Broadband four-wave optical parametric amplification in bulk fused silica

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Efficient broadband amplification in bulk Kerr media is demonstrated. The properties of noncollinearly phase-matched four-wave mixing parametric amplification process, pumped with fundamental Nd:glass wavelength of 1055 nm, are studied in and narrow band regime. 80-fold signal gain and pump to signal energy conversion efficiency of 9% was observed. Continuum amplification was achieved in the spectral range FWHM of 73.4 nm around 741 nm, which corresponds to spectral width of 25 fs transform limited pulse, with gain factor of 22. © 2007 Optical Society of America

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Applications for ultrashort light pulses with tunable central wavelength can be found in many disciplines - in physics, chemistry, biology, to mention most common ones. Possibility to generate such pulses with desired intensity can be solved by amplifying suitable spectral range of (relatively weak) supercontinuum and, if necessary, by compressing it temporarily.

Amplification of broadband pulses via three wave mixing in second order nonlinear response (birefringent) optical crystals is widespread and well established technique [1]. Amplification bands as broad as 300 nm in visible region, corresponding to 4.4 fs duration are achieved by utilizing non collinear interaction geometry (NOPA) between pump and seed pulses so that the angle between pump and seed pulses remains (almost) constant in wide spectral range [2]. For further amplification technique called optical parametric chirped pulse amplification is applied until material damage and third order nonlinear response threshold together with crystal dimensions become limit for even further increase in pulse intensity [3].

In Kerr media, characterized by third order nonlinear response, intensity threshold for triggering parametric amplification is higher compared to that of third order nonlinear response birefringent crystals. Also, self- and cross phase modulation, self focusing, stimulated Raman scattering and optical breakdown come into play at almost the same intensity threshold [4]. Thus the Kerr media widely is used as a source of supercontinuum. Amplification is much more difficult to achieve as the intense pump pulse breaks up into filaments and the tiny overlap area of pump and signal pulses (filaments) limits overall conversion efficiency to scale of few percents [5, 6]. Consequently largest efforts are dedicated and efficient parametric amplification has been achieved in optical fibers which serve as optical amplifiers for telecom signals [7].

Recently, it was observed in water that filamentation of intense elliptical pump pulse can be held back by the presence of weak seed signal of matching pulse cross section and precisely overlapped space and in time. The pulses will enter a 1-dimensional spatial soliton regime and excellent overlap of the pulses over relatively large distances is attained. Pump to signal energy conversion as high as 15% have been demonstrated [8, 9].

In this Letter we demonstrate efficient broadband amplification via four-wave mixing (2ωpump = ωsignal + ωidler) in bulk Kerr media. There are two possibilities to achieve broadband amplification – either by achromatic phase matching which requires introducing angular dispersion, predefined by phase matching curve, to signal pulse or by making use of the flat region of the phase matching curve where the propagation angle between pump and signal pulses is almost constant in wide spectral range.

If to compare phase matching in birefringent crystals and in Kerr media, in birefringent crystals different polarizations and crystal cutting angle give additional degree of freedom to adjust the shape of phase matching curve. In Kerr media for four wave mixing such additional degree of freedom is not present, the pump and signal pulses have to be noncollinear in order to achieve phase matching.

We choose to study the region on fused silica phase-matching curve (Fig. 1, angles are given in air) where the interaction angle of signal remains almost constant in the wavelength range of approximately 70 nm around 740 nm, pumped by 1055 nm central wavelength pulses which can be generated for example by Nd:glass laser. From Fig. 1 it can be seen that the corresponding idler propagation angle varies form 3.5° – 4.5° and, unlike the amplified broad band signal, is divergent. The central wavelength of amplification band is tunable as much it is to adjust pump wavelength - the position of the flat region of phase matching curve depends on pump wavelength. Fused silica as nonlinear media is favorable for its high optical damage threshold and for its broad transition band in visible and near infrared region.

Experiments were carried out with a Nd:glass laser system (Twinkle, Light Conversion Ltd.) delivering 1 ps pulses.
duration, 6mJ energy fundamental wavelength pulses at 1055nm at 10Hz repetition rate. The laser output was split into two parts. The first portion of the laser radiation was spatially filtered and made variable in energy (by a combination of a λ/2-plate and thin-film polarizer) and then utilized as a pump for the amplification process. The second portion of laser output was used to generate input signal - the seed. (Note: in following we call the input signal the "seed" and amplified seed is referred as signal.) As the seed we used the output of optical parametric generator (OPG; Topas, Light Conversion Ltd.) delivering 1ps duration pulses of variable wavelength between 640−1300nm and alternatively continuum of 170nm spectral width, centered at 740nm.

