Supercontinuum Emission from Focused Femtosecond Laser Pulses in Air

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Abstract. We present our experimental results from the measurements of Supercontinuum emission (SCE) from air resulting from propagation of tightly focused femtosecond (40 fs) laser pulses. The effect of linearly polarized (LP) and circularly polarized (CP) light pulses on the SCE in two different external focal geometries (f/6, f/15) is presented. A considerable shift in the minimum wavelength of SCE is observed with external tighter focusing.

Keywords: Supercontinuum, Polarization, External focusing effects, femtosecond pulses
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INTRODUCTION

Super continuum emission (SCE) covering the visible spectral region and extending towards the infrared wavelength associated with filamentation is a well known phenomena resulting from the propagation of an intense ultrashort laser pulse through a medium, with a transverse power, P, above the threshold power for self-focusing P_{Cr} of a medium[1,2]. The SCE and filamentation is the result of dynamical balance between self-focusing and plasma defocusing. Our attention is on the filamentation and the associated Supercontinuum emission (SCE) in the tight focusing geometry. Tight focusing of the ultrashort laser pulses has many applications which include femtosecond laser microsurgery [3], therapy with laser accelerated ions [4], and direct particle acceleration [5,6]. In this article, we present the effect of tight focusing on the evolution of SCE from fs laser pulses propagating in air. We also studied the effect of polarization on SCE under the tight focusing geometry.

EXPERIMENT

The experimental setup for generating SCE from air is illustrated in figure 1. Transform limited pulses with duration of 40 fs, 800 nm, p-polarized with a repetition rate of 1 kHz (Coherent; Legend-USP) are focused into air. The amplifier was seeded with ~15 fs pulses from an oscillator (MICRA, Coherent, 1W average power, 80 MHz repetition rate, and 800 nm). BK-7 lenses of focal length 60 mm and 150 mm were used to attain the focal geometries of f/6 and f/15 respectively. The input diameter before the focusing element was 10±0.1 mm.

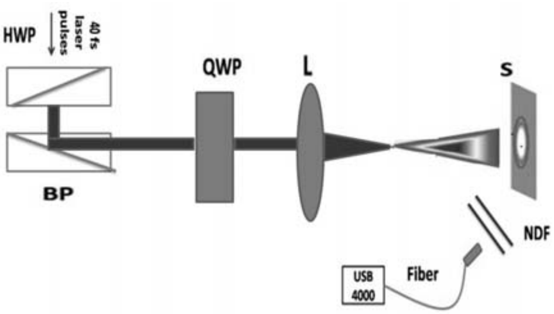

FIGURE 1. Experimental setup for investigating SCE from water using focused fs pulses. The various components in the figure are identified as follows HWP-Half Wave Plate, BP-Brewster Polarizer, QWP-Quarter Wave Plate, L- Lens, C-Cuvette, S-Screen, NDF-Neutral Density Filter.

The pulse duration was measured using *'Silhouette'* (Coherent, USA) based on the Multiphoton Intrapulse interference phase scan (MIIPS) technique. An attenuator, combination of a half wave plate (HWP) and a Brewster polarizer (BP) was used to vary the input pulse energy entering the medium. A quarter wave plate (QWP) was employed after the attenuator to change the polarization of the pulse. The SCE spot was scattered using a Teflon sheet kept at a constant distance from end face of the cuvette

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for both the focusing geometries. The scattered light was collected using a fiber optic coupled spectrometer (USB 4000, Ocean Optics Spectrometer). A set of calibrated neutral density filters were placed in front of the spectrometer to avoid saturation. SCE spectra were collected for 350 shots to reduce the noise from pulse to pulse fluctuations. The experiment was performed for both linearly and circularly polarized pulses. The pulse energy was varied from 0.8 to 1.8 mJ and was monitored using a power meter (Coherent, PM30). The critical power for self focusing can be calculated from the equation $P_{Cr} = 3.77\lambda^2/8\pi n_0 n_2$ where λ is the central wavelength, n_0 and n_2 are the linear and nonlinear refractive indices, respectively. The P_{Cr} for air is calculated to be 3GW [7].

