# Supercontinuum Emission from Water using 40 fs Pulses in the External Tight Focusing Limit

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**Abstract** We present our results from the measurements of Supercontinuum emission (SCE) resulting from the propagation of tightly focused 40 femtosecond laser pulses through distilled water. The effect of linearly polarized (LP) and circularly polarized (CP) light pulses on the SCE in different external focal geometries (f/6 & f/12) is studied in detail. A considerable shift in the minimum wavelength of SCE under tighter focusing limit is observed.

**Keywords:** Femtosecond laser pulses, Propagation, Supercontinuum, polarization, tight focusing.
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## INTRODUCTION

The propagation of intense femtosecond (fs) pulses in transparent condensed media or gases is characterized by strong modification of its spatial and temporal profile due to dynamic interplay between self-collapsing of the laser pulse and associated spectral broadening due to self-phase modulation (SPM) [1-3]. The broad frequency sweep, Supercontinuum emission (SCE) of the pulse, extending from ultraviolet to the infrared range, is spectral manifestation of spatiotemporal modifications of the focused laser beam in a nonlinear medium. SCE associated with filamentation of fs laser pulses occurs when the laser power (P) exceeds critical power for self-focusing ($P_{Cr}$) in the medium [3,4]. The potential application of this phenomenon includes optical pulse compression, [5] fs-LIDAR, and remote sensing [6]. Despite wide variety of applications, generation of SCE phenomenon associated with filamentation has mainly been associated with long range propagation of intense fs laser beams in a variety of media confined to unfocused or loosely focused geometries [7,8]. While many applications using SCE require larger blue shifted spectrum, the extent of blue shift of the SCE from a medium is reported to be constant due to the phenomenon of intensity clamping [8]. In the current work, we present the effect of external focusing on the evolution of SCE spectral blue shift resulting from the propagation of focused 40 fs pulses in distilled water under different focusing geometries. We demonstrate the significance of external tight focusing on SCE for both linearly polarized (LP) and circularly polarized (CP) pulses.

## EXPERIMENTAL DETAILS

The experimental setup for generating SCE from water 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 an 8 cm long glass cuvette containing doubly distilled water. 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 120 mm were used to attain the focal geometries of f/6 and f/12 respectively. The input diameter before the focusing element was 10±0.1 mm.

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 into 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 for both the focusing geometries. The scattered light was collected using a fiber optic coupled spectrometer (USB 4000, Ocean Optics Spectrometer). A color CCD camera was used to image the self-emission from the

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propagating filament inside the water cuvette and to estimate the diameter of the energy reservoir surrounding the filament inside the medium. A set of calibrated neutral density filters were placed in front of the spectrometer to avoid saturation.

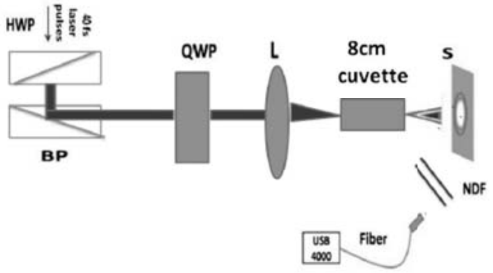

FIGURE 1. Experimental setup for investigating SCE from water using focused fs pulses. The various components in the figure are identified as follows HWP-Half Wave Plate, BP-Brewster Polarizer, QWP-Quarter Wave Plate, L- Lens, C-Cuvette, S-Screen, NDF-Neutral Density Filter

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 2 mJ and was monitored using a power meter (Coherent, PM30). The critical power for self focusing in water ($P_{Cr}$) is ~4.4 MW according to the equation $P_{Cr} = 3.77\lambda^2/8\pi n_0 n_2$ where $\lambda$ is the central wavelength, $n_0$ and $n_2$ are the linear and nonlinear refractive indices, respectively. The corresponding input powers are in the range of 3700–9100 $P_{Cr}$ for both f/6 and f/12 geometries.

## RESULTS AND DISCUSSION

The fs pulses propagating in water produced SCE with conical colored rings with predominantly white color in the central portion. The SCE spectra observed for different focal geometries of f/6 and f/12 at an input power of 9100 $P_{cr}$ for CP pulses are shown in figure 2. Tighter focusing in case of f/6 geometry has resulted in increased conversion of incident laser pulse into SCE, indicating the role of tighter focusing on the evolution of SCE spectrum in terms of the increased peak intensity at the focal plane. As the input polarization of the pulse was changed from LP to CP (simply by rotating the quarter wave plate) a reduction in the SCE intensity for both f/6 and f/12 geometries was observed, which is in agreement with earlier reports [9,10]. 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 [4].

