

Radiation and Scattering of Linear Waves and Solitons in Photonic Crystal Fibers

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We report theoretical and experimental results on several novel soliton related effects in ultra-small core photonic crystal fibers. Effects reported rely on peculiar dispersion characteristics, which are not attainable in telecom fibers.

In this work we report recent theoretical and experimental results on several aspects of propagation of femtosecond optical pulses in silica-core photonic crystal fibers. In particular we consider such new effects as exponential amplification of the resonant radiation emitted by solitons; reabsorption of the radiation by solitons; compensation, cancellation and reversal of the soliton self-frequency shift by the radiation pressure; generation and tuning of new resonant frequencies by mixing of solitons and cw. Above effects rely on steep frequency dependence and slope reversal of the group velocity dispersion in ultra-small core PCFs.

Recent advent of photonic crystal fibers (PCFs) calls for rethinking and reexamining of many approaches and applications of traditional nonlinear and fiber optics [1,2]. In particular ultra-small core ($\sim 1\mu\text{m}$) silica PCFs offer values of the effective nonlinear coefficient γ two orders of magnitude better compare to the conventional telecom fiber. Also, and what is particularly important for the results reported below, small core and large air filling of the cladding strongly modify fiber dispersion. In particular, results reported in this paper rely on the existence of the two zero GVD points and presence of the spectral regions with opposite GVD slopes.

This work has originated from several previously known effects and observations, which, to the best of our knowledge, have not been considered simultaneously. First, it is well known that in the femto-second regime the Raman effect in silica fibers leads to linear in z (propagation coordinate) shift of the soliton frequency towards the red part of the spectrum [3]. Second, it has been shown that positive/negative GVD slope leads to emission of the blue/red shifted quasi-cw radiation by solitons [4]. This radiation in its turn exerts pressure on the soliton leading to the red/blue shift of the central soliton frequency – so called spectral recoil effect [4]. In telecom fibers GVD slope is positive and both Raman and recoil effects pull the soliton towards the red part of the spectrum. In small-core PCFs, however, GVD has both negative and positive slopes in the range from 0.5 to $2\mu\text{m}$, see Fig. 1. It suggests that inside this spectral range, where the Raman and recoil effects pull in opposite spectral directions, there is a possibility of existence of the frequency locked solitary waves.

Formation of this frequency locked solitons with trailing tail of the red shifted resonant radiation has indeed

been observed in our experiments and modelling [6], see Fig. 2. Also we have developed and plan to present main results of a comprehensive theory of this effect, which quantitatively predicts the amplitude and frequency of the radiation and the soliton locking frequency.