RESULTS AND DISCUSSIONS

The SCE from tightly focused 40 fs laser pulses propagating in air have shown a central white disk surrounded by colored rings. Fig 2(a) shows the SCE spectrum observed from the propagation of linearly polarized (LP) fs pulses in air under different focal geometry and at an input power of 1.8 mJ.

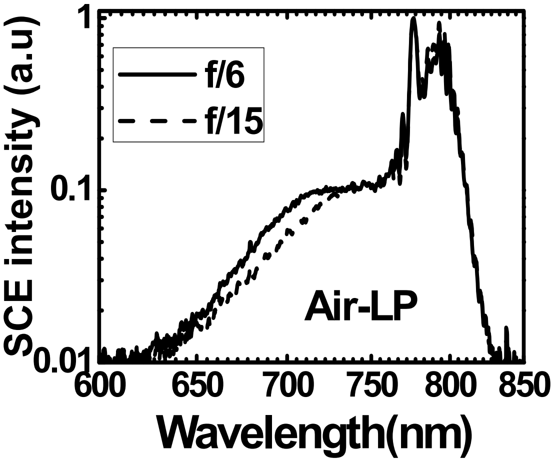

FIGURE 2. SCE spectrum from air for f/6 (black color) and f/15 (red color) focusing geometries at an input power of $12P_{cr}$

At a given input power, the SCE spectrum from both LP and CP pulses for the f/6 focusing geometry is more compared to f/15 focusing geometry which indicates the conversion of laser energy to SCE spectrum is higher for tight focusing geometry compared to loose focusing geometries. A strong blue pedestal wing for the f/6 focusing geometry indicates stronger plasma enhanced self-phase modulation.

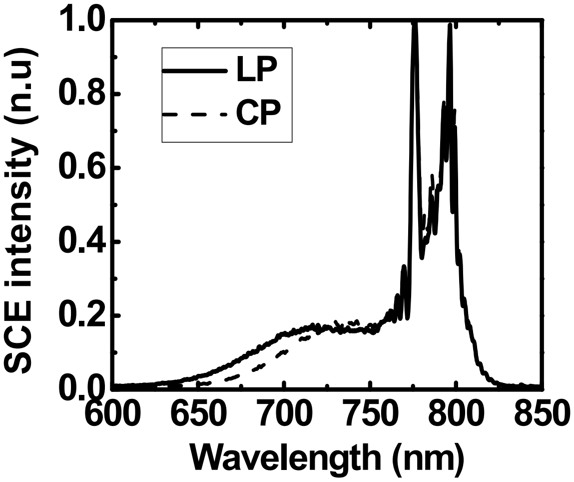

FIGURE 3. SCE spectrum from air for linearly polarized (black color) and circularly polarized (red color) fs laser pulses at an input power of $12P_{cr}$.

As the polarization of the laser is changed from linear to circular the SCE intensity is considerably reduced for all focusing geometries as reported earlier [8,9]. Figure 3 shows the variation of SCE with LP and CP pulses. The ratio of 1.5 of the critical powers for self focusing with LP and CP pulses explains the reason for MPE being less efficient for CP pulses [10].

The blue edge of the SCE spectrum i.e., the minimum cutoff wavelength (λ_{min}) or maximum positive frequency shift (ω_{max}) as a function of the input laser power from the collected SCE spectra is found to decrease continuously with increasing input power for different focusing geometries. The λ_{min} is found to be blue shifted for tight focusing conditions compared to loose focusing geometry. A similar behavior is observed in CP pulses also. Figure 4 shows the variation of λ_{min} for f/6 and f/15 focusing geometries for LP pulses. In the tight focusing geometry initial high beam curvature, due to external focusing, leads to complete ionization of the medium, in turn preventing the plasma defocusing to play an important role in the intensity clamping. [11]

