OPTICAL PHYSICS

Nonlinear effects get into shape

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Nonlinear optical effects are by default weak but they can be enhanced by sculpting the resulting spectrally periodic pulses from a fibre laser into an optimal shape.

Since the invention of the laser in 1960 and the first demonstration of second harmonic generation a year later', the field of nonlinear optics has witnessed an enormous growth, leading to the observation of new physical phenomena and giving rise to novel concepts and applications. However, nonlinear optical effects are inherently weak, hindering the development of both fundamental investigations and the development of practical devices. Different approaches exist to enhance nonlinear effects, often relying on the fact that nonlinear effects scale with the intensity of the light that stimulates them. But there is another way. Writing in *Nature Physics*, Joshua P. Lourdesamy and collaborators have now exploited the dependence of optical nonlinearities on the shape of the incoming pulse and of its spectrum to achieve a 3.5-fold enhancement of the resulting nonlinear effects.[8]

Nonlinear optics has made possible a range of advanced solid-state and fibre lasers, soliton physics and supercontinuum generation. It has enabled high-resolution spectroscopy and microscopy, and has been central to fundamental Nobel Prize-winning research[2]. Besides these great achievements over the last sixty years, nonlinear optics also promises to have a major impact on future technologies: quantum computing, quantum communications, point-of-care medicine, miniaturized sensing platforms and many other applications that are set to have a bright future.

Yet, these advances would not have been possible without considerable efforts to greatly improve initially weak nonlinear effects. Nonlinear optics is perturbative and the strength of a response depends crucially on the intensity of the original light, the material this light interacts with and the strength of the interaction. Scientists have used the combined developments of high-intensity ultrafast lasers, highly nonlinear optical materials, and wavelength-scale optical waveguides such as optical fibres and photonic integrated circuits[2] to increase light-matter interactions by several orders of magnitude. This has given an incredible boost to the efficiency of nonlinear optical effects, enabling applications beyond laboratories[3].

More recently, there have been other developments to further strengthen nonlinear effects using photonic crystals and slow light[4], optical microcavities[5], and more recently plasmonic metamaterials[6,7]. But there is another approach that has not been fully explored yet and that can be used in addition to the existing methods. It is based on the fact that nonlinear effects depend not only on light intensity but also on the pulse shape and the spectrum of the incident light.

Lourdesamy and collaborators experimentally implemented a specific pulse shaping in a fibre laser and demonstrated a nonlinear enhancement factor as large as 3.5. To achieve this improvement, the team built a passively mode-locked soliton fibre laser by nonlinear polarization rotation. They inserted in the laser a programmable spectral pulse shaper, which is used to tailor the net cavity dispersion by applying a phase mask consisting of a number of periodically spaced identical maxima, like those shown in red in Fig. 1b. This dispersion engineering forces the laser to generate a spectrally periodic soliton with a spectrum consisting of equidistant lines, as shown in blue in Fig 1b. In the time domain, the resulting pulse is a train of pulses under a smooth soliton-like envelope, as shown in blue and dashed back in Fig. 1c, respectively.

The basis of the method is that the effective nonlinear coefficient for the envelope depends on the carrier wave, specifically on the number of maxima. Hence, modifying the carrier while keeping the envelope unchanged, modifies the nonlinear coefficient as well —it can thus be optimized. In particular, Lourdesamy et al. showed that the effective nonlinear parameter increases with an increasing number of maxima, and they experimentally demonstrated a nonlinear enhancement factor of 3.5 for five maxima. This means that the nonlinear effect induced by the new pulse envelope is 3.5 times larger than that of a conventional soliton pulse of the same energy. Nonlinear effects increase more strongly for larger amplitudes —around the peaks of the pulse — than they decrease near the nodes. These peaks become more pronounced as the number of maxima increases. As a result, the nonlinear enhancement becomes stronger. This improvement is comparable to some of the first slow light experiments[9,10], which showed enhancements of nonlinear effects by a factor 4.