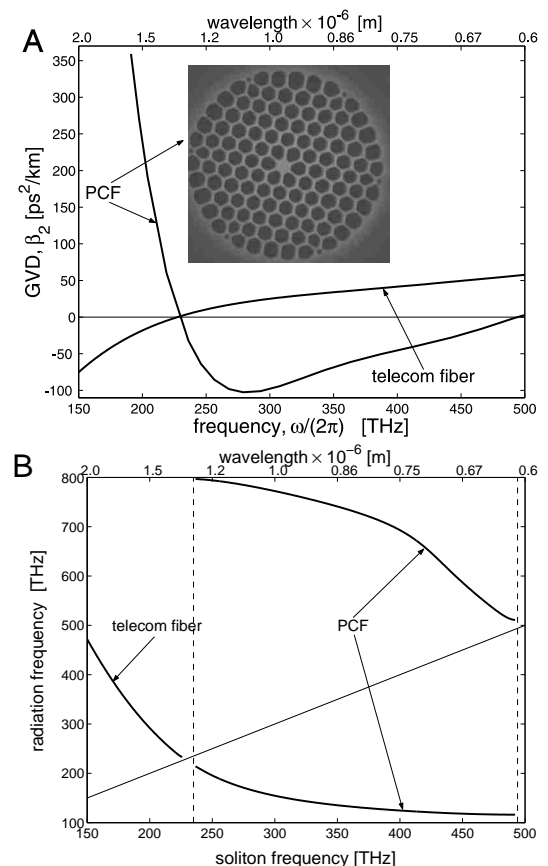


FIG. 1. (A) Group velocity dispersion plots for the telecommunication fiber (SMF 28) and PCF used in our experiments. Inset shows the scanning electron micrograph of the PCF transverse section. Core diameter of the PCF $\approx 1.2\mu\text{m}$. (B) Dependence of the frequency of the Cherenkov resonances from the soliton frequencies for the telecom fiber and PCF. Two vertical dashed lines mark the zero GVD points in the PCF. Full diagonal line marks the boundary where the radiation and soliton frequencies coincide. The radiation branches above/below this line are, respectively, blue/red shifted relative to the soliton carrier frequency. The top axes in (A) and (B) are marked in the wavelength units.

Our theory and experiments give the following picture

of the radiation emission and amplification. Energy exchange between the soliton and the resonant dispersive wave reaches its maximum in the region, where energy is fed into the wave from the most intense central part of the soliton spectrum. This is because the amplitude of the emitted radiation is primarily determined by the spectral amplitude of the soliton at the radiation frequency ω_r . The spectral amplitude at the frequency ω_r for an ideal soliton with the central frequency ω_s is proportional to $1/\{\exp[-(\omega_r-\omega_s)\pi\tau/2]+\exp[(\omega_r-\omega_s)\pi\tau/2]\}$, where τ is the soliton duration. Thus, for values of ω_r approaching ω_s , the intensity of the emitted wave increases exponentially.

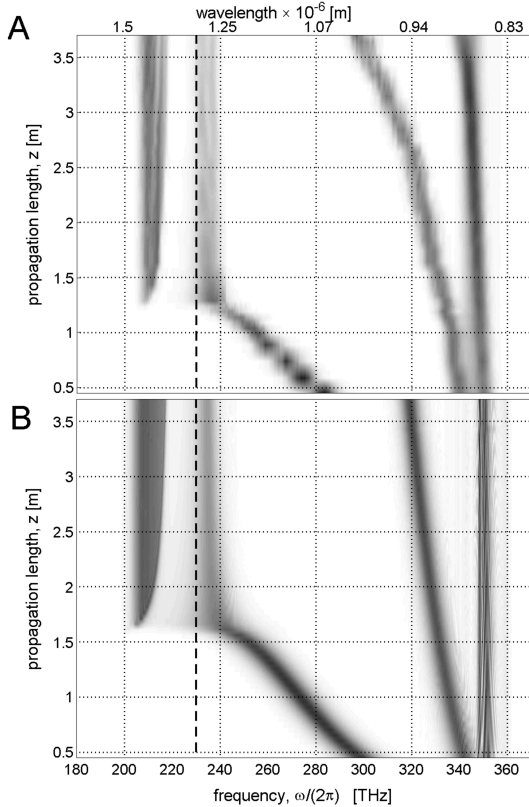


FIG. 2. (A) Experimentally measured spectral evolution of the femtosecond optical pulse (duration 200 fs , peak power 230 W) propagating down the PCF. (B) Corresponding numerical modelling. The top axes are marked in the wavelength units. Resonant radiation band appears on the left from the black dashed vertical line marking the zero GVD frequency.

The Raman scattering generates a red shift in the soliton carrier frequency, which is directly proportional to the propagation distance z . Therefore, as the soliton approaches the red-shifted zero GVD point with a negative GVD slope, the intensity of the red-shifted branch of the resonant radiation increases exponentially in z . The exponential growth of the radiation saturates, however, as the soliton recoils against the radiation toward the blue side of the spectrum, which leads to a balance between the red Raman self-frequency shift and the blue recoil

on the soliton from the radiation. This balance produces frequency-locked solitary pulses with a growing tail of resonant radiation, see Fig. 2.