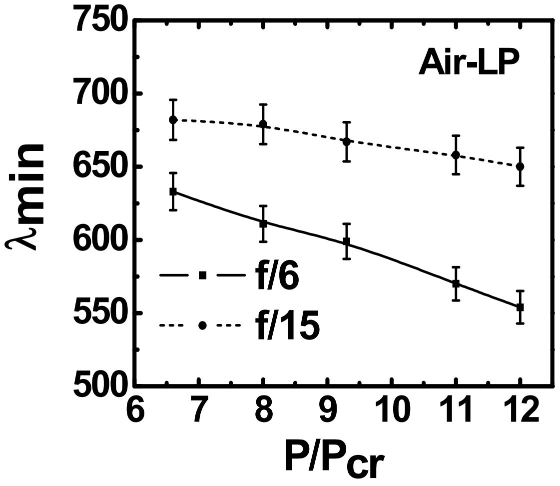

FIGURE 4. Variation of minimum wavelength (λ_{min}) with P/P_{cr} for f/6 and f/15 geometries for linearly polarized fs pulses.

CONCLUSIONS

We have studied the SCE for both LP and CP pulses resulting from the propagation of ultrashort laser pulses in air. In conclusion, there is no constant minimal cutoff wavelength for the Supercontinuum emission. This clearly indicates that under tight focusing geometries "intensity clamping" is not the ultimate limiting factor. Enhanced and extended SCE under tight focusing conditions in transparent media with table top kHz amplifiers has a potential in extending the applications of SCE to tabletop.

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REFERENCES

1. R.W. Boyd, S.G. Lukishova, and Y.R. Shen, Eds. *Self-focusing: Past and Present: Fundamentals and Prospects*, Springer Science+Business Media, Inc., New York, USA, (2009).
2. S.L. Chin, *Femtosecond laser filamentation*, Springer Science+Business Media, Inc., New York, USA, (2009).
3. C.L. Arnold, A. Heisterkamp, W. Ertmer and H. Lubatschowsdki, Opt. Exp. **15**, 10303(2007)
4. Y. I. Salamin, Z. Harman, and C. H. Keitel, Phys. Rev. Lett. **100**,155004 (2008).
5. V. Malka, S. Fritzler, E. Lefebvre, M.-M. Aleonard, F. Burgy, J.-P. Chambaret, J.-F. Chemin, K. Krushelnick, G. Malka, S. P. D. Mangles, Z. Najmudin, M. Pittman, J.-P. Rousseau, J.-N. Scheurer, B. Walton, and A. E. Dangor, Science **298**, 1596 (2002).
6. A.G.R. Thomas, A. G. R. Thomas, P. M. Nilson, M. C. Kaluza, S. Bandyopadhyay, A. E. Dangor, R. G. Evans, P. Fernandes, M. G. Haines, C. Kamperidis, R. J. Kingham, S. Minardi, M. Notley, C. P. Ridgers, W. Rozmus, M. Sherlock, M. Tatarakis, M. S. Wei, Z. Najmudin, and K. Krushelnick, Phys. Rev. Lett. **98**, 095004 (2007).
7. P. Prem Kiran, Suman Bagchi, Siva Rama Krishnan, C. L. Arnold, G. Ravindra Kumar, and A. Couairon, Phys. Rev. A **82**, 013805 (2010)
8. C. Santhosh, A.K. Dharmadhikari, J.A. Dharmadhikari, K. Alti, D. Mathur, Appl. Phys. B. **99,** 427 (2010).
9. S. Sandhu, S. Banerjee, D. Goswami, Opt. Comm. **181**,101 (2000).
10. A. Couairon and A. Mysyrowicz, Phys. Rep. **441**, 47 (2007).
11. P. Prem Kiran, S. Bagchi, C.L. Arnold, S. Sivaram Krishnan, G. Ravindra Kumar, and A. Couairon Opt. Exp. **18**, 21504 (2010).