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Propagation of ultrashort laser pulses through water

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Abstract: In this paper, propagation of ultrashort pulses through a long 3.5 meter water channel was studied. Of particular interest was the attenuation of the beam at various lengths along the variable path length and to find an explanation of why the attenuation deviates from typical Beer Lambert law around 3 meters for ultrashort laser pulse transmission. Laser pulses of 10 fs at 75 MHz, 100 fs at 80 MHz and 300 fs at 1 KHz were employed to investigate the effects of pulse duration, spectrum and repetition rate on the attenuation after propagating through water up to 3 meters. Stretched pulse attenuation measurements produced from 10 fs at a frequency of 75 MHz were compared with the 10 fs attenuation measurements. Results indicate that the broad spectrum of the ultrashort pulse is the dominant reason for the observed decrease in attenuation after 3 meters of travel in a long water channel. The repetition rate is found not to play a significant role at least for the long pulse scenario in this reported attenuation studies.

OCIS codes:(010.7340) Water; (320.2250) Femtosecond phenomena

References and links

1. M. Nisoli, S. D. Silvestri, O. Svelto, R. SzipO, K. Ferencz, C. Spielmann, S. Sartania, and F. Krausz, "Generation of 0.1-TW5-fs optical pulses at a 1-kHz repetition rate," Opt. Lett. **22**, 15562-1564 (1997).
2. R. W. Ziolkowski and J. B. Judkins, "Propagation characteristics of ultrawide-bandwidth pulsed Gaussian beams," J. Opt. Soc. Am. A **9**, 2021-2030 (1992).
3. M. A. Porras, "Ultrashort pulsed Gaussian light beams," Phys. Rev. E **58**, 1086-1093 (1998).
4. M. A. Porras, "Propagation of single-cycle pulsed light beams in dispersive media," Phys. Rev. A **60**, 5069–5073 (1999).
5. G. P. Agrawal, *Nonlinear Fiber Optics, 3rd ed.* (Academic Press, 2001).
6. J. C. Li, H. F. Zhang, D. R. Alexander, D. W. Doerr and N. R. Tadepalli, "Diffraction characteristics of 10 femtosecond laser pulses passing through an aperture," J. Opt. Soc. Am. A **22,** 1304-1310 (2005).
7. H. F. Zhang, J. C. Li, D. R. Alexander and D. W. Doerr, "Diffraction characteristics of a Fresnel zone plate illuminated by 10 femtosecond laser pulses," Appl. Opt. **45,** 8541-8546 (2006).
8. H. R. Lange, G. Grillon, J. F. Ripoche, M. A. Franco, B. Lamouroux, B. S. Prade and A. Mysyrowicz, "Anomalous long-range propagation of femtosecond laser pulses through air: moving focus or pulse self-guiding?" Opt. Lett. **23**, 120-125 (1998).
9. E. T. J. Nibbering, P. F. Curley, G. Grillon, B. S. Prade, M. A. Franco, F. Salin and A. Mysyrowicsz, "Conical emission from self-guided femtosecond pulses in air," Opt. Lett. **21**, 62-64 (1996).
10. M. Mlejnek, E. M. Wright, and J. V. Moloney, "Dynamic spatial replenishment of femtosecond pulses propagating in air," Opt. Lett. **23**, 382-384 (1998).
11. B. La Fontaine, F. Vidal, Z. Jiang, C. Y. Chien, D. Comtois, A. Desparois, T. W. Johnston, J.-C. Kieffer, and H. Pépin, "Filamentation of ultrashort pulse laser beams resulting from their propagation over long distances in air," Phys. Plasma **6**, 1615-1621 (1999).
12. 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**, 73-75 (1995).
13. J. N. Sweetser and I. A. Walmsley, "Linear pulse propagation in stationary and nonstationary multilevel media in the transient regime," J. Opt. Soc. Am. B **13,** 601-612 (1996).
14. L. Brillouin, *Wave propagation and group velocity* (Academic, New York, 1960).
15. O. Avenel, E.Varoquaux and G. A. Williams, "Comment on observation of the formation of the 0 π Pulse," Phy. Rev. Lett. **19**, 2058 (1984).
16. G. C. Sherman and K. E. Oughstun, "Description of pulse dynamics in Lorentz media in terms of the energy

