Self-steepening is an abrupt process

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Abstract

We discover that self-steepening occurs so fast with slight change in the input energy that it could be considered as an on–off process whose potential application could be far reaching. This observation was carried out by generating a stable uniform pattern of femtosecond filaments inside a methanol cell and measuring the evolution of the white light spectra. We found that the white light supercontinuum, a consequence of self-steepening, turned on almost instantaneously with respect to a very slight change in the energy.

1. Introduction

Ultrafast laser science has developed rapidly during the last decade [1–7]. A large amount of work has been done on the physics of propagation and interaction of ultrafast pulses in solids, liquids, and gases. The nonlinear propagation results in a variety of physical phenomenon such as self-focusing, self-phase modulation (SPM), filamentation, supercontinuum generation, and self-steepening, etc. [8].

SPM in a neutral optical medium is caused by the temporal variation of the refractive index. The consequence is a symmetric spectral broadening towards both the red and the blue sides (stokes and anti stokes broadenings) [9,10]. Another consequence of the intense femtosecond pulse propagation is self-steepening. Self-steepening is a direct consequence of self-focusing. Due to self-focusing the front part of the pulse propagates slower that the back part of the pulse resulting in the steepening of the pulse. Self-steepening of the pulse causes a sharp drop at the trailing part of the pulse resulting in an asymmetric broadening of the spectrum of the pulse towards the blue [8,10–12]. Mainly due to these two phenomena, the spectrum of the pulse extends from the near UV to near IR which is popularly called white light (supercontinuum) generation [3,13–15].

Theoretical calculation by Gaeta [12] show that as the power of the pulse approaches certain threshold power (collapse point), the peak intensity grows sharply. This results in the formation of a steep edge at the back of the pulse (i.e., an optical “shock wave”) and is accompanied by a large phase jump. A closer look at the spectra obtained after free propagation of intense femtosecond laser pulses in different condensed media at different input laser energies by Liu et al. [10] show that there is a fast broadening (corresponding to the large phase jump in Gaeta’s work [12]) towards the blue at a certain threshold energy. However, this fast broadening was never studied in more detail.

Centurion et al. [16] observed a phase transition to a faster filamentation rate at the onset of conical emission. They attribute this to the interaction of conical emissions with
the constellation which creates additional filaments. In another experiment to investigate the coherence properties of a linear array of white light sources produced in bulk media by ultrashort laser pulses [17], no significant spectral broadening occurs up to a well defined value of the input pulse energy, above this energy limit a sharp increase in generation efficiency takes place followed by saturation. They explained this behavior based on modifications in the spatial profile of the pulses due to self-focusing. At low power the pulses do not suffer sufficient self-phase modulation to significantly broaden their spectrum, at some point they reach the critical power for self-trapping and the intensity in the so-formed filament suddenly increases and gives rise to the new spectral components in the visible region.

In this work we observe experimentally that this fast broadening which is the consequence of self-steepening [11,12] turns on almost instantaneously with slight energy change. To make this observation, we spatially modulate intense femtosecond laser pulses using a mesh to produce a periodic structure of the diffraction pattern. The diffracted beam is sent through a methanol cell to produce predictable and highly reproducible filamentation patterns [18–20]. This is done to avoid multiple random filamentation. We record the white light as a finger print of self-steepening. We observe that right after the threshold of white light generation, the energy of the white light increases sharply by increasing the pump energy by just a little bit indicating that self-steepening is almost an on–off process. This phenomenon could be used for fast switching purposes and its application could be far reaching. This experiment is in agreement with the theoretical calculation of Gaeta’s work [12].

