Intense and Collimated Supercontinuum Generation Using Microlens Array

Mengmeng Yue, Lihe Yan, Yanmin Xu, Vanthan Nguyen, and Tao Chen

***Abstract*— A method of high power supercontinuum (SC) generation is proposed, in which femtosecond pulses are focused into a transparent medium using a microlens array (MLA). The MLA combining a telescopic system is used to form long-path multiple filaments inside the medium, and another symmetrically arranged telescopic system and MLA are used to collimate of the emitting multiple SC beams from filaments. The reshaped stable SC beam shows a Gaussian intensity transverse distribution and similar spectra and chirp properties with that generated by single filament, while the pulse energy can be increased by more than two orders.**

***Index Terms*— Laser beams, optical pulses, optical arrays, pulse modulation.**

I. Introduction

FEMTOSECOND laser has found many applications in laser processing and ultrafast spectroscopy due to its high peak power and ultrashort pulse width since its discovery [1]–[6]. When an ultrashort laser pulse is focused into a nonlinear medium, the interplay between self-focusing, natural diffraction and plasma divergence will lead to a long self-guided structure called filament, which gives rise to an extreme spectral broadening of the pulse, termed supercontinuum (SC) generation [2]–[7]. The SC source can be generated in a number of transparent media from gases, liquids and solids providing a broadband spectral ranging from the ultraviolet to infrared [8], [9]. SC with high pulse energy will facilitate seeding ultrafast optical parametric amplifiers [10], biomedical imaging [11] and ultrafast multi-dimensional molecular spectroscopy [12], [13]. Due to its important role in fundamental researches and applications, generation of high power SC source in femtosecond regime has stimulated great research interests. Although many approaches have been proposed to increase the SC pulse energy, the damage threshold of media with high nonlinearity poses a major restriction for the improvement of SC energy because the incident pulse intensity is limited to the damage threshold of the sample [14]. Photonic crystal fibers can be manufactured with controlled dispersion to generate extremely broad and flat SC spectra. But Photonic crystal fibers is usually used to confine femtosecond laser into small-diameter cores, significantly reducing the threshold power for SC generation [15].

Focusing laser beam by microlens arrays (MLA) can form multiple filaments in transparent materials, and the SC sources emitted from individual filament have a high degree of spatial and temporal coherence [16]. Using this focusing scheme, the incident light is focused to multiple points in the material, hence high power laser can be sustained and the integral SC power can be improved dramatically. Although the MLA focusing method provides an alternative to generate high-power SC [16]–[19], some intrinsic drawbacks have limited the usage of the SC sources. First, the focus position of laser beam and the filament length have a significant impact on the conversion efficiency in the SC generation process [20]–[23]. When using MLA as the focusing elements, it's difficult to adjust the focusing conditions of laser beam facilely, and the high cost of MLA makes it impractical to change the element according to different situations [24], [25]. Second, the emitted SC arrays from the media are easily diverged in a short propagation distance and thereby impossible to be used in practical applications.

In this letter, we propose using a MLA and a telescopic system to focus the femtosecond laser into transparent medium to generate SC, which allows to adjust the focusing parameters easily. To collimate the emitting multiple filaments, another symmetrically arranged telescopic system and MLA are used. The reshaped SC beam shows a Gaussian intensity transverse distribution, and shows similar spectra and chirp properties with that generated by a single filament. The pulse energy of stable SC source is increased by more than two orders than that generated by a single filament.

II. Experiments

A schematic of our setup is sketched in Fig. 1(a). The laser source is a commercial system (Libra, Coherent Inc.), consisting of the pulses from a Ti: Sapphire oscillator, amplified through a CPA system that provides linearly polarized 60 fs Gaussian pulses centered at 800 nm, at a 1 kHz repletion rate. The laser power instability from pulse to pulse is less than 0.5 percent. A variable attenuator (VA) is used to control the input beam intensity continuously. The input beam is

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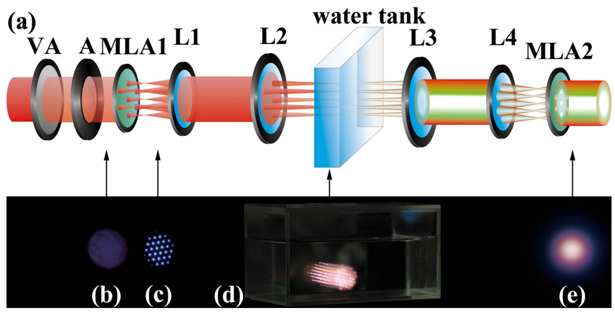