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velocity and attenuation of time-harmonic waves," Phy. Rev. Lett. **16**, 1451-1454 (1981).
17. K. E. Oughstun, "Propagation of electromagnetic pulses in a linear dispersive medium with absorption (the Lorentz medium)," J. Opt. Soc. Am. B **5**, 817-849 (1988).
18. C. M. Balictsis, "Uniform asymptotic description of ultrashort Gaussian-pulse propagation in a causal, dispersive dielectric," Phy. Rev. E **47**, 3645-3669 (1993).
19. K. E. Oughstun and C. M. Balictsis, "Gaussian pulse propagation in a dispersive, absorbing dielectric," Phy. Rev. Lett **77**, 2210-2213 (1996).
20. H. Xiao and K. E. Oughstun, "Failure of the group-velocity description for ultrawideband pulse propagation in a causal dispersive, absorptive dielectric," J. Opt. Soc. Am. B **16**, 1773-1785 (1999).
21. K. E. Oughstun, "Asymptotic description of pulsed ultrawideband electromagnetic beam field propagation in dispersive, attenuative media," J. Opt. Soc. Am. A **18**, 1704-1713 (2001).
22. Y. Yamaoka, L. Zeng, K. Minoshima and H. Matsumoto, "Measurements and numerical analysis for femtosecond pulse deformations after propagation of hundreds of meters in air with water-vapor absorption lines," Appl. Opt. **43,** 5523-5530 (2004).
23. S. Choi and U. Osterberg, "Observation of optical precursors in water," Phy. Rev. Lett. **92,** 193903-1-3 (2004).
24. A. E. Fox and U. Osterberg, "Observation of non-exponential absorption of ultra-fast pulses in water," Opt. Express **14,** 3689-3693 (2006).
25. U. Gibson and U. Osterberg, "Optical precursors and Beer's law violations; non-exponential propagation losses in water," Opt. Express **13**, 2105-2110 (2005).
26. F. M. Sogandares and E. S. Fry, "Absorption spectrum (340-640 nm) of pure water. I. Photothermal Measurements," Appl. Opt. **36**, 8699-8709 (1997).
27. L. Kou, D. Labrie and P. Chylek, "Refractive indices of water and ice in the 0.65-2.5 μm spectral range," Appl. Opt. **32**, 3531-3540 (1993).
28. N. R. Tadepalli, D. R. Alexander, D. W. Doerr, J. C. Li and H. F. Zhang, "Femtosecond pulse stretching in microscope objectives used for micro/nanomachining," J. Laser Appl. **17**, 270-272 (2005).

1. Introduction

Due to rapid development in ultrashort femtosecond pulsed laser technology, the propagation properties of a few cycle pulsed light beams in free space and optical systems are of current research interest [1–5]. As compared with longer quasimonochromatic laser beams, the spatial and temporal characteristics of ultrashort pulses can interact with each other during propagation, which gives rise to some novel interaction phenomena; including pulse time delay, reduction of diffraction [6-7] and the degree of focusing, pulse broadening and frequency red-shifting are just a few examples. Recently, considerable attention has been paid to the nonlinear propagation of femtosecond optical pulses through different media [8–12]. However, linear pulse propagation through media is applicable for many free space optical communication purposes. John N. Sweetser and Ian A. Walmsley [13] investigated the effects of the coherent propagation of an ultrashort pulse through multilevel media theoretically and found that the transmitted field shows significant deviation from both Beer's law absorption and the conventional area theorem. This discrepancy is the same class of phenomena as the long known Sommerfeld and Brillouin precursors [14] under certain circumstances [15] and a series paper have been devoted to study the behaviors of precursors using saddle point method [16-21]. Y. Yamaoka *et al.* [22] observed pulse splitting and the enhancement of the pulse broadening due to the linear pulse propagating through 100-m in air with water-vapor absorption lines. Moreover, ultrashort pulses propagation through pure water has been studied by S. Choi *et al.* [23]. They observed the breakup of the pulse after propagating through 700 mm length of water. Recently, A. Fox *et al.* [24] observed non-exponential Beer Lambert absorption as function of path length for various femtosecond pulses propagating in pure water.

