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# High power supercontinuum generation by dual-color femtosecond laser pulses in fused silica

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High power supercontinuum (SC) is generated by focusing 800 nm and 400 nm femtosecond laser pulses in fused silica with a microlens array. It is found that the spectrum of the SC is getting broader compared with the case of a single laser pulse, and the spectral energy density between the two fundamental laser wavelengths is getting significantly higher by optimizing the phase matching angle of the BBO. It exceeds μJ/nm over 490 nm range which is from 380 nm to 870 nm, overcoming the disadvantage of relative lower power in the ranges far from the fundamental wavelength.

**Keywords:** filamentation, supercontinuum generation, microlens array

**PACS:** 42.65.Jx, 42.65.–k, 42.72.Bj **DOI:** 10.1088/1674-1056/ac46be

## 1. Introduction

A laser beam that propagates through a nonlinear medium can form a unique structure which is termed as filamentation, accompanying a spectral broadening whose range spans from infrared to ultraviolet (UV), a phenomenon known as the supercontinuum (SC) generation.[1] Nonlinear processes that participate simultaneously in filamentation and SC generation are considered as self-phase modulation,[2] self-steepening,[3,4] and plasma formation.[5] The broadband spectral characteristics of the SC stimulate many potentials in various research fields and applications, such as gas sensing,[6,7] electronic spectroscopy,[8] cavity ring-down spectroscopy,[9] and few-cycle femtosecond pulses generation.[8,10] High spectral power of SC is one of the critical requirements of many applications such as absorption spectroscopy and oxygen saturation mapping from optical coherence tomography.[11] Our previous work has demonstrated the generation of high spectral power white-light SC from a filament array of 800 nm femtosecond laser pulses in bulk media without sample damage.[12] The diffraction pattern characteristic of microlens array (MLA) focusing was used to optimize the number and position of filaments in a bulk medium and generate a white-light SC that reaches a μW/nm spectral power at 1 kHz repetition rate in the region of 450 nm–650 nm.[12] The use of MLA as the focusing element is a promising scheme for high power SC generation in solid media. However, the spectral density in the near ultraviolet range is still very low compared with the fundamental wavelength range. If the fundamental laser wavelength is changed to 400 nm, the spectral energy density in the longer wavelength range is relatively low.[12,13] That is to say, the spectral intensity of the SC generated from filamentation is always relatively low in the ranges far from the fundamental wavelength.

To overcome the shortcoming, a dual-color laser pulse has been proposed to generate much broader SC. Dubietis *et al.* experimentally investigated filamentation and SC generation in a birefringent medium (BBO crystal), and found that the SC spectrum width between 400 nm and fundamental laser wavelength can be well controlled.[14] Furthermore, they obtained the SC generation from collinear two-color filamentation in sapphire crystal, and also found that the transition between SC generation and its extinction will occur in a narrow delay region.[15] However, the output energy of the spectral enhanced SC is still limited to the level of μJ. In this work, by using an MLA, a mJ level SC with a very broad spectral range is obtained from the dual-color femtosecond filament array in fused silica. We find that saddle-shaped SC spectra with two spectral humps can be effectively controlled by rotating the angle of a BBO crystal which is used to generate the second harmonic (SH) pulse.

## 2. Experimental setup

The experimental setup is shown in Fig. 1. The laser pulses are generated from a Ti:sapphire femtosecond laser system (Libra, Coherent Inc.) that operates at a central wavelength of 800 nm, with a pulse energy of 3.1 mJ, pulse duration of 50 fs, and repetition rate of 1 kHz. By using a BBO crystal with a thickness of 0.8 mm, SH pulses are generated, and then dual-color laser pulses are obtained. The dual-color

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pulses are focused by a $10 \times 10$ mm MLA (pitch = 1.015 mm, $f = 218.3$ mm, part number #64-487, Edmund Optics). Filament array is then formed in a fused silica block which has a length of 30 mm and is located 210 mm away from the MLA. The SC is collected by a lens into an integrating sphere and analyzed by a spectrometer (USB 4000, Ocean Optics). Alternatively, an imaging lens ($f = 100$ mm) is used to image the filaments pattern on a screen located 5 m away from the exit face of the fused silica block. A digital camera is also used to image the filaments from the side of the block.

