Intense supercontinuum generation in the near-ultraviolet range from a 400-nm femtosecond laser filament array in fused silica*

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An intense supercontinuum (SC) in the near-ultraviolet range is generated from filamentation by focusing a 400-nm laser into fused silica with a microlens array (MLA). The spectrum of the SC is shown to be sensitive to the distance between the MLA and fused silica. In our optimal conditions, the near-ultraviolet SC can cover a range of 350–600 nm, where a bandwidth of approximately 55 nm above the 1μJ/nm spectral energy density and 20 nm bandwidth with tens of μJ/nm are achieved. In addition, the energy conversion efficiency of the 400 nm laser for SC generation is further analyzed. A maximum conversion efficiency of 66% is obtained when the entrance face of fused silica is set around the focus of the MLA.

Keywords: filamentation, supercontinuum generation, microlens array, fused silica

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1. Introduction

High spectral energy density supercontinuum (SC) produced by femtosecond filamentation has attracted a great deal of attention for many years due to its various applications, such as in carried-envelope phase stabilization,[1,2] metrology,[3] microscopy beyond the diffraction limit,[4] optical coherence tomography,[5] and cavity ring-down spectroscopy.[6,7] For these applications, an SC source is required with controllable wavelength coverage, high spectral energy density, and stable emission. For some applications, ultraviolet absorption detection for example, a high energy near-ultraviolet SC source is needed. As a white light source, a near-ultraviolet SC is usually generated by filamentation of a femtosecond laser pulse with a central wavelength of 800 nm in transparent media.[8] The generation of SC by filamentation mainly results from several nonlinear effects, such as self-phase modulation, self-steepening, and electron generation.[9] With a relatively high nonlinear coefficient, fused silica is commonly used as a transparent optical medium for the filamentation of femtosecond laser pulses.[10] Meanwhile, the free electron density of a filament in fused silica is higher than that generated in some other often-used media, such as water and gas, making the SC more intense.[11] However, the output energy of the SC is limited by the damage threshold of fused silica.[12] In our previous work, the use of an MLA redistributes the laser energy and breaks the limitation of the input laser energy for the single focal lens case in solid optical media.[13,14] In this case, a filament array which contains more filaments is generated and acts as a coherent emission source emitting more powerful SC. The spectral power in the visible region reached the mW/nm-level, but only 0.01 mW/nm in the near-ultraviolet region. In order to enhance the near-ultraviolet SC power, the filamentation of a 400 nm laser, instead of an 800 nm laser, could be used to enhance the emission. On the other hand, the filamentation of a 400 nm laser occurs easily with higher electron densities due to the stronger ionization ability.[15] The features of 400 nm laser filamentation would benefit the generation of SC in the near-ultraviolet region.

In this work, we adopt the same MLA element used in our previous work[14] to form filament arrays in fused silica by using femtosecond laser pulses with a central wavelength of 400 nm. A strong near-ultraviolet SC emission with a spectral energy density of up to tens of μJ/nm is generated for the first time to the best of our knowledge. The energy conversion efficiency of the obtained SC is further analyzed.

2. Experimental setup

The experimental setup is shown in Fig. 1. An amplified Ti:Sapphire femtosecond laser system (Libra, Coherent Inc.) with a central wavelength of 800 nm and pulse duration of 50 fs at a repetition rate of 1 kHz was used. Its maximum output pulse energy is 3.6 mJ. A BBO crystal was used for the frequency doubling to have 400 nm laser pulses. Mirrors

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with a high reflectivity at 400 nm and high transmission at 800 nm were put to filter out the fundamental laser. A maximum energy of 870 μJ can be obtained for a 400 nm laser pulse by adjusting the BBO angle. The laser was focused by an MLA which has a size of 10×10 mm^2 with a focal length of 218.3 mm and a pitch of 1.015 mm. A fused silica block with a length of 50 mm was placed in a translation plate, which was used to modulate the distance between the MLA and fused silica precisely. A plano-convex lens with a focal length of 200 mm was also used for the SC emission comparison with the case of MLA. The SC emission was collected by an integrating sphere and recorded by a spectrometer. Neutral density filters were used for changing the laser energy.

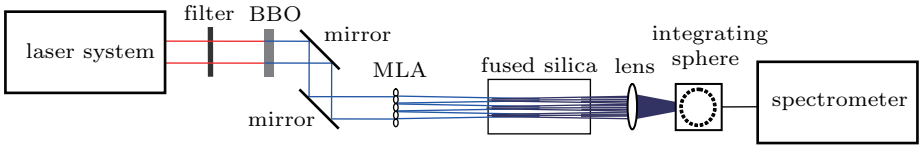


Fig. 1. (color online) Experimental setup.

