A new and improved approach to supercontinuum generation in solids

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Abstract: A stable octave-spanning supercontinuum with excellent beam quality is generated by high-intensity spectral broadening in bulk fused silica plates in a cascaded arrangement.
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A prerequisite to the realization of single-cycle attosecond bursts of light that can be used to probe ultrafast dynamics of electrons in matter is the availability of an octave-spanning supercontinuum of coherent radiation. After years of investigation it is now understood that interaction of an intense laser pulse with a medium via the combination of nonlinear processes of self-focusing, Kerr effect, self-phase-modulation, filamentation, self-steepening, and nonlinear four wave-mixing, the bandwidth of a femtosecond light pulse can be extended multifold to become a supercontinuum spanning over one or more octaves in the frequency space [1,2]. The generally accepted approach now to the generation of a supercontinuum in the visible region is by passing an intense millijoule-level femtosecond laser pulse through a small-core meter-long hollow fiber filled with a gas medium [3]. The focused laser intensity for this to work well is typically well over 10^{14} W/cm^2. The advantage of using a gas medium is that optical damage is of minimal concern. However, consistent alignment through the fiber core requires active control. Intensity fluctuations and beam wander are often problematic issues.

Solids have been investigated since the early days of research in supercontinuum generation. The shortcomings of a solid medium are relatively low damage threshold and high optical dispersion that easily leads to multiple filamentation and limits the bandwidth that can be reached in the supercontinuum. These shortcomings have rendered solids uninteresting [4]. Yet the ease of alignment and the large nonlinearity of a solid versus a gas medium are attractive attributes such that a solid medium deserves further investigation. Here we propose and describe a novel arrangement that is successful in producing an octave-spanning supercontinuum in a solid medium with good beam quality and good efficiency. The approach involves limiting the thickness of a solid medium so that the laser beam exits the crystal before self-focusing occurs to the point that damage occurs or filamentation is reached to avoid damage to the crystal [5] and by strategically placing additional thin solid plates downstream in the beam to allow cascaded nonlinear interaction to produce spectral broadening. With this approach we have succeeded in generating a supercontinuum in a solid medium that has a bandwidth that can rival that from gases. The efficiency we observed is in the same order of magnitude as with a gas medium. The beam quality is excellent with a M^2 of 1.1. And using a solid medium will permit users to operate at least a factor of ten lower in intensity compared to gases, thus allowing supercontinuum generation and making few-cycle femtoseond pulses available to multi-kHz to MHz repetition rate lasers. The system is compact, easy to align, and can operate for a long period of time. We believe this is the first time that a consistent, durable, broad bandwidth supercontinuum with high beam quality has been generated in a solid medium. Using fused silica as the medium, the supercontinuum spectrum ranges from 420 nm to >1000 nm at the 30 dB point.

The experimental setup is shown in Figure 1. We began with 25 fs long pulses centered at λ = 790 nm from a commercial 1 kHz chirp-pulse amplified mode-locked Ti:sapphire laser (Femtopower™ HE PRO CEP). We focused the beam by a 1.5 m focal length concave mirror on the solid medium which as a beginner is a 100 μm thick optically-polished fused silica plate aligned at Brewster's angle to minimize reflection loss. The highest incident pulse energy used was 133 μJ. The transmitted beam was sent to an optical spectrum analyzer with attenuation for spectral analysis or to a thermopile power meter. After the transmitted spectrum has been recorded, a second crystal of similar thickness was inserted at a distances down the beam path just beyond the point where damage would occur to produce a cascaded spectral broadening effect. The insertion of crystal plate was repeated until the spectrum no longer broadens.