Pump and seed pulses (both OPG output and continuum) were adjusted in time by means of an optical delay line and focused into 12nm long fused silica sample using a cylindrical lens of \( f_{\text{horizontal}} = \infty, f_{\text{vertical}} = +750 \), yielding pulse cross sections of 3.7mm × 195μm of the pump and 2.8mm × 135μm of the seed at the input face of the sample. The angle between pump and signal beams was adjusted for largest energy conversion due to optimum phase matching, which is 1.65° and slightly differs from the value predicted by theory. This discrepancy can be result of intensity dependent nonlinear refractive index change induced in fused silica sample. The two beams were crossed in the plane containing the long axes of the ellipses in order to optimize spatial overlap across the beam path along the entire sample.

Four-wave mixing parametric amplification process is highly sensitive to the interaction angle. If the signal pulse propagation direction deviates from optimal value by 0.5°, the signal energy reduces approximately to 1/e of maximum value under optimum angle. The deviation angle is considered to be dependent of both pump and signal pulse bandwidth [5] and also refractive index change induced in sample.

In first series of experiments we studied the properties of the amplification process. The interaction was seeded with 1ps duration pulses of 730nm central wavelength, propagating at optimum phase matching angle 1.65°. Regardless the seed energy, the amplification starts at pump energies around 0.5mJ, in case of beam sizes shown above, gain – signal energy over seed energy – 2 is achieved around 1mJ, growth is exponential until saturation occurs around 1.8mJ. Reaching pump energy saturation is accompanied with conical emission and thus filamentation. Maximum conversion efficiency from pump to signal energy is of 9% while pump energy is 1.8mJ and seed energy 13 − 16μJ. For further details see reference [10].

Seed energy dynamics – fix pump energy and vary 730nm seed energy in the range from 0.3μJ to 16μJ – shows signal energy increment continues to grow linearly with seed energy logarithm whereas the gain decreases in similar manner. Maximum signal energy of 180μJ was reached with seed of 15μJ energy and 1.8mJ pump. See Fig. 2. The signal energy and gain values depends on pump pulse energy.

Fig. 1. Phase-matching curve of fused silica pumped with 1055nm central wavelength pulse. Seed phase-matching angle in air in respect to its wavelength is plotted. The almost constant signal propagation angle region on the phase-matching curve and corresponding idler are shown in bold.

Fig. 2. Signal energy dynamics and gain pump energy at saturation threshold of 1.8mJ. Signal can rise up to 180μJ which corresponds to conversion efficiency of 9%. Higher gain values are achieved at lower seed values and at higher pump pulse energies.

In case of amplifying continuum spectra the energy per wavelength interval cannot be set constant. Using tunable wavelength OPG as wavelength scanable narrowband source we have such option. Amplification bandwidth scanning was performed with OPG at two different seed energies – 0.25μJ and in higher seed energy regime of 8μJ – by changing the seed wavelength in the range from 680nm to 820nm while preserving interaction angle and delay which were set to maximum conversion efficiency for 730nm, at 1.9mJ pump energy. See Fig. 3. Amplification bandwidth at FWHM for 8μJ seed was measured 75nm, and that for 0.25μJ seed was 65nm, centered to 742nm in both cases. The difference in amplification bandwidth is result of seed dynamics variations at different wavelengths and interaction conditions they experience.

In second series of experiments we measured amplification of continuum signal. 150μJ and 700nm central
Fig. 3. Gain bandwidth scanning at two different seed energy values in the wavelength range of 680 – 820 nm at 1.9 mJ pump energy. We see that overall gain is higher at smaller seed values but also the gain bandwidth is narrower. This is result of different interaction conditions for different wavelength seed pulses.

wavelength TOPAS output was shaped to a conical pulse (Bessel-X pulse [11] and consequent papers) which was directed to 43 mm long fused silica sample. In the axial direction continuum pulses of 170 nm spectral width at 1/e² maximum, centered at 740 nm, were generated while the pumping radiation will travel under axicone angle and can be easily filtered out. After spatial filtering and propagation in optical scheme we utilized 0.75 \mu J out of 3.6 \mu J continuum energy in interaction. While generating continuum in this manner, compromise was made on pulse stability as the spectral composition of the broadband signal is changing from shot to shot. The data performed here is average of 100 shots.

Continuum amplification is shown on Fig. 4. Full width at half maximum of amplification bandwidth is 73.4 ± 5 nm, central wavelength 741 nm. The bandwidth corresponds to transform limited pulse duration of 25 fs. The continuum was amplified 16 times, to 11.5 \mu J at 1.8 mJ pump pulse energy. If to take into account that only 72.5% of the continuum energy is estimated to fall into amplification bandwidth the gain is 22.

Fig. 4. Amplification of axicon-generated 170 nm full-width-1/e-maximum continuum.

In conclusion we have studied the properties of four-wave mixing parametric amplification in Kerr media pumped with 1055 nm central wavelength pulse in both narrow- and broadband regime. The narrowband measurements give valuable information of signal energy dynamics with variable pump and seed energies and allow to scan amplification bandwidth under highly controlled conditions. Utilizing this knowledge continuum pulses generated by means of axicone were successfully amplified 22-fold in 73.4 nm spectrum range, centered to 741 nm. The amplification bandwidth corresponds to spectral width of transform limited 25 fs pulses.

References

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