Fig. 1. Schematic diagram of the experimental setup. VA: variable attenuator; A: aperture; MLA1, MLA2: microlens array; L1, L4: lenses with focal length of 100mm; L2, L3: lenses with focal length of 200mm.

focused by a commercial 18×18 array of fused silica-based MLA (MLA1) with focal length of 40.0 mm and lenslet pitch of 1.0 mm. A circular aperture (A) is placed before the MLA to control the spot size of the input beam. The laser spot morphologies before and after the MLA are shown by Fig. 1(b) and (c), the latter of which indicates that the input laser is focused to a spots array. Due to the short focal length of the lenslet, the sub-beams diverged easily in a finite distance, and it's hard to form long filament inside transparent medium limiting the generation efficiency of SC sources. To overcome this problem, a telescope system formed by lenses of focal lengths f1=100 mm (L1) and f2=200 mm (L2) is placed after MLA1. The object plane of the telescope system is located at the focal plane of MLA1. After passing through the telescope system, the multiple beams are focused into a 50 mm cuvette filled with deionized water. By adjusting the distance of L1 and L2, we are able to control the focusing position and divergence of the incident beams facilely, and finally multiple stable filaments are generated in the medium as shown in Fig. 1(d). Every filament propagates parallelly with each other, and the filamentations sustain almost 4 cm inside the medium.

The emitted SC sources from the multiple filaments are easily diverged. For collimation, the SC sources are passed through another telescope system consisted of L3 (f=200 mm) and L4 (f=100 mm), and then another MLA (MAL2) with the same specifications as MLA1. By adjusting the distance between L3 and L4 and rotating MLA2 carefully, the multiple SC sources are finally collimated, and the morphology of the reshape SC beam is given by Fig. 1(e). The final emitted SC beam is composed of a strong central white light spot surrounded by several colored conical emission rings.

III. Results and Discussions

Firstly, the property of SC generated by multiple filaments were formed and investigated. The beam diameter of the emitted white light spot is measured to be 13.5 mm with its energy mainly distributed in the central region. Figure 2(a) shows the corresponding three-dimensional transverse intensity profile of reshaped SC beam emitted from collimating MLA. The black square in Fig.2 (b) shows the measured radial intensity distribution of the collimated SC beam. As shown by the red solid line, the radial intensity distribution can be fitted

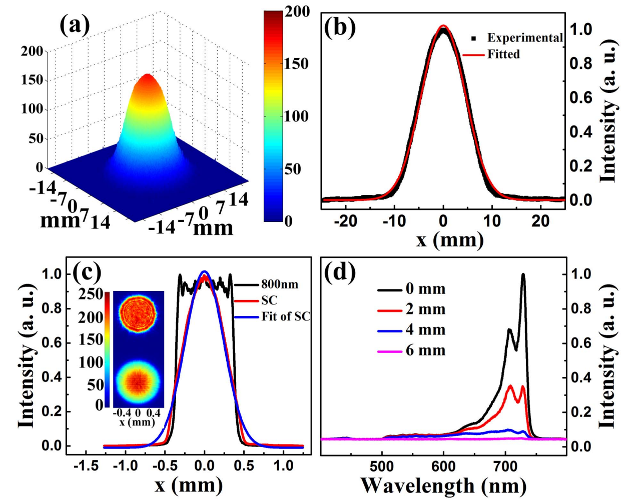

Fig. 2. (a) 3-D transverse intensity distribution of the reshaped SC beam. (b) Transverse spatial profile of the reshaped SC beam. (c) Spatial mode cleaning effect of filament. (d) Spectral content distribution of the SC at various distances from the center of a SC spot.

using a Gaussian function, indicating that the output light spot has a Gaussian mode. The divergence property of the generated SC light is also studied qualitatively. By carefully adjusting the collimating elements including L3, L4 and MLA2 shown in Fig. 1(a), the SC beam spots size can keep in a few centimeters in a several meter propagation distance. The divergence angle is enlarged compared with that of the incident fundamental laser. By selecting achromatic elements, the divergence of SC beam can be reduced effectively.