2. Experiment and results

A pulsed Ti:Sapphire laser beam with repetition rate of 10 Hz, pulse duration of 44 fs (at FWHM) with central wavelength of 810 nm is used in this experiment. The pulse has a bandwidth of 23 nm (FWHM) with linear polarization. The pulse energy can vary from 0.1 to 14 mJ. The top view of the experiment setup is shown schematically in Fig. 1. The laser beam passes through a metallic mesh (1) (square mesh with 240 μm center to center and 24.4 μm wire thickness) and enters a 1 cm thick cell filled with methanol (2). The mesh is fixed on a translation stage at a distance of 15 mm from the cell. This is the distance where the Fresnel diffraction reconstructs the image of the mesh on the entrance of the methanol cell. After the methanol cell we put a broadband dielectric mirror (3) reflecting around 800 ± 75 nm to eliminate any transmission of the fundamental laser pulse to the CCD camera (9) (Cohu model: 4810). A green filter (5) (centered at 510 nm, bandwidth, 165 nm) is put in front of the CCD camera. Also for some sets of experiment we used neutral density filters (6) and later on we calibrate the images accordingly. As shown in the setup a lens with f = 180 mm (4) is used to image the exit surface of the methanol cell onto the image screen (7). Another lens with f = 5 cm (8) is put after the image screen to direct the formed image onto the entrance of the CCD camera.

In Fig. 2, we show twelve sets of diffraction patterns for different input energies measured right after the mesh, starting from 0.219 to 0.477 mJ. At 0.21 mJ which is near the threshold energy, a few bright diffraction spots (filaments) start to appear. These spots are located exactly in the shadow region where the wires cross and they blink (turn on–off) from shot to shot. Below this energy, no spots are produced. By increasing the energy to 0.266 mJ, although the spots get more stable and their number increases, sometimes some of them still blink. At the moderate energy of 0.284 mJ and higher, stable spots in each laser shot are observed. Also new spots start to show up between the initial spots.

Using the same setup as shown in Fig. 1, we direct the output beam from the methanol cell to a spectrometer. All filters are removed but the 800 nm mirror is kept in front of the spectrometer. We record the spectra at twelve different energies. Fig. 3 shows four representative examples at energies (0.196 mJ dashed line, 0.213 mJ dotted line, 0.228 mJ dashed-dot line, and 0.616 mJ dashed-dot-dot line) in a semi-log plot (remark: due to using the 800 ± 75 nm reflecting mirror in front of the spectrometer, the spectra above 725 nm and below 875 nm are blocked; therefore the peaks at 725–1000 nm are artificial). The solid line in Fig. 3 is the spectrum of the input laser beam taken at very low energy without the 800 nm reflecting mirror by sending the laser output beam directly to the spectrometer. Fig. 3 shows a sudden and big increase in the broadening towards the blue side when the energy changes from 0.196 to 0.228 mJ. After this point, increasing the energy does not broaden the spectrum anymore.

For further understanding we plot, as a function of the input energy, the maximum broadening Δλ of the spectra (measured from the central wavelength of fundamental beam (800 nm) to the wavelengths where the intensity has dropped to 10% of the average intensity of the 800 nm). The result is shown in Fig. 4. This graph which is similar to those recorded by Liu et al. for the propagation in water, chloroform and, glass [10] clearly shows two different regimes. There is a distinctive jump in the plot after which it becomes flat. Before the jump position (broadenings below Δλ < 150 nm), SPM is the main cause of broadening.
As soon as self-steepening starts in the propagation it causes a huge broadening in the blue side resulting in the jump in the spectrum (broadenings from \(\sim 150\) to \(\sim 350\) nm). This is in accordance with the theoretical and numerical prediction of Gaeta \[12\] and Akozbek et al. \[11\]. They found that SPM alone could not give the very large experimentally observed broadening and it takes self-steepening to generate the very large broadening towards the blue side. The position of the jump represents the boundary (or transition) between SPM and self-steepening. Thus, the part of the spectrum below 650 nm (800 – 150 nm) can be considered as being principally due to self-steepening while that above 650 nm mainly due to SPM. Because of intensity clamping, the spectrum would not broaden further by increasing the energy \[10\] and this is the reason why the plot becomes flat. As is clear from Fig. 3, the consequence of further energy
increase results in the growth of the signal level, mainly due to the creation of new filaments [10].