3. Results and discussion

When the fused silica was placed at 230 mm away from the MLA and 160 mm from the single lens, respectively, the spectra of the output laser beam were measured and are shown in Fig. 2. For the case of a single lens, 80 μJ of 400 nm laser energy was used to avoid damaging the fused silica. As a result, the broadening of the SC spectrum is limited to a range from about 380 nm to 450 nm and the spectral energy density of the SC is relatively low. However, in the case of the MLA, the input laser energy can be increased further without any damage to the fused silica. With the increase in laser energy, the range of the SC spectrum becomes broader and the intensity of the SC becomes higher. The spectrum can cover a range of around 350–600 nm for the optimal conditions in the experiment. In fact, the spectrum can reach deeper into the ultraviolet side if there is no 350 nm spectral limitation of the spectrometer used in our experiment. The energy density of the SC in the near-ultraviolet range is one order of magnitude higher than that by the single lens, and three orders of magnitude higher than that generated by filamentation of the 800 nm laser with MLA shown in our previous work.[13] In particular, the spectral energy density of SC near 400 nm reaches the order of tens of μJ/nm when 870 μJ of laser energy, which is the maximum energy that can be obtained in our experiments, was used. Therefore, the use of a 400 nm laser and MLA is beneficial to the generation of near-ultraviolet SC. Furthermore, although the output SC is emitted from individual filaments formed by the MLA, it shows a near-Gaussian intensity transverse distribution, as shown in the inset of Fig. 2.

The characteristics of the SC are shown to be dependent on the distance between the MLA and fused silica. Figure 3(a) shows the SC spectra generated by the 400 nm laser with pulse energy of 870 μJ as a function of the different separation distances between MLA and fused silica. It can be seen that when the entrance face of the fused silica is located before the focus of the MLA, the spectral range becomes broader with the increase in the separation distance and reaches a maximum as the entrance face approaches the focus of the MLA. When the entrance face of the fused silica is beyond the focus, the spectral broadening is weakened. The behavior of the SC evolving with the separation distance is similar to that of SC generated by IR laser which results from the evolution of the multiple filaments with the propagation distance.[16]

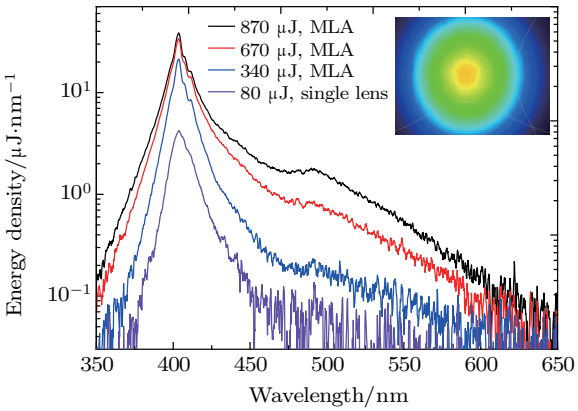


Fig. 2. (color online) Typical SC spectra generated by the MLA with different incident laser energies, and by a single lens with incident energy of 80 μJ. A CCD image in false color of the SC beam in the far field is shown in the inset.

In order to quantitatively study the near-ultraviolet SC spectrum, the energy conversion efficiency of the 400 nm laser is calculated by defining it as the energy ratio of the continuum part (except the central spectrum range of 394–406 nm) to the whole. Figure 3(b) shows the conversion efficiency of the SC as a function of the separation distance between MLA and fused silica for 870 μJ incident laser energy. The conversion efficiency, whose evolution is coincident with that of the spectral range shown in Fig. 3(a), increases firstly with separation distance when the fused silica is located before the MLA focus and then reaches its maximum as the separation distance approaches the focus. A maximal conversion efficiency of 66% is achieved. Beyond the focus, the conversion efficiency decreases with the separation distance.

