at the center with only a few distinguishable filaments(Fig.2-h). For the lower power the beam profile also becomes unstable by the time it propagates to the output, although the side lobes are relatively weaker and some filaments survive(Fig. 2-f).

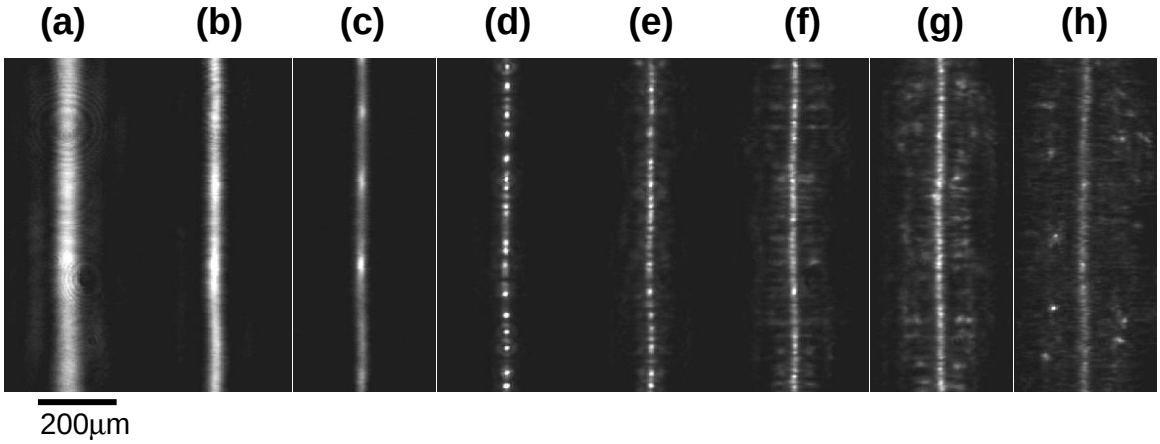

Figure 2: Beam profile at the output of the CS_2 cell. The power increases form left to righ: a) P = 12P_{cr}, b) 40P_{cr}, c) 80P_{cr}, d) 170P_{cr}, e) 250P_{cr}, f) 390P_{cr}, g) 530P_{cr}, h) 1200P_{cr}. The critical power is P_{cr}=190KW.

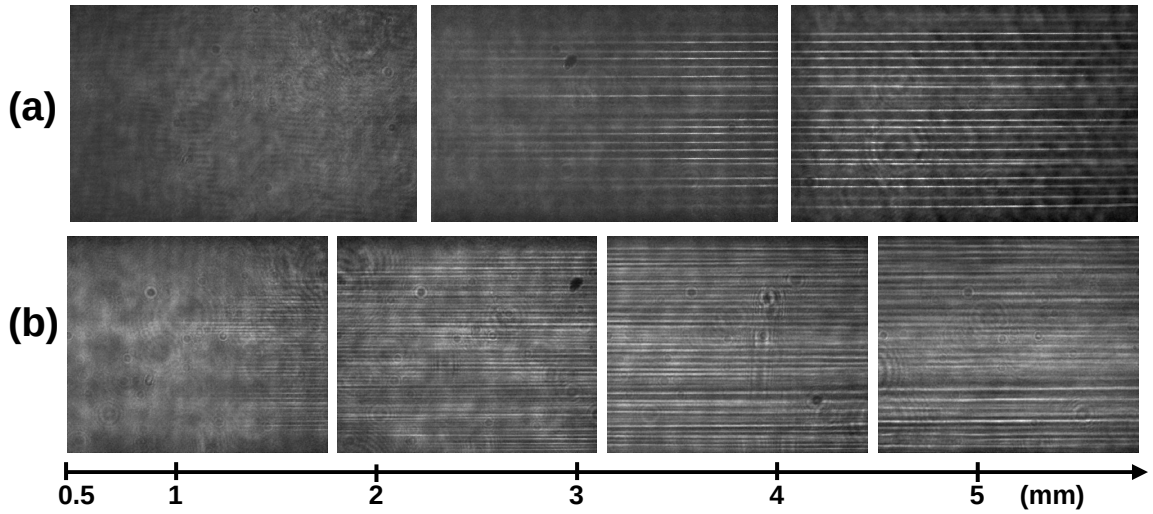

Figure 3: FTOP images of pulse filamentation. The pulse propagates from left to right. The power is $390P_{cr}$ in (a) and$1200P_{cr}$ in (b).

4. CONCLUSION

We have observed the propagation of high power femtosecond pulses in a Kerr medium as a function of input power and propagation distance. Initially the beam self focuses with a coarse redistribution of the intensity which generates some local maxima. The beam then breaks up into stable light filaments which propagate for several millimeters. Finally the number of filaments decreases, light is scattered out of the central maximum and the beam profile becomes unstable to small fluctuation in input energy. The effects of input power and propagation distance are coupled. The number of filaments changes with propagation distance, while the filamentation distance depends on input power.

ACKNOWLEDGMENTS

This work was supported by the Engineering Research Centers Program of the National Science Foundation under award EEC-9402726 and the Center for Optofluidic Integration funded by the Defense Advance Research Projects Agengy (DARPA).

REFERENCES

1. M. Fujimoto, S. Aoshima, M. Hosoda, and Y. Tsuchiya, “Femtosecond time-resolved optical polarigraphy: imaging of the propagation dynamics of intense light in a medium”, Opt. Lett. **24**, 850 (1999).
2. R Boyd, *Nonlinear Optics*, Academic Press, 2003.
3. A. J. Campillo, S. L. Shapiro, and B. R. Suydam, "Periodic breakup of optical beams due to self-focusing", Appl. Phys. Lett. **23**, 628 (1973).
4. M. Mlejnek, M. Kolesik, J. V. Moloney, and E. M. Wright, "Optically Turbulent Femtosecond Light Guide in Air", Phys. Rev. Lett. **83**, 2938 (1999).
5. L. Berge, S. Skupin, F. Lederer, G. Mejean, J. Yu, J. Kasparian, E. Salmon, J. P. Wolf, M. Rodriguez, L. Woste, R. Bourayou, R. Sauerbrey, "Multiple filamentation of Terrawatt laser pulses in air", Phys. Rev. Lett. **92**, 225002 (2004).
6. H. Schroeder and S. L. Chin, "Visualization of the evolution of multiple filaments in methanol", Opt. Comm. **234**, 399 (2004).
7. Makoto Hosoda, Shin-ichiro Aoshima, Masatoshi Fujimoto, and Yutaka Tsuchiya, “Femtosecond snapshot imaging of propagating light itself”, Appl. Opt. **41**, 2308 (2002).