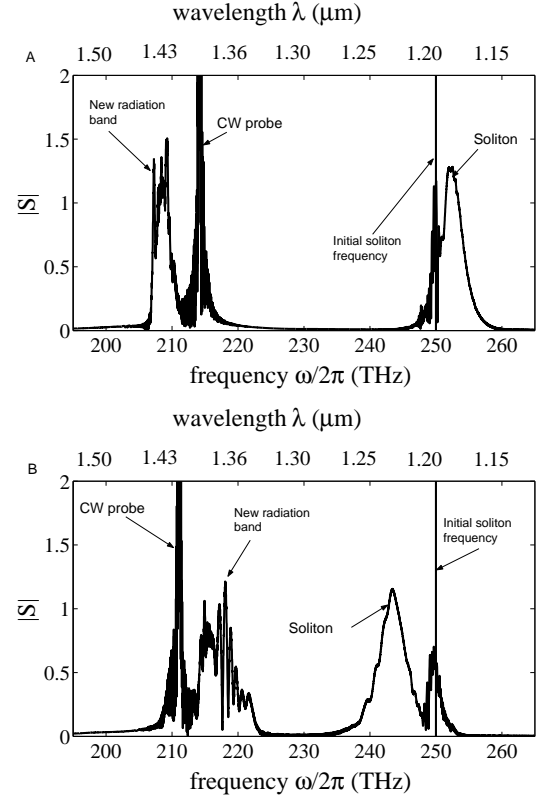


FIG. 3. Spectra resulting from interaction of a probe cw field ($\simeq 3\text{ W}$) and a soliton (200 fs , $\simeq 40\text{ W}$ peak power). (A) shows the case when Raman induced soliton self-frequency shift is overcome by the radiation pressure from the probe and newly generated cw fields, which results in the blue shift of the soliton frequency. (B) shows the case when Raman effect and radiation pressure both pull the soliton towards the red part of the spectrum.

Motivated by the above results we have build-up the ongoing theoretical and experimental research program studying interaction between the solitons and relatively weak, order of 1 W of the soliton peak power, 'probe' cw fields propagating in PCFs. Some of the results of this work are described below and more will be presented during the conference. We should note that previous studies of the cw-soliton interaction in fibers with ideal, i.e. frequency independent GVD, have been very limited. One of the main theoretical results reported so far has been that the Raman free ideal NLS solitons can be slowed down and trapped by the sufficiently strong cw having the same frequency as the soliton [5].

Our main aim is to investigate effects of the fast variations of the GVD values on the interaction between the cw and soliton. Below we report series of numerical results obtained for the fiber shown in Fig. 1(a). In particular we have found that mixing of the cw and soliton

leads to generation of strong radiation bands, which have frequencies generally different from the frequency of the resonant radiation emitted by the soliton itself and discussed above. Position of the new radiation bands can be efficiently controlled by tuning the frequency of the probe cw field. New radiation bands are absent in fibers with flat GVD characteristics and can be practically observed in our fiber only in the region, where $\beta_2(\omega)$ has negative slope.

CW radiation has been found to exert detuning dependent pressure on the soliton. This pressure can either enhance or fully suppress and reverse Raman induced soliton self-frequency shift (SSFS). Fig. 3(B) shows the case with Raman effect and cw pressure acting in the same spectral direction, and Fig. 3(A) shows the situation, when the soliton gets blue shifted, which means that traditional SSFS has been completely suppressed and reversed by the interaction of soliton with cw. We are currently developing analytical theory and work on the experimental observation of these effects, which should be completed before the conference. We also plan to report on interesting effects resulting from the soliton collisions in the fibers with steep GVD.

Note also that generation of new frequencies reported here can not be explained in terms of standard four-wave

mixing theories. Because here energy and momentum are transferred between the pulse as a whole and cw, which violates usual Stokes vs anti-Stokes symmetry. Effects described above are not only interesting on their own, but also can be potentially useful for frequency conversion application and for interpretation of supercontinua spectra generated in photonic crystal fibers and other types on nonlinear media. Results of our work show how novel and unexpected phenomena can be discovered in photonic crystal fibers due to the unique combination of their dispersive and nonlinear properties.

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