Enhancement of third-harmonic emission from femtosecond laser filament screened partially by a thin fiber

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The third-harmonic (TH) emission characteristics from femtosecond laser filament, the center of which is screened by a thin metallic fiber, are experimentally investigated. The intensity of the TH emission has been enhanced for 1 order of magnitude by comparing with the undisturbed filament. The physical mechanism of the TH enhancement is analyzed to be the diffraction of the TH emission on the fiber and a redistribution of laser energy during the reconstruction of the two-colored filament. These two factors can release a part of the TH energy from the filament core into the background and keep more TH energy after the termination of filament. © 2010 Optical Society of America

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When ultraintense femtosecond laser pulses propagate in air, a long self-guiding plasma filament can be generated in the results of the dynamic balance between the nonlinear Kerr self-focusing and plasma defocusing. Besides long filamentation, there are many interesting phenomenon such as supercontinuum generation, third-harmonic (TH) emission, conical emission, etc. The TH emission is a fundamental process during the femtosecond laser filamentation, which has the potential applications in remote sensing and achieving high-intensity coherent UV light sources [1–3]. The dynamics of the copropagation of fundamental wave (FW) and TH have been investigated intensively under various conditions, such as different wavelengths, pulse durations, divergent angles, and focusing conditions [4–15].

Earlier theory and experiment showed that, in the single filamentation regime, the evolution of the peak intensity of the TH emission follows that of the FW. When the FW filament terminates, the TH emission almost disappears because the phase-matching condition between the FW and TH is difficult to be realized. However, artificially inducing some disturbance for laser field is a possible way to change the phase relationship between the FW and TH, and to enhance the TH emission [16–19]. Suntsov *et al.* investigated the TH emission from a filament perpendicularly crossed with a plasma string generated by another laser pulse, and the enhancement of the TH emission for 2 orders of magnitude was observed [20]. Xi *et al.* performed numerical simulations on the TH emission from femtosecond laser filament, the center of which is screened by a small droplet [21]. The great enhancement of the TH emission was also obtained. The main mechanism was analyzed to be the reconstruction of filament and diffraction of the TH on the droplet.

In this Letter, we have experimentally confirmed the theoretical prediction of Xi *et al.* in [21]. In order to simplify the experimental setup, we used a thin copper fiber of 60 μm diameter to screen the filament core, instead of a droplet. The significant enhancement of the TH emission for 1 order of magnitude was observed from the disturbed filament.

The laser system used in the experiment is a homemade Ti:sapphire chirped-pulse amplification system, which can deliver 30 fs pulse with up to 640 mJ energy in the best condition. The central wavelength is close to 800 nm and the repetition rate is 10 Hz. For the experiment reported here, the pulse energy was set to be 4.5 mJ to achieve the single filament regime. The real pulse duration measured by an autocorrelator was 50 fs. The laser pulse was focused using a lens with a 4 m focal length. A copper fiber with a 60 μm diameter was placed perpendicularly into the optical path of the laser filament as shown in Fig. 1. The fiber could be moved along the filament or in the transverse direction. A spectrometer was placed at 656 cm distance from the focus lens. After the termination of filament, the laser beam was collected into the slit of the spectrometer by a quartz lens with a 120 mm focal length. Before putting the collection lens, we injected the laser into the slit of spectrometer directly (only with attenuators that did not affect the divergence angle of the laser beam) and checked the beam size by moving the spectrometer transversely. It was shown that the sizes of both the FW and TH beams were much smaller than our col-

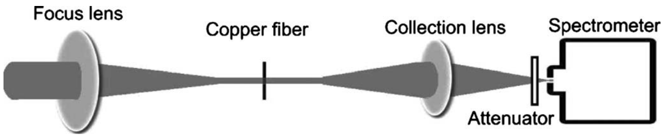

Fig. 1. Experimental setup.

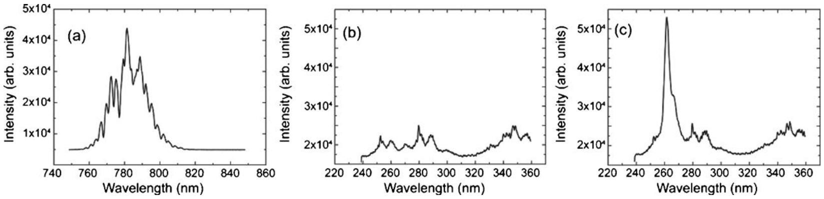

Fig. 2. Spectrum of (a) FW and (b) TH emission from undisturbed filament; (c) spectrum of TH emission from copper fiber-screened filament.

lection lens. The size of the fiber-screened TH beam at the position of the spectrometer did not change significantly as that of the unscreened case. So we can make sure that all the TH emission energy has been collected into the spectrometer. The spectra of the FW and TH were detected with different attenuations.

