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Enhanced Soliton Self-Frequency Shift in a Longitudinally Varying Taper

A. C. Judge,[1,*] **O. Bang,**[2] **B. J. Eggleton,**[1] **B. T. Kuhlmey,**[1]
E. C. Mägi,[1] **R. Pant,**[1] **and C. M. de Sterke**[1]
[1]*Centre for Ultrahigh-Bandwidth Device for Optical Systems, Institute for Photonics and Optical Science, School of Physics, University of Sydney, Sydney, NSW 2006, Australia*
[2]*DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Building 345V, DK-2800 Kgs. Lyngby, Denmark*
[*]*Corresponding author: a.judge@physics.usyd.edu.au*

We propose a method for the enhancement of the soliton self-frequency shift in a tapered PCF with a carefully designed waist diameter profile which optimises the dispersion and nonlinearity at the soliton wavelength.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and temporal solitons.

Summary:

The soliton self-frequency shift (SSFS) is the phenomenon whereby the central frequency of a solitary optical pulse undergoes a redshift while propagating in an optical fiber due to the inelastic, nonlinear scattering of its photons off the molecular lattice of the glass. Since its discovery [1], the SSFS has been exploited as a means of obtaining a source of short, wavelength-tunable pulses [2, 3].

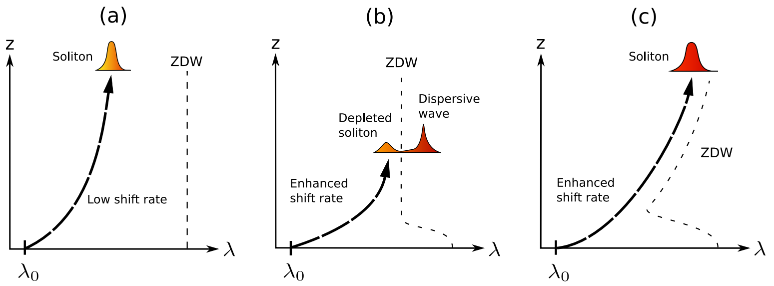

Figure 1: Schematic of the enhancement of the SSFS through the use of a longitudinally varying taper. (a) untapered fiber, (b) uniform waist taper, and (c) optimised longitudinally varying taper.

Due to the inherent nonlinearity of the process, the rate of the SSFS is enhanced by increasing the energy density of the pulse. Thus the process of tapering a fiber, whereby the light guiding region is reduced on the transverse scale, can lead to an increase in the light confinement and a subsequent enhancement of the shift rate of a propagating soliton. However, tapering also alters the dispersion in the fibre, and may do so in such a way that the spectral region of anomalous dispersion is reduced with the long wavelength limit, or second zero dispersion wavelength (ZDW), being shifted to the blue. Since the impingement of a soliton upon the second ZDW leads to a cancellation of its redshift and emission of resonant dispersive waves [4] this reduces the maximum redshift attainable by a soliton over that in the untapered fibre. Furthermore, the energy in the soliton can be significantly depleted by the emission process.

Here we describe a method of designing an optimal taper waist diameter profile which enhances the SSFS rate while mitigating the limitation imposed by the second ZDW. In Figure 1 we illustrate schematically how this is achieved. In the untapered fibre (a) the relatively low nonlinearity and high dispersion lead to a low rate of redshift. Tapering the fiber to a uniform waist in (b) enhances the shift rate through a higher nonlinearity but is accompanied by a shortening of the second ZDW. The soliton reaches a point where the dispersion in the taper facilitates the emission of low amplitude waves in the normally dispersive regime resulting in the halt of the redshift. If the waist diameter of the taper is varied as in (c) such that the soliton experiences the maximum possible nonlinearity at a level of dispersion that minimises the loss of energy to dispersive waves, the soliton may achieve a redshift above that realised in cases (a) and (b).