Figure 2 shows the spectrum of the incident beam and those of the transmitted beam after passing through one to four pieces of 100 μm thick fused silica plates respectively. The incident power was 6.3 GW and the intensity of the input was 1.5×10^{13} W/cm^2. For fused silica, the critical power of self-focusing is $P_{cr} \sim 1.6$ MW. Thus the laser power readily incurs self-focusing in the first crystal plate. At the same time initiation of self-phase modulation leads to a slightly-broadened symmetric spectrum. With a second plate located in an appropriate distance as close to the previous one as possible without optical damage more broadening is obtained. The spectrum became the widest,

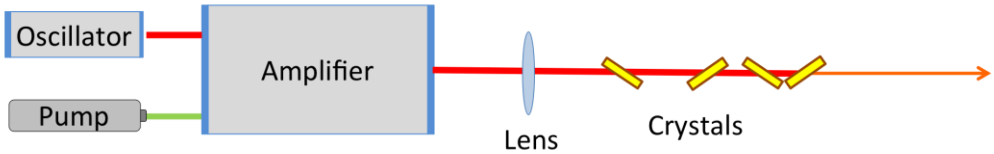

Figure 1. Schematic of the experimental setup. A supercontinuum spectrum can be generated by a single beam focused onto multiple pieces of thin fused silicas aligned consecutively down the beam path.

ranging from 420 nm to 1000 nm after we inserted four plates. A fifth plate did not increase the width. The final spectrum is asymmetric with the short wavelength side enhanced (extended) compared to the long wavelength side that reflects the self-steepening effect [5]. An isolated sub-cycle pulse can be realized by properly compressing this pulse. As expected, the crystal thickness has an important effect on spectral broadening. If the crystal were too thick, the intensity of the pulse would be high enough to cause damage within the crystal. With a thick crystal, although the generated spectrum would have been widened the beam quality would also be bad to make it unsuitable for subsequent applications. One common consequence of using a thick crystal is multiple filamentation. The multiple plate scheme proposed and demonstrated here is designed to avoid beam breakup and damage. The output beam profile is shown in Figure 3(a). Also shown is the profile of one from a thick plate (Figure 3(b)) for comparison. The beam profile of the central lobe in Figure 3(a) contains over 70% of the energy and has an equivalent Gaussian M^2 of 1.1.

Since spectral broadening results from nonlinear optical interaction the spectrum is expected to be phase-coherent. However this has yet to be tested.

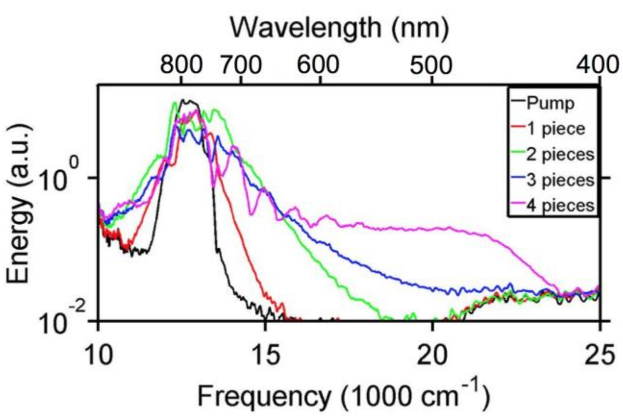

Figure 2. The broadband spectrum with different number of thin plates of crystal.

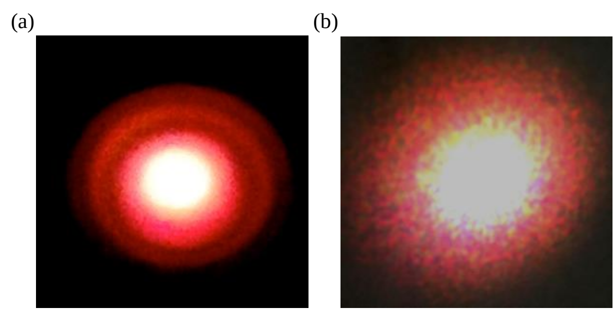

Figure 3. Image of transverse profile of generated supercontinuum beam (a) from four thin plates and (b) from a thick plate.

In conclusion we have demonstrated that a multi-octave spectrum can be generated successfully in a relatively simple setup by cascade broadening in several solid plates. The beam quality is good and stable. Work is underway to test the phase coherence, to try other materials for a broader spectrum and to compress the spectrum to produce a transform-limited pulse.

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