Here, we give a brief explanation about the formation of the Gaussian mode of the generated SC beam. In the case of single beam, SC emission takes the form of an intense core surrounded by weaker radiation forming a conical emission. It has been demonstrated that the conical emission had a striking feature of an excellent spatial mode quality, which could be attributed to several mechanisms such as self-phase modulation, and four-wave mixing [23]. We repeat the spatial mode cleaning effect of the filament. As shown in Fig. 2(c), when a beam with a flat-top profile (as shown by the upper graph and the black line) is focused into water using a convex lens, the generated SC beam shows a Quasi Gaussian distribution (as shown by the lower graph and the red line). In our experiments, the emitted multiple SC beams are considered to be Gaussian profiles. When they are collimated by MLA2, the beam waist and divergence of individual SC is enlarged due to the short focal length of the lenslets [26]. The superposition of the neighboring Gaussian SC beams would cause the redistribution of SC light intensity leading to a Gaussian profile at far field. In addition, the spectral content distribution of the SC at various distances from the center of the SC spot is measured and shown in Fig. 2 (d). From the center (0 mm) to the edge (6 mm), there is no significant difference in spectral content except the intensity.

Secondly, we investigate the influence of focusing characteristics on the conversion efficiency of SC. To study the influence of focal lengths of telescope system on the

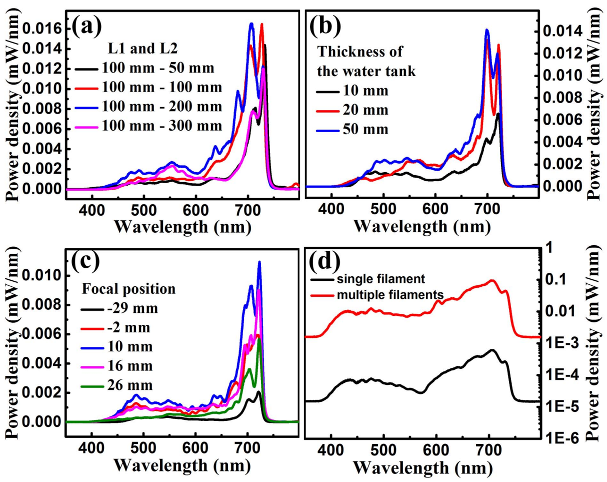

Fig. 3. The influence of (a) Focal lengths of L1 and L2, (b) thickness of the water tank and (c) focal position on the conversion efficiency of SC. (d) SC spectra measured during the generation of s single filament and multiple filaments.

conversion efficiency, the focal length of L2 is changed from 50 mm to 300 mm while the focal length of L1, input laser power and focusing position inside the water are kept the same. The power density of emitting SC as a function of wavelength is given in Fig. 3 (a). The results indicate that the power density of SC changes obviously with adjusting the focal length and numerical aperture of L2. When the focal length of L2 is fixed at 50 mm, the divergence angle of the focused beam is too large. Because the incident light is easily diverged, the length of formed filaments is short and the SC generation efficiency is low. With increasing the focal length of L2, longer filaments are easily formed inside the water, and the SC generation efficiency is increased. When the focal length of L2 become 300 mm, however, the laser spot size at the focal point is enlarged and the laser power density is decreased. As a result, the conversion efficiency of SC decreases. Under our conditions, using the combination of 100 mm (L1) and 200 mm (L2) focal length, we can get the highest conversion efficiency of SC.

The influence of the thickness of water tank on the conversion efficiency is also studied. From Fig. 3 (b) we can see that the power density of SC increases quickly with increasing the thickness of sample from 10 mm to 20 mm, and increases slightly from 20 mm to 50 mm. The thicker sample (50 mm) can ensure a longer interaction length to form a longer filament. However, when the thickness of sample is further increased, the filament length stops increasing as the laser energy might be absorbed by the induced plasma. Similarly, we studied the influence of focal position on the conversion efficiency and the results are shown in Fig. 3(c). We set the incident surface of water tank as zero point, and defined the direction of the propagation of light as positive while the direction against the propagation as negative. When the focal position moves from negative to positive, filaments are easily formed as the spot size at the incident surface of water become smaller, and the power density of SC increases. The estimated filaments increase from 19 mm to 31 mm when we adjust the focal position from -29 mm to 10 mm.