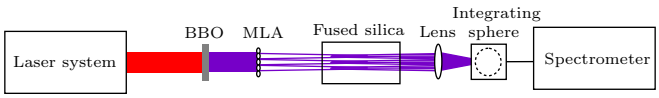



**Fig. 1.** The schematic experimental setup.

## 3. Results and discussion

A typical fluorescence image of the filament array is shown in Fig. 2(a) where we can see clearly the formation of a filament array inside the fused silica. For different BBO rotation angles, the filament array changes correspondingly. Figures 2(b)–2(e) show the filament array images in the cross section of the laser beam for several conditions. We can see that, with the increase of the BBO rotation angle, the color of the filaments changes dramatically. The filaments are getting brighter and brighter, and blue light is also getting obviously stronger and stronger.

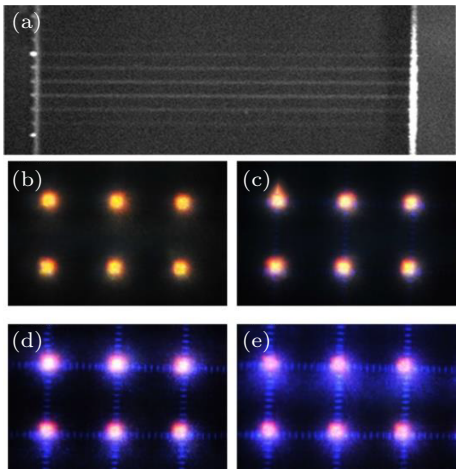



**Fig. 2.** Typical images of filament array (a) from the side view and (b)–(e) distributions for the cases of (b) 0°, (c) 40°, (d) 80°, and (e) 120° of the BBO rotation angle, respectively.

To find the spectral differences of the colorful filament array, the spectra of the output beam are measured. Figure 3 presents the SC spectrum as a function of the BBO rotation angle. It can be seen that the spectrum of the SC is getting broader and broader as the rotation angle increases from 0°, and falls after the degree of about 120°, and then start to increase again to a second high intensity at around 300° and falls again as the angle increases till 360°. Two obvious spectral humps are formed when the BBO rotation angle is 120° and 300° respectively, corresponding to the two maxima of conversion efficiency of the BBO at the two rotation angles (Fig. 4).

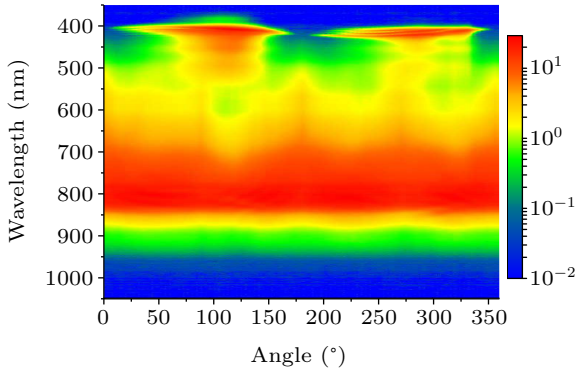



**Fig. 3.** The evolution of the SC spectrum intensity as a function of the BBO rotation angle.

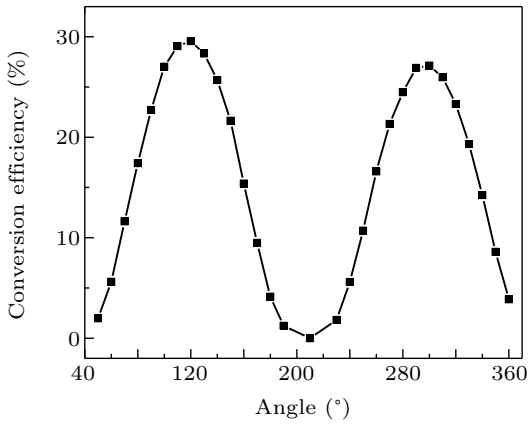



**Fig. 4.** Conversion efficiency of the BBO as a function of rotation angle.

Several typical spectra for different rotating angles of the BBO are shown in Fig. 5. At the beginning of the BBO rotation, there is no SH generation, and the SC is only generated from the filament array formed by the fundamental laser pulses. The cut-off wavelength in the blue side is about 400 nm, and the spectral energy density in this side is extreme low, which is coincident with the result in our previous work.[12,13] It is only 0.04 μJ/nm at 400 nm. However, when the BBO rotating angle is increased from 0° to 120°, the spectral energy density in the blue side increases gradually, and double-peak type of spectra emerge. It reaches 28 μJ/nm at 400 nm as the BBO is set at 120°. It is almost three orders of magnitude higher than the 0° case. The cut-off wavelength in the blue side is moving towards the ultraviolet range. On the other hand, although the spectra intensities around 800 nm are always high and do not change much with the change of the angle, the spectrum distribution between the two peaks has a dramatic change. The spectral energy density in the range of ~ 530 nm–800 nm is getting lower and lower, while the density in the range of 400 nm–530 nm has an exactly reverse change as the rotating angle of the BBO is increased from

0° to about 120°. Furthermore, a very broad spectral range covering 490 nm, which is from 380 nm to 870 nm, exceeds μJ/nm of spectral energy density. The controllable change of spectrum between 400 nm and 800 nm provides a possibility to have a kind of flat-plateau white-light laser source with a high spectral energy density. For example, one can choose the SC emission of 60° case, which is relative flat from 430 nm–600 nm and has several μJ per nm of energy density, for visible related applications. Alternatively, one can choose the SC of 120° case, which has tens of μJ per nm of energy density in the 400 nm range, for UV related applications.