In order to demonstrate the basic concept of our longitudinally varying taper we have simulated pulse propagation in a number of scenarios by numerically solving the generalised nonlinear Schrödinger equation (GNLSE) [5],

$$\partial_z A(z,T) = i\sum_{m=2}^{18}\frac{i^m\beta_m(z)\partial_T^m}{m!}A(z,T) + i\left(\gamma_0 + i\gamma_1\partial_T\right)A(z,T)\int G(T-T')|A(z,T-T')|^2 dT', \tag{1}$$

where β_m and γ_m represent $\partial_\omega^m\beta$ and $\partial_\omega^m\gamma$ respectively. The fiber parameters were obtained from simulations of the NL-15-670 fiber from Crystal Fibre using the COMSOL package. The spectral evolution of identical initial pulses for four different fibre diameter profiles, labelled (a)-(d), are shown in Figure 2, where the behaviour predicted in Figure 1 is confirmed. The shift rate in the tapered fiber (b) is enhanced above that in the untapered fiber (a). Reducing the taper waist diameter in (c) leads to the transferrance of energy from the soliton to normally dispersive waves and cancellation of the soliton redshift by the associated spectral recoil. In (d) a taper is designed such that the group velocity dispersion (GVD) at the soliton centre frequency is maintained at $-100\ \mathrm{ps}^2/\mathrm{km}$ in the waist region. In this case the generation of dispersive waves across the second ZDW is avoided while the wavelength of the soliton at the end of the fiber is increased above that in the other three examples. Thus it is shown, in principle, that careful design of the longitudinal profile of a taper can enhance the SSFS over that in a taper with a uniform waist diameter.

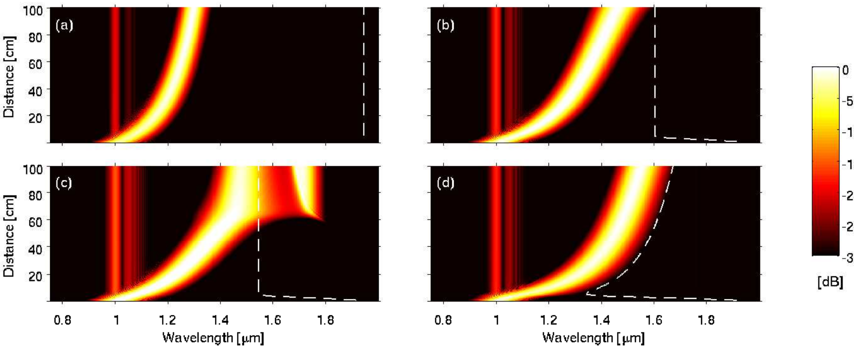

Figure 2: Spectral evolution of an initial fundamental soliton pulse for various taper profiles: (a) an untapered fiber, (b) a uniform waist diameter scaling of 0.83, (c) a uniform waist diameter scaling of 0.80 and (d) a taper of variable waist diameter initially scaled down by a factor of 0.70 in the transition from the untapered fiber with a dispersion threshold of $-100\ \mathrm{ps}^2/\mathrm{km}$. The initial soliton in each case has an energy of 200 pJ at $1\ \mu\mathrm{m}$. For the tapered fibers the waist region is preceeded by a 5 cm transition region from the untapered fiber diameter. The final central wavelengths corresponding to the soliton features are (a) 1.30 μm, (b) 1.46 μm, (c) 1.48 μm and (d) 1.55 μm. The second ZDW is indicated by the white dashed line in each panel. The colour dB scale for the spectral energy density, shown on the right of the figure, is the same for all plots.

In summary, we use numerical solutions to the GNLSE, with identical initial conditions, to demonstrate the enhancement of the SSFS in a taper with a longitudinally varying waist diameter over that in a taper with a uniform waist. The enhancement is achieved by varying the taper waist diameter along its length in order to present an optimal level of group velocity dispersion to the soliton at each point, thus avoiding the spectral recoil due to the emission of dispersive waves. In doing so, the increased nonlinearity and dispersion engineering afforded by the reduction of the core size are exploited while circumventing the limitation imposed upon the soliton redshift by the associated shortening of the second ZDW. Variation of the input energy of the soliton may then be used to tune the final wavelength over a wider range than that obtainable in a uniform waist taper.

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