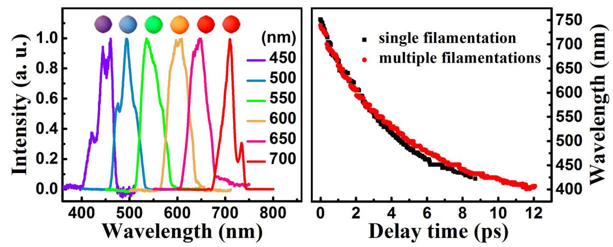

Fig. 4. (a) Chirp character of the multiple filaments SC and a single filament SC. (b) Gated spectra obtained from SC using doped tellurite glass as the nonlinear material.

The filaments length and conversion efficiency reaches the highest value when the focal position is adjusted to 10 mm. The filament length decreases to 3 mm when the focus moves to 26 mm. As a result, shortening the filament length decreases the power density of SC.

From the above experiments we can see that, the focusing parameters play important roles in generating high-power SC light. Using our setup, these parameters can be adjusted facilely, and the SC power can be increased effectively. We compared the generation power of the SC light using conventional single lens and MLA methods under the optimal experimental conditions (focal lengths of L1: 100 mm, focal lengths of L2: 200 mm, thickness of the water tank: 50 mm, focal position: 10 mm inside the water). To ensure the uniformity of the laser power irradiated on the lenslets of the MLA, the incident fundamental laser beam is expanded and passed through an aperture. The central region of the laser spot with a nearly homogeneous intensity distribution and a spot diameter of about 13 mm is incident onto the MLA. About 150 discernible filaments with naked eye are formed in the water when the laser power was increased to 212 mW carefully. Each filament emits a stable SC beam, and finally the 150 SC beams form a strong, stable and collimated SC beam after passing the collimating elements, the power of which is measured to be 8.3 mW. The typical spectrum of the emitted SC light is given by the red line in Fig. 3 (d), which covers the range from 400 nm to 750 nm above tens of μW/nm spectral power after blocking the fundamental light using a short-pass filter. The SC spectrum generated using a conventional single lens method is also plotted by the black line as shown in the figure. The SC generated by multiple filaments shows the spectrum with that generated by single filament, while the spectral power is increased by more than two orders. It should be noted that, by further increase the fundamental laser power and the spot size irradiated onto the MLA, or choosing MLA with smaller pitch size, more lenslets can be involved and more filaments can be generated, and as a result the generated SC light power can be further enhanced.

Furthermore, we measured the chirp character of the SC pulse using the typical femtosecond time-resolved optical Kerr gate method using a doped tellurite glass as the nonlinear material [27]. By varying the delay time between the gating pulse and SC pulse, gated spectra centered at different wavelength are acquired. By plotting the central wavelength of the gated spectra as a function of the delay time, the chirp character of the SC can be obtained. Figure 4(a) shows the acquired gated spectra centered at about 450nm, 500nm, 550nm, 600nm, 650nm and 700nm, respectively. The corresponding spots of the gated light are given in the inset of Fig. 4(a). The FWHM (full width at half maximum) of gated spectra is estimated to be 45nm. The black square and red circle in Fig.4(b) show the temporal distribution for different wavelength components of a single filament SC and multiple filaments SC, respectively. From Fig. 4(b) we can see that a 60fs femtosecond laser pulse focused into the water generates a SC pulse with duration of several picoseconds. The multiple filaments SC pulse shows the similar chirp character with that of a single filament, while the small difference is attributed to the dispersion of the additional optical elements inserted into the optical path when generating multiple filaments. Moreover, the intensity of wavelength between 400nm and 420nm of a single filament SC is too weak to be detected, while that of multiple filaments SC is still considerably high.

IV. Conclusion

In summary, we have demonstrated the generation of intense and collimated SC light source by using the technique based on a microlens array and a telescopic system. The use of a telescopic system allows the manipulation of the focal length facilely. Another same telescopic system and MLA are employed to collimate and reshape the emitting multiple SC beams. Intense multiple filaments SC with a Gaussian intensity distribution on the transverse plane is obtained. Comparing with that SC generated by a single filament, the SC spectral power density of multiple filaments increases by two to three orders of magnitude in the region of visible light. Furthermore, we discussed the chirp character of the emitted SC white-light pulse. We believe that the intense SC generated and collimated by use a MLA and telescopic system would be an alternative white-light source which meets the requirements of practical applications such as metrology and compression of extremely high peak power, few-cycle femtosecond pulses.

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