In order to further investigate the characteristics of non Beer Lambert behavior of ultrashort pulses propagating through water, this paper presents the work where different femtosecond laser pulses with different operating characteristics were used to perform additional attenuation studies and measurements through water. In the following section, results are presented on the spectra of the laser beam after propagating through different path lengths of water. In addition, attenuation of pulses of different pulse duration and different repetition rates were compared. Results indicate that the broad spectrum of the ultrashort pulse is the dominant reason for deviation from the Beer Lambert attenuation occurring after traveling a given distance. Furthermore, the current work shows that the temporal duration of

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the pulses and the repetition rate does not play a significant role in the observed deviation in the Beer Lambert attenuation as reported in Ref. [2].

2. Experiment

A mirror-dispersion-controlled femtosource Ti:Sapphire laser (wavelength 650-950 nm) was used to generate ultrashort pulses (pulse duration $\geq$10 fs). This system produces horizontal polarized pulses with the wavelength centered around 800 nm at 75 MHz repetition rate with a typical pulse duration of 10 fs and a monochromatic continuous wave (cw) beam at 800 nm along the same light path. The second femtosecond laser system consisted of a Photonics Industry regenerative amplified laser system. This amplified laser system produced approximately 100 fs laser pulses whose wavelength is centered around 800 nm. Ti:sapphire oscillator (Spectra-Physics, Tsunami) operates at 80 MHz. Approximately 300 fs pulses with repetition rate of 1 KHz from the Photonics Industries, Model TRA-50-2 can be generated using the amplifier along with the oscillator.

Optical components stretch an ultrashort pulse and change the relative phase of each spectral component. To avoid reduction of measurement of power caused by multiple reflections at the interfaces and obtain data at different path lengths, a “telescopic” water tube setup was designed for the attenuation measurement reported in this paper. In Fig. 1, a 10 fs pulse train goes through a variable length (telescopic) water tube. Before entering the tube, the reflected beams from beam splitter 1 and 2 are directed to an autocorrelator (Femtometer, Dispersion Minimized Autocorrelator, Femtolasers) and to a spectrometer (AVS-s2000, Avantes, wavelength from 530-1100 nm) so that the initial pulse duration is monitored. They are removed when the data are being collected.

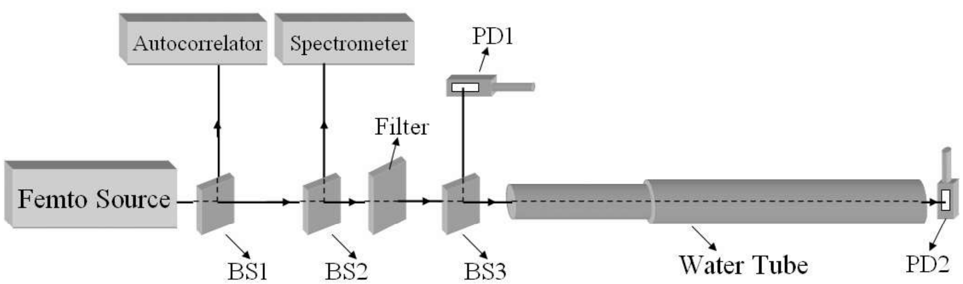

Fig. 1. Experimental setup for studying the propagation of the laser pulse through water. (BS, beam splitter. PD, photodiode detector).

In order to eliminate possible nonlinear phenomena such as thermal blooming, two-photon absorption etc., a neutral density filter was used to decrease the incident power. The power linearity of the photodiode detectors was investigated to make sure the power was within the linear range of the detectors. The reflected power from the beam splitter 3 (BS3) and transmitted power at the end of the tube were measured simultaneously by the photodiodes (PD-300-3W, PD300-SH from Ophir). A USB interface connected to the detectors allowed data to be collected on a computer at 15 Hz. A second spectrometer (Field Spec Pro. Analytical Spectral Devices (ASD) Inc. Wavelength from 450 -2500 nm) which has broader spectrum range was used to record the spectrum of the beam through water at different path lengths. The ASD spectrometer made it possible to investigate whether new frequencies might be generated during passage through any of the path lengths through the variable water length experimental setup.

