Nonlinear Dispersion Properties Of Sub-wavelength Photonic Crystals

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Abstract:
Nonlinear pulse compression and pulse broadening have been demonstrated with a coherent array of sub-micron silica spheres embedded with silicon nanoparticles ('nano with nano').
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Summary

The most common pulse compression scheme is a combination of a frequency chirp with a dispersion compensator. The frequency chirp is achieved by nonlinear medium, most notably a Kerr medium. Periodic structures, such as, phase grating, have been used as a dispersion media needed for the compensation process [1]. Photonic crystals embedded with nonlinear material such as, silicon nanoclusters, bear the potential of incorporating the two requirements in one structure. The fcc structure of silica based opaline sample was ion implanted with Si ions. Following annealing, 5-6-nm clusters of silicon were formed within a 0.3-μm thick region, as determined by SEM and Raman spectroscopy [2]. The structures have been shown to be highly nonlinear [3], reaching index changes on the order of δ_{NL}>0.1 at λ=0.8-μm, and strongly dispersive [4]. Unlike Bragg fibers [5], we employ here a transverse scheme, namely, the dispersion is achieved via *transverse Bragg reflections* [6] while maintaining non-resonance conditions along the propagation direction.

The optical wave propagation in photonic crystal is rather complicated. An insight into the wave propagation within a transverse structure may be obtained as follows. The wave propagation consists of many spatial modes. The transverse propagation constant of the *q*th mode may be in resonance with the periodic structure, namely, $\beta_x^{(q)} \sim k_0 n_0 \sin(\theta q(\pi/\Lambda)$, where Λ is the transverse pitch. From this equation we may calculate that the incident angles for transverse Bragg condition are 19^0 and 43^0 for a non-implanted opaline structure and an opal containing 5-6-nm Si clusters, respectively. The coupling strength, with coupling, $\kappa = \pi \Delta n/\lambda_0 \cos\theta$, Δn=0.5, λ=0.8-μm and interaction length L=10-μm, is κL~30 for a 10-μm thick opal.

The propagation constant in the direction of propagation is $\beta_z^{(q)}=\{k_0^2 n^2(0)-[\beta_x^{(q)}]^2\}^{1/2}$. The time of arrival per unit length of a spectral line, ω, of mode number, q, is,

$$\tau(\omega,q)=\partial\beta_z^{(q)}/\partial\omega \sim (1/c)[n+(1/8)(q\lambda_0/\Lambda)^2/n]. \quad (1)$$

Here we used, n, the effective linear refractive index and, $k_n=\omega n_0/c=2\pi/\lambda_n$. Consider a 100-fs pulse. The delay-time introduced by the modal dispersion is $\delta\tau=\tau(\omega,q+1)-\tau(\omega,q)=(2q+1)0.2$-fs/μm. Shown in Fig. 1 is the broadening of the pulse by a non-implanted and implanted opaline samples as a function of angle. As predicted, a large broadening occurs at the transverse Bragg angle. Based on the previous arguments, the pulse propagation is made via multi-spatial modes.

The opal structure may compensate for frequency chirp introduced by an external means. Such pulse 'compression' for a 10-μm thick non-implanted opaline samples are shown in Fig. 2. The incoming pulse of 100-fs from a Ti:sapphire laser was positively chirped, without a change in the spectral width, using a 15-cm long, water-filled cuvette. The pulse duration after the water cuvette was 265-fs and the corresponding re-compression was 60-fs. The compression for the implanted sample was not as effective as the non-implanted sample. The reason is that the implanted region distorts the incident phase for the non-implanted segment thereby, resulting in a non-optimized effect. At low power levels (see also Fig. 1) the broadening from the combined effects is actually maximized. Also, owing to the negative signs of both linear and nonlinear dispersions one may expect a substantial broadening.

Nonlinear properties may be incorporated upon replacing n(I) by, $n=n_0+\gamma I$; here I is the intensity distribution of the propagating pulse, commonly taken to be of gaussian shape, $I=I_0 exp(-2t^2/\tau_p^2)$. Self-phase modulations will increase the pulse spectrum and include a spectral chirp owing to the large index changes. The linear dispersion will determine the relative time-of-arrival of the tail and peak of the pulse, which corresponds to the relative time of arrival of the high and low frequencies, respectively. The nonlinear effect was indirectly demonstrated by measuring the pulse broadening of a 100-fs input pulse as a function of intensity. In Fig. 3 we show changes in pulse broadening as a function of pulse energy at two angles: (a) at the angle of maximum pulse compression and (b) at an angle of minimum compression. Note that κL~0.2 for the nonlinear region. One may observe a saturation of index change for large energy densities. We also added the flat response of a non-implanted, 10-μm thick opaline structure. The latter demonstrates that, in general, the silica-based opaline structure does not contribute to the self-phase modulations. The small dip near 250 μJ/cm^2 may indicate a true compression owing to the positive nonlinearity of the silica spheres; this is still under investigation. One should expect that as the nonlinear chirp increases, its effect on the pulse broadening decreases. This is because the nonlinear chirp contributes a term like $A/(1+A^2)$, where A is proportional to the instantaneous frequency [7].

In summary, we have shown that by incorporating nano silicon clusters (a nonlinear medium) within an opaline structure and employing a transverse diffraction scheme we were able to manipulate ultra-short pulses.

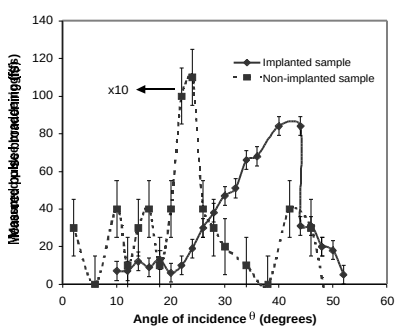

Fig. 1. Pulse broadening as a function of incident angle, θ. The theoretical estimation of the Bragg peaks are 19^0 and 43^0 for non-implanted and Si implanted samples, respectively.

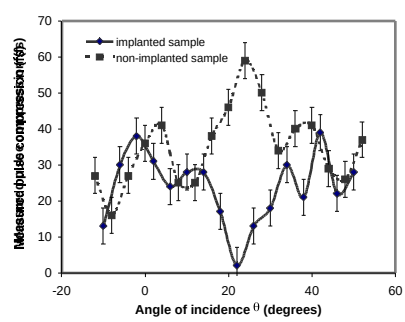

Fig. 2. Pulse compression for a pre-chirped pulse at 265-fs as a function of the incident angle, θ, for implanted and non-implanted 10-μm thick opaline samples. The implanted region was 0.3-μm.

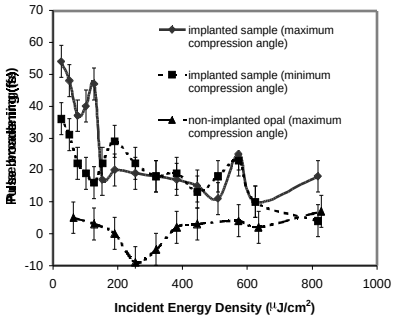

Fig. 3. Change in pulse broadening as a function of pulse energy density

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