A single filament was generated using a femtosecond laser pulse with 4.5 mJ energy. The filament started from about 440 cm and terminated at about 500 cm distance after the lens. We firstly measured the spectra of the FW and TH from the undisturbed filament as a reference. In our experiment, the real central wavelength of the FW was about 780 nm as shown in Fig. 2(a). The wavelength of the TH was expected to be about 260 nm. We can find in Fig. 2(b) that the TH emission can be detected but the intensity is very low, which is just a little above the background level. Figure 2(c) is a sample of the TH emission spectra obtained with the copper fiber placed across the filament center at 474 cm distance after the focus lens. Figures 2(b) and 2(c) were obtained with the same attenuation and plotted in the same scale, so the spectral intensities can be directly compared. We can see much stronger TH emission at 260 nm in Fig. 2(c). These signals in Fig. 2 included the noise from the spectrometer and the environment. We can see that the noise intensity is about 1.5×10^4 from Figs. 2(b) and 2(c); the TH intensity should subtract this noise intensity. In this way, we can find that the intensity of the TH emission was enhanced by about 1 order of magnitude.

Although the experimental setup was a little different from [21], which used a 40 μm diameter droplet to screen the filament, the basic mechanism should be the same as in detail analyzed in [21]. As for the fundamental filament, most of the energy is located in the background. For the TH filament, most energy is concentrated in the core. In the undisturbed case, the TH emission—acting as an oscillating component of the FW—will be clamped with the intensity of the FW [13]. The conversion of the TH is very low after the termination of the FW filament. For the disturbed filament, firstly, both FW and TH undergo some energy loss due to the screening of the copper fiber and then the background energy replenishes the filament core, but due to the diffraction on the copper fiber, part of the TH energy is transported to the low-density background. Secondly, the reconstruction of the two-colored filament causes a strong fluctuation of the laser field, and during this process the coherent length between the FW and TH can be increased [13]; this situation causes a significant local enhancement of the TH emission. After the establishment of a new filament, the TH intensity follows the FW again in the core, but part of the TH energy also escapes the core area during the reconstruction of the two-colored filament.

In order to find the optimal position of the fiber, we moved the fiber along the filament and in the transverse direction. Figure 3 shows the dependence of the TH emission intensity on the position of the copper fiber along the transverse direction with 10 μm resolution. The position $x=0$ indicates the center of the filament. We can see from Fig. 3 that the efficient enhancement can be achieved only when the fiber screens the filament center, because screening the filament center can induce the filament reconstruction with a strong fluctuation of the laser field. This effect can provide valuable support of the mechanism of the TH enhancement described above. The copper fiber was also moved along the laser propagation direction from the filament beginning to its end. The position in the transverse direction was fixed in the center of the filament.

The TH emission intensity with the fiber placed at different positions along the filament is presented in Fig. 4. We can see from Fig. 4 that the enhancement of the TH emission can be achieved when the fiber is placed from 460 cm to less than 490 cm. Actually the dependence of the TH emission on the position of the fiber is essentially matched with the longitudinal distribution of energy density of the undisturbed filament. The maximum of the TH energy is achieved only when the fiber is located in the strongest part of the filament. This is in good agreement with the result in [20].

In conclusion, we have experimentally investigated the TH emission from femtosecond laser filament, the center of which was screened by a thin copper fiber. Significant enhancement of the TH emission has been observed by screening the filament as the theo-

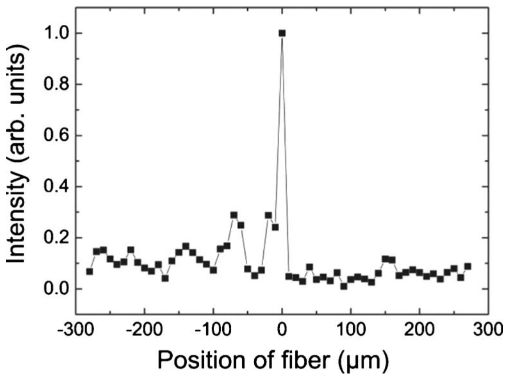

Fig. 3. TH emission intensity as a function of the position of the fiber along the transverse direction.

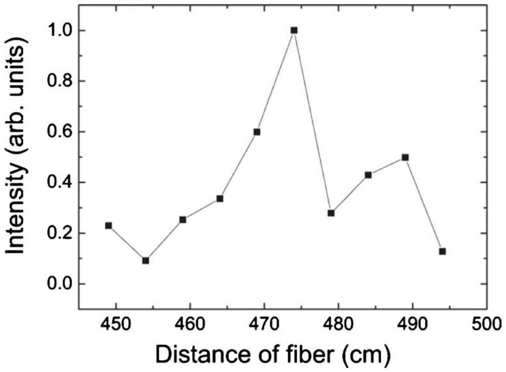

Fig. 4. TH emission intensity as a function of the position of the fiber along the filament.

retical prediction in [21]. The diffraction of the TH emission on the fiber and the reconstruction of the two-colored filament lead to a redistribution of the energy. Part of the TH energy is transported into the low intensity background area and can survive after the filament termination.

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