3. Results and conclusion

According to Beer’s law, the attenuation of the incident power with distance through media is

$$I(z) = I_0 \exp(-\alpha z) \quad (1)$$

where $\alpha = \frac{2\omega k}{c} = \frac{4\pi k}{\lambda}$, k is the extinction coefficient, I_0 is the input power and z is the distance.

Taking the log of Eq. (1), one obtains $\log_{10}\left(\frac{I(z)}{I_0}\right) = -\left(\frac{\alpha}{\ln 10}\right)z$. Initial experiments were designed to compare the cw monochromatic beam attenuation at 800 nm to the 10 fs pulsed beam (i.e., center wavelength at 800 nm and a repetition rate at 75 MHz). In addition, the spectra of the transmitted beam after passing through the water were measured. As shown in Fig. 2, the spectrum of the original 10 fs pulsed laser beam has a broad wavelength distribution centered at a wavelength at 800 nm. Since there is relatively strong absorption of water at 750 nm and longer wavelengths, at longer path lengths the spectral intensity at 750 – 800 nm decreases and the center wavelength shifts to around 680 nm (see Fig. 3). The spectra obtained at 214 cm and 338 cm water path lengths are quite different from the shorter path length measurements where longer wavelengths are still dominant. Furthermore, theoretical calculations presented in Fig. 4 verify the experimental measurements. Similar calculations were performed [25], where an initial Gaussian spectrum was assumed and the shift of the peak was observed.

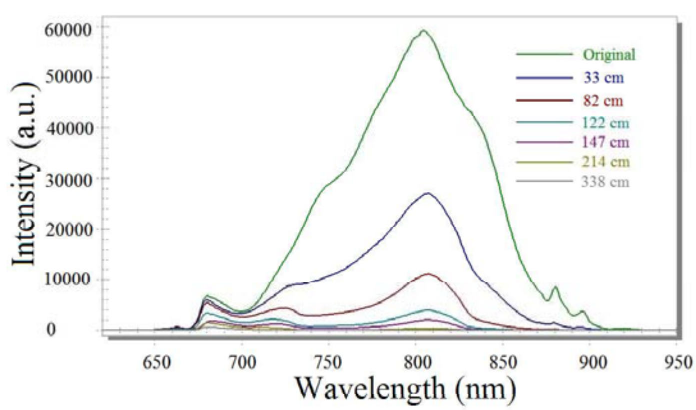

Fig. 2. The spectra of output pulsed beam at different path lengths through water.

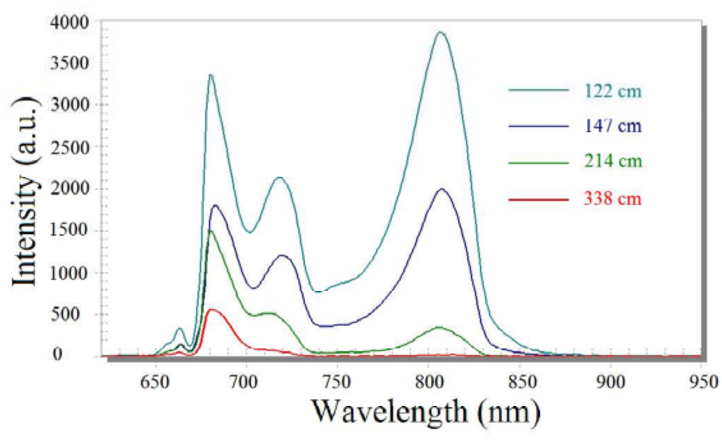

Fig. 3. The enlarged spectra of output pulsed beam at longer path lengths through water.

The inset in Fig. 4 is the water absorption coefficient from 600 nm to 1000 nm [26-27] and was used to obtain the results presented in Fig. 4. As a result of absorption along the path, the center wavelength of the pulsed laser beam shifts from 800 nm to 680 nm after propagating 200 cm through water. Power measurement results are given in Fig. 5. The dot-dash-dot and dotted lines are the theoretical Beer Lambert attenuation calculations for 10 fs pulsed beam and cw monochromatic beams through water with wavelengths at 800 nm and 680 nm using the extinction coefficients from the above references.