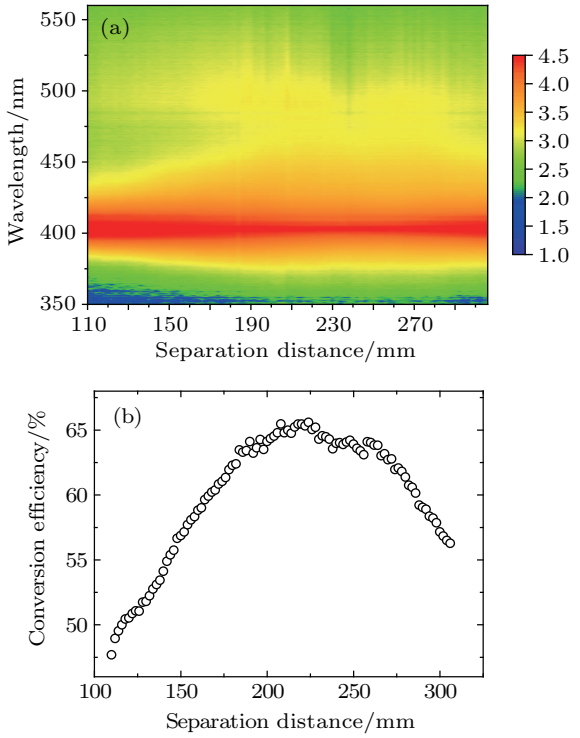


Fig. 3. (color online) (a) SC spectrum plotted in logarithmic scale (arbitrary units) and (b) corresponding conversion efficiency generated by 400 nm laser filamentation as a function of separation distance between MLA and fused silica. The laser pulse energy of 870 μJ was used.

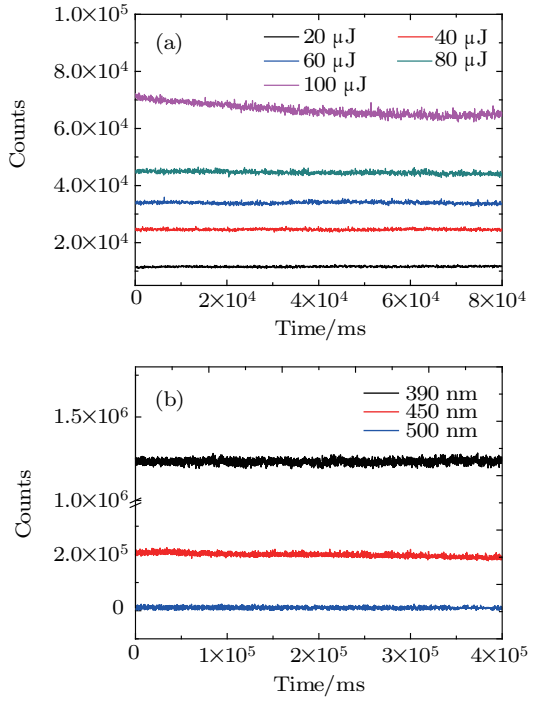


Fig. 4. (color online) (a) Counts evolution in the pixel of the spectrometer corresponding to 390 nm with different incident laser energies for a single lens case. (b) Counts evolution in three pixels of spectrometer corresponding to 390 nm, 450 nm, and 500 nm respectively, with 870 μJ incident laser energy.

In the case of a single plano-convex lens with $f =$ 200 mm, the input energy is limited to avoid damaging the fused silica. We attempted to avoid damaging the fused silica for a single lens. The source stability is evaluated by monitoring the count number with the increasing energy, as shown in Fig. 4(a). It is found that when the incident laser energies are 20 μJ, 40 μJ, 60 μJ, and 80 μJ respectively, the corresponding time evolutions of the counts at 390 nm appear as flat lines, which indicates no damage in the fused silica. However, when the energy is increased to 100 μJ, the curve of the count evolution becomes unstable, which is not linear with the time any more. It indicates damage in the fused silica caused by the strong filamentation induced by the higher input energy.[17] For the MLA case, the counts in three pixels of the spectrometer corresponding to 390 nm, 450 nm, and 500 nm, respectively, were monitored. It is shown in Fig. 4(b) that there is no phenomenon of damage in the fused silica when 870 μJ of incident laser energy was used. Thus, it can be concluded that the use of the MLA as the focal element to form a filament array in the fused silica allows a higher incident laser energy, and benefits the enhancement of the output energy of the SC in the near-ultraviolet range when the 400 nm laser is used.

4. Conclusion

We have demonstrated that the SC generation in the near-ultraviolet range from femtosecond filamentation can be greatly enhanced by using an MLA as the focal element and 400 nm laser, double frequency Ti:Sapphire laser, as the incident laser. The spectral energy density reaches the level of μJ/nm in the range of 370–525 nm, and tens of μJ/nm in 393–417 nm under our experimental conditions. We also found that the SC emission is strongly dependent on the separation distance between the MLA and fused silica. When the entrance surface of the fused silica was located around the focus of the MLA, the SC has a higher energy conversion efficiency from the 400 nm laser to other spectral regions. Compared with the cases of the single lens as the focal element, and generally using 800 nm laser as the incident laser, focusing a 400 nm laser into fused silica with an MLA is an effective method to generate high energy near-ultraviolet SC which is coherent and is very useful in various fields,[18] including biological applications,[19–21] photochemistry,[22] laser absorption spectroscopy,[23] and so on. However, the SC beam has a bigger divergent angle due to the external focusing by the MLA. Therefore, further efforts should be done to collimate it, for example by using another MLA with the same parameters.

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