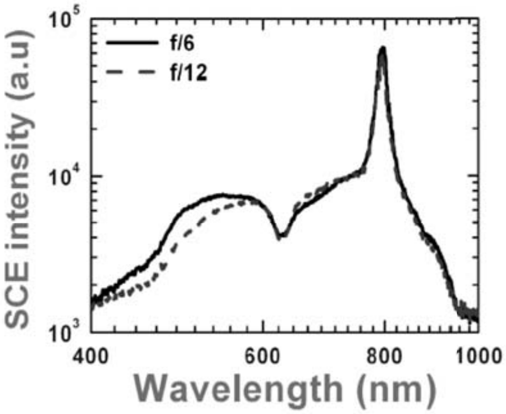

FIGURE 2. SCE spectra from water with f/6 (black) and f/12 (red) focusing geometries at an input power of 9100 PCr for circularly polarized pulses.

The blue edge of the SCE spectrum i.e., the minimum cutoff wavelength ($\lambda_{min}$) or maximum positive frequency shift ($\omega_{max}$) as a function of the input laser power from the collected SCE spectra is found to decrease continuously with increasing input power for both focusing geometries. Figure 3 shows the variation of $\lambda_{min}$ for both f/6 and f/12 focusing geometries for LP and CP pulses. The $\lambda_{min}$ is found to be blue shifted for f/6 focusing conditions compared with f/12 focusing geometry. This clearly indicates the presence of higher intensities in the vicinity of interaction region for f/6 focusing geometry revealing the blue shift of the SCE spectra due to the external focusing of the fs pulses inside transparent media

The lower bound of the maximum peak intensity around the focal plane in the f/6 focusing geometry is estimated from the diameter of the energy reservoir (**$2\omega_0$ ~360 μm)** surrounding the filament observed in the water .The intensity corresponding to 9100 $P_{cr}$ is **$9\times10^{13}$ W/cm$^2$**.The estimated intensity of ~$10^{14}$ W/cm$^2$ in the vicinity of focal region inside the medium reveals that under tight focusing conditions it is possible to go beyond the well-known "intensity clamping" phenomenon [8]. 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 any significant role in the intensity clamping. The intensities larger than the clamping values in air [11] due to the external tight focusing conditions are reported recently.

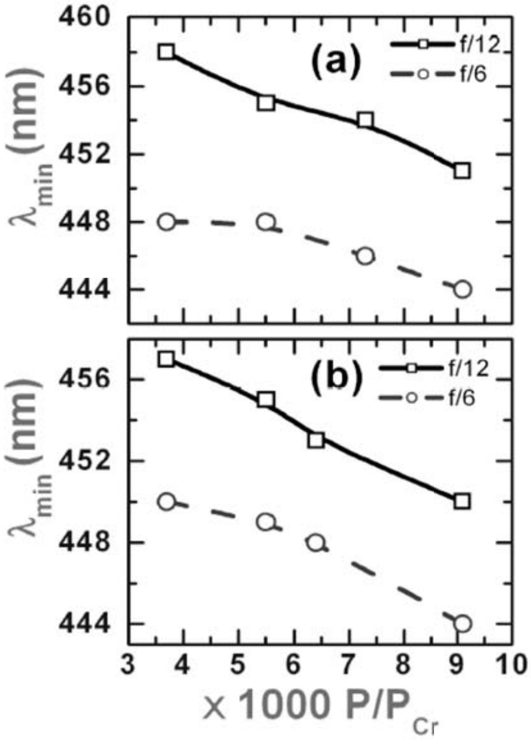

**FIGURE 3.** Variation of minimum wavelength ($\lambda_{min}$) with P/P$_{cr}$ for f/6 and f/12 geometries for (a) linearly and (b) circularly polarized fs pulses respectively

## CONCLUSIONS

In conclusion, effect of external tight focusing on the evolution of SCE resulting from the propagation of 40 fs laser pulses of both linear and circular polarization in water is studied. The SCE from tight focusing geometry is always higher than the loose focusing geometry for both LP and CP pulses. For tight focusing geometries, ultrashort laser pulse filamentation in water, the minimal cutoff wavelength ($\lambda_{min}$) for the SCE does not saturate but monotonically decreases with increasing laser intensity. This exhibits that under tight focusing conditions, the phenomenon of "intensity clamping" is not the ultimate limiting factor. Deposition of laser intensities of approximately $10^{14}$ W/cm$^2$ near the focal region with tighter focusing conditions enhancing the blue shift of SCE paves path for novel intense sources of radiation and several possible practical applications.

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