To have a better insight into this phenomenon and based on the above observation, three different parts of the white light spectrum were selected. We used one interference filter at 450 ± 5 nm to look at the portion of the white light that is generated due to self-steepening only, a wide broadband green filter (510 ± 82.5 nm) looking into the range where SMP contributes only slightly and an interference filter at 650 ± 5 nm that transmits the part of the spectrum mainly due to SPM. These filters are used one by one in the setup of Fig. 1 (the CCD camera is replaced by a photodiode and the image screen is also removed). We scanned the energy of the beam from 0.2 to 1.6 mJ (energy is measured after the mesh). The amplitude of the photodiode signal is recorded with respect to the input laser energy; the photodiode signal and the energy are averaged over 50–100 laser shots. The result using the 450 ± 5 nm interference filter is depicted in Fig. 5 (solid square). In this log–log graph the signal initially grows very rapidly with a small change in the input laser energy (slope: about 20.8) and it drops to a value of about 1.3. Increasing the energy causes the slope to grow to about 3.7 and again it drops to the value of about 1.7.

In this configuration, we replace the 450 ± 5 nm interference filter by the green filter. Again the energy is scanned from lower to higher values. In the signal vs. energy log–log graph (Fig. 5, solid circle), the signal grows again rapidly initially (slope: about 19.5), then it drops to a small value of about 2.2. In the last step we replace the green filter by a 650 ± 5 nm interference filter. Near the threshold energy for white light generation, the photodiode signal is more stable than the other two cases. The result is shown in Fig. 5 (solid triangle). The signal starts earlier at a lower energy of 0.04 mJ and increases slowly till the energy reaches ~0.2 mJ at which a steep jump occurs; however, the steepness is not as strong as those in the two previous cases using 450 nm interference filter and green filter. This latter slope has a value of about 7.2 and it drops to a lower value of 2.2 as the energy increases.

3. Discussion and conclusion

We emphasize that the steep jump in spectral broadening in Fig. 4 corresponds to self-steepening. This jump occurs between ~0.196 and ~0.228 mJ. This energy interval overlaps largely with those of the Fig. 5 where the steep jumps are between ~0.2 and ~0.23 mJ in Fig. 5 (solid square), ~0.19 and ~0.22 mJ in Fig. 5 (solid circle), and ~0.2 and ~0.22 mJ in Fig. 5 (solid triangle). This indicates that all the steep zones in Fig. 5 correspond to the situation where self-steepening occurs. At lower energies no signal is observed for the green or the 450 nm filters but a small slope of 1.3 at energies between ~0.1 and ~0.19 mJ is observed for the 650 nm filter. Here is the regime that broadening is
mainly due to SMP. In the case of Fig. 5 (solid triangle) where the steep slope is not as high as those in Fig. 5 (solid square and circle), this overlap indicates that in the spectral region around 650 nm where we expect SPM according to Fig. 4, self-steepening is still significant enough to cause a noticeable change in the slope at higher energies. This is not surprising since self-steepening contributes also to the longer wavelength region [11,12] though not as much as the contribution to the blue. The mixture of the slow rise SPM and the fast rise self-steepening would result in a fast rise but not as steep. The separation of SPM and self-steepening is where the curve first turns in Fig. 5 (solid triangle). However, at shorter wavelengths, soon after the occurrence of some SPM, a little increase in the laser energy would lead to the sudden jump in Fig. 4 making the determination of the SPM zone very difficult. This difficulty was also encountered in the work of Liu et al. [10] where they could only measure the steep jump followed by the flattening of the spectral broadening in chloroform and glass. The conclusion here is that self-steepening turns on almost instantaneously soon after SPM occurs.

After the steep rise in Fig. 5, the signals flatten out because the filaments contributing to the white light generation become mature [18] (Note: According to Schroeder and Chin [18], a mature filament is one that has undergone self-steepening). Further increase in energy would increase the number of new ‘children’ filament [21,22] because some weaker zones in the diffraction pattern are now powerful enough to undergo self-focusing and filamentation. However, because of filament competition [22], not all of them would become mature [18]. Thus there is a mixture of SPM and self-steepening; hence, in Fig. 5, around 450 nm (solid square), the rise in the signal is not as sharp. It again flattens as the energy further increases. In the wavelength ranges of 510–650 nm (Fig. 5, circle and triangle, respectively), the second rise in the signal is not so obvious. This indicates that indeed, there are many filaments which are not mature but contribute to SPM. With a large number of immature filaments, SPM would become measurable easier than before and hence the continuous slow rise of the signals in Fig. 5.

In conclusion, we experimentally confirm that self-steepening is an almost instantaneous process (with respect to slight energy change) which would find important fast switching applications in the future.

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References