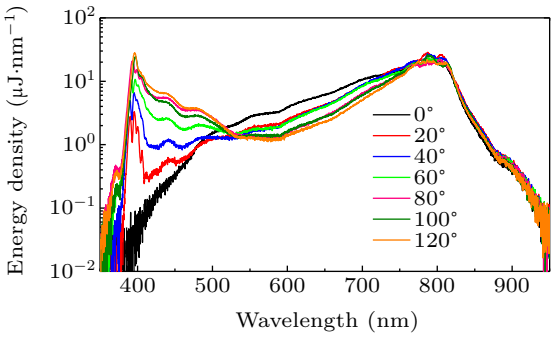



**Fig. 5.** SC spectra generated by dual-color laser pulses at different BBO rotation angles.

Furthermore, the separation distance between MLA and fused silica will also greatly influence the filamentation and SC generation.[12,13,16] Our previous experiments have demonstrated that the SC will have a maximal conversion efficiency when the front surface of the fused silica is placed around the focus of the MLA.[13] Here, we change the separation distance step by step and monitor the spectral intensity of 600 nm which locates in the middle of the saddle-shaped SC. The result is shown in Fig. 6. We can see that the spectral intensity of 600 nm is getting stronger and stronger when the fused silica position is closing to the focus of the MLA, which is coincident with that in the 400 nm laser case.[13] However, in order to reduce the risk of damage of the fused silica and get a stabler high-power SC generation, one should place the fused silica beyond the focus of the MLA.[16]

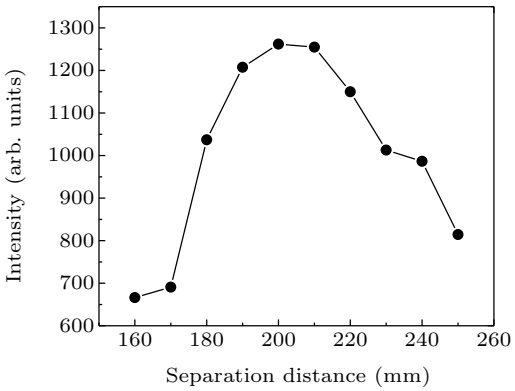



**Fig. 6.** Spectral intensity of 600 nm of the SC as a function of separation distance between MLA and fused silica.

It should be noted that in the process of filamentation and SC generation from the dual-color pulse, the fundamental laser and the SH pulse have no interaction, and the output SC is just a superposition of the spectra of the two kinds of pulses, which is justified by measuring the SC spectra of the two pulses individually. One reason is that there is a time delay between the fundamental pulse and SH pulse due to the walk-off effect in the frequency doubling process, resulting in a temporal separation of the two pules. Furthermore, the big wavelength difference of the two color pulses will bring a big difference of group velocity dispersion in fused silica, which will also enlarge the temporal separation. Another important reason comes from the fact that the evolutions of filamentation in the fused silica for the two pulses are totally different due to the Talbot effect, which leads to the spatial separation of dual-color filaments.[16] Therefore, the delicate design of the experiment is needed to eliminate the temporal and spatial walk-offs of two or multiple color pulses to obtain nonlinear enhancement of high-power SC output.

## 4. Conclusion

In this paper, we propose a simple and convenient method to generate a high-power saddle-shaped SC from a dual-color filament-array in fused silica. The SC has an output energy at the level of mJ, and the SC spectral energy density exceeds μJ/nm over the 490 nm range which is from 380 nm to 870 nm, overcoming the disadvantage of relative lower power in the ranges far from fundamental wavelength. Although the method has limitations of the fundamental and SH pulses having temporal and spatial walk-offs and the energy proportion of each color laser pulse not changing independently, it does not prevent the output SC with very high power and very broad spectral range finding various applications. It would have prominent advantages in cavity ring-down spectroscopy,[9] white-light LIDAR,[6] and other techniques which need high power SC.

## Acknowledgments

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