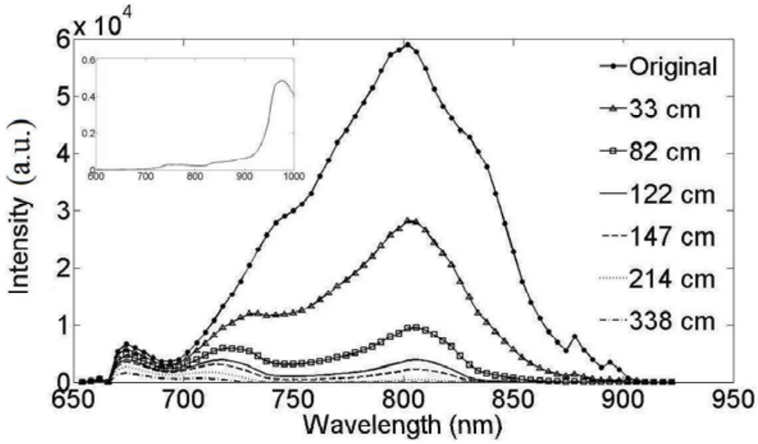

Fig. 4. Theoretical calculation of the spectra of output pulsed beam at different path lengths through water.

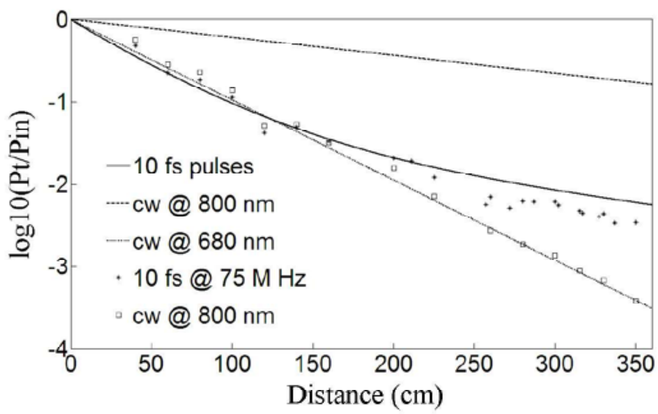

Fig. 5. The attenuation of cw beam and 10 fs pulsed beam at 75 MHz propagating through water and theoretical calculations of attenuation for 10 fs pulsed beam(solid line), 680 nm(dot-dash-dot line) , and 800 nm(dotted line) monochromatic beams.

The experimental results show that the 10 fs at 75 MHz case begins to deviate from the cw case after propagating about 200 cm in the water channel. The deviation becomes greater for increased distance beyond 200 cm. The cw data agreed with theoretical calculation based on Eq. (1), using the extinction coefficient from Ref. [26] and is shown as the dotted line in Fig. 5. The deviation from the Beer Lambert attenuation can be explained by the relative strong absorption of water at the longer wavelengths.

Ultrashort pulses experience loss resulted by each frequency component:

$$I(z)=\int_0^{\infty} I_0(\lambda)\exp(-\alpha(\lambda)z)d\lambda \tag{2}$$

Here $I_0(\lambda)$ is the original spectrum of 10 fs pulses and the absorption coefficient $\alpha(\lambda)$ is a function of wavelength.

The solid line in Fig. 5 is the theoretical attenuation of the 10 fs pulses based on Eq. (2) using the frequency dependent absorption coefficients and has similar decay trends as the experimental 10 fs pulsed laser attenuation data. As the dot-dash-dot theoretical line shows, the attenuation of the 10 fs laser pulses data tended toward the attenuation line at 680 nm after 200 cm propagation. This trend is attributed to the spectrum contents change of the pulsed beam at longer path lengths.

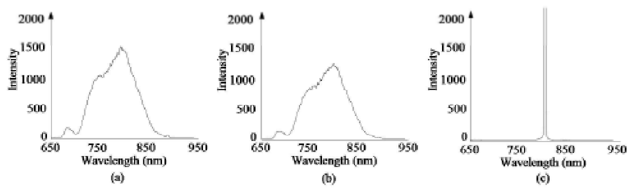

Fig. 6. The spectra of 10 fs (a), stretched pulse (b) and cw case(c).