Although it is known that the magnitude of nonlinear effects depends on the pulse shape — and indeed this has been used for all-optical signal processing — the controlled approach employed by Lourdesamy and collaborators leads to an optimal enhancement, which is achieved using phase effects only. The proposed technique effectively makes it possible to increase the nonlinear effects, but not the optical nonlinearities, which remain a material property. The technique represents the temporal equivalent of the periodic spatial modulation of a waveguide, for which the resulting spatial modulation of the carrier can also lead to enhanced nonlinear effects.

Although the demonstration was carried out in the context of nonlinear optics, this pulse shaping approach is more general and it may equally be applied to improve nonlinear effects in Bose-Einstein condensates and other nonlinear phenomena.

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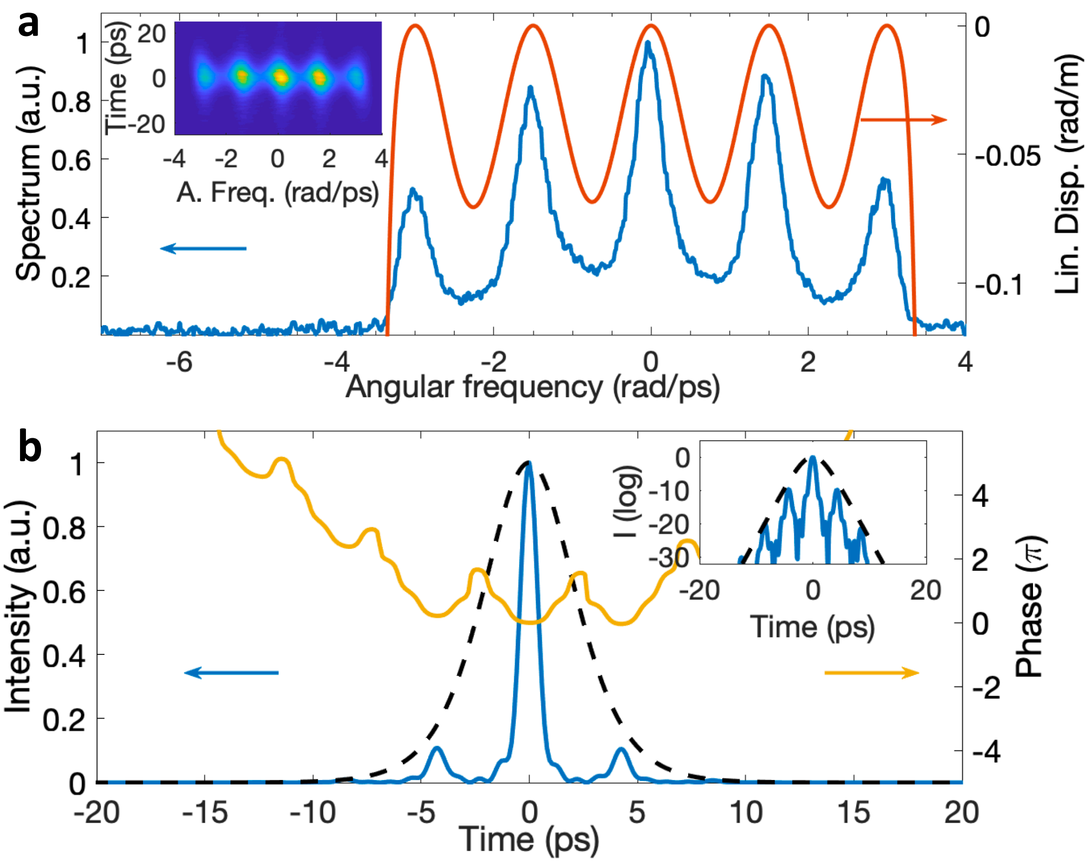

Figure 1 *(adapted from ref (8]) :* Experimental measurement of the spectrally periodic pulses from the fiber laser for enhancing nonlinear effects. a, Laser output spectrum (blue) for applied linear dispersion relation with 5 maxima (red) with the pulse shaper and measured spectrogram (inset). c, Retrieved temporal intensity (blue) and temporal phase (yellow). Sech-squared Soliton shape fit (dashed black) with 5 ps width. The inset shows the temporal intensity on a log scale.