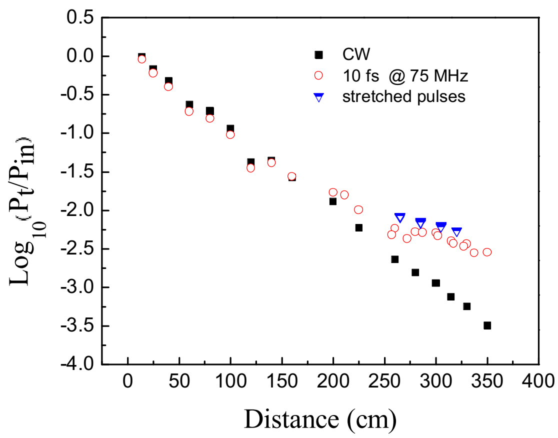

Fig. 7. The attenuation of stretched pulsed beam, cw beam and 10 fs pulsed beam at 75 MHz propagating through water.

In order to further study whether the temporal shortness of the ultrashort pulses and the repetition rate affect on the attenuation behavior in water, stretched pulses in the time domain were used in the following experiments. Different thickness of fused silica plates were used to stretch the 10 fs pulses to approximately 90 fs,140 fs, 200 fs and 250 fs [28]. It is important to note that the spectra of stretched pulses are the same as that of the 10 fs pulses except for the intensity profiles in Figs. 6(a) and 6(b). Figure 6(c) is the spectrum for the cw beam produced from the same laser system. In Fig. 7, it is shown that the stretched pulses have decreased attenuation as compared to the cw case. Since all the stretched pulses followed the 10 fs pulse data, it is concluded that the temporal shortness of the ultrashort pulses does not play a role for the decreased attenuation observation. The conclusion based on the current work is that it is the shift of absorption spectrum that leads to the attenuation difference. Our data and conclusion further explain the conclusion of A. Fox *et al*. [16].

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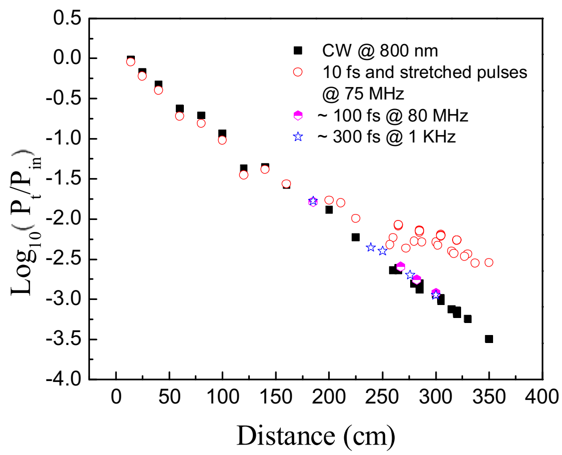

Fig. 8. The attenuation 100 fs pulsed beam at 80 MHz, 300 fs pulsed beam at 1 KHz, cw beam and 10 fs pulsed beam at 75 MHz propagating through water.

A second femtosecond laser system was employed to perform similar experiments at 100 fs pulses at a frequency 80 MHz and 300 fs pulses at a frequency 1 KHz. The results are plotted in Fig. 8. As shown in Fig. 8, 100 fs pulses at 80 MHz and 300 fs pulses at 1 KHz do not produce the previously observed deviation in the attenuation and follow the cw results. This is to be expected since the spectra of the 100 fs and 300 fs pulses generated by the femtosecond laser systems have much narrower FWHM frequency range which is approximately 10 nm for both the 100 fs and the 300 fs pulses. Both of these pulse cases do not have the shorter wavelengths in the spectrum that also have the smaller absorption coefficient values. Therefore, the attenuation of the 100 fs and 300 fs pulses essentially act like the cw beam case. Secondly, the results of 300 fs pulses at 1 KHz do not show any deviation as reported by A. Fox *et al*. [24]. This leads us to conclude that at lease when the pulse is relatively long the low repetition rate does not result in less power attenuation. This again further explains the conclusion presented in the previous work by A. Fox *et al*. [24].

Thus, the explanation for the deviation in the Beer Larmbert attenuation for femtosecond pulses, at more than 2 meter path lengths, is the broad spectrum of wavelengths that are present in the ultrashort pulse. In this work, no observation of any pulse splitting could be observed.

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