Impact of frequency-dependent nonlinearity on soliton trajectory in microstructured optical fiber

Surajit Bose[1,2], Oliver Melchert[1,3], Stephanie Willms[1,3], Ihar Babushkin[1,3], Uwe Morgner[1,3], Ayhan Demircan[1,3] & Govind Agrawal[4]

[1]Institute of Quantum Optics, Leibniz University Hannover, Germany
[2]Institute of Photonics, Leibniz University Hannover, Germany
[3]Cluster of Excellence PhoenixD, Hannover, Germany
[4]The Institute of Optics, University of Rochester, USA

Outline

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2. Modelling of pulse propagation equation

3. Microstructured optical fiber

4. Frequency-dependent nonlinear medium

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Introduction

- Optical pulses can propagate as solitons by balancing the effects of group velocity dispersion and self-phase modulation

- Dynamics of the short optical pulse are usually explained by generalized nonlinear Schrödinger equation

$$\frac{\partial \tilde{A}_\omega}{\partial z} = i\beta(\omega)\tilde{A}_\omega + i\gamma(\omega)(1-f_R)F(A|A|^2) + if_R\gamma(\omega)\times F\left(A\int_0^\infty h_R(\tau)\ |A(z,t-\tau)|^2 d\tau\right)$$

$$\gamma(\omega) = \frac{n_2\omega}{cA_{eff}(\omega)} \qquad A_{eff}(\omega_0) \longrightarrow \gamma(\omega) = \gamma_0 + \gamma_1\ (\omega - \omega_0)$$

(Includes: Dispersion, SPM, Self-steepening and Raman)

- GNLSE have some limitations

- The photon number remains conserved for $\gamma_1 = \frac{\gamma_0}{\omega_0}$ i.e. $\gamma(\omega) = \frac{\gamma_0\omega}{\omega_0}$

K. J. Blow and J. Wood IEEE J. Quan. Elect. **25**, 2665-2673 (1989)   G. P. Agrawal, Nonlinear Fiber Opt. (Academic, 2007)

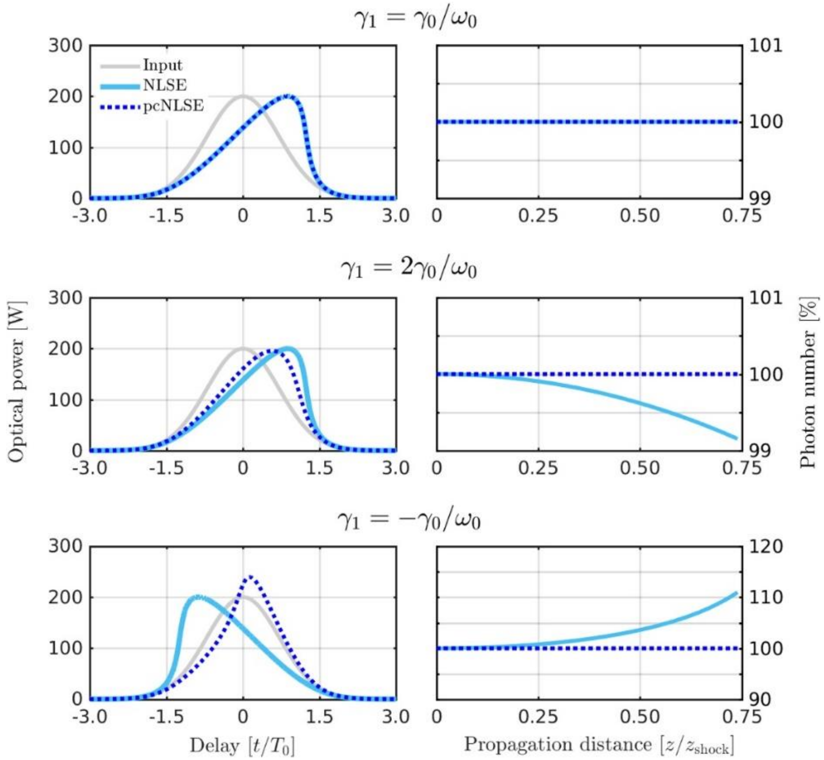
Modified Nonlinear Schrödinger equation

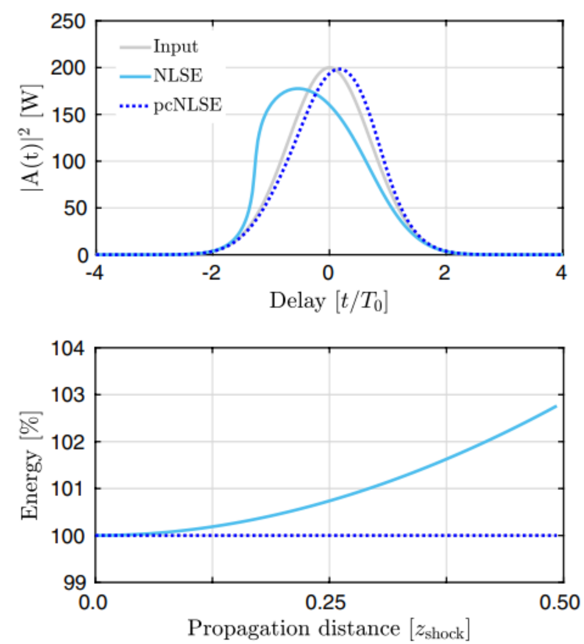
$$\frac{\partial \tilde{A}_\omega}{\partial z} = i\beta(\omega)\tilde{A}_\omega + i\frac{\bar{\gamma}(\omega)}{2}F(C^*B^2) + i\frac{\bar{\gamma}(\omega)^*}{2}F(B^*C^2)$$

$$\overline{\gamma(\omega)} = \sqrt[4]{\gamma(\omega)\times(\omega)^3}$$

$$\tilde{B}_\omega = \left(\frac{\gamma(\omega)}{\omega}\right)^{1/4}\tilde{A}_\omega \qquad \tilde{C}_\omega = \left(\frac{\gamma(\omega)}{\omega}\right)^{*1/4}\tilde{A}_\omega$$

$$E = \sum_\omega |\tilde{A}_\omega|^2 \qquad N = \sum_\omega \frac{(|\tilde{A}_\omega|^2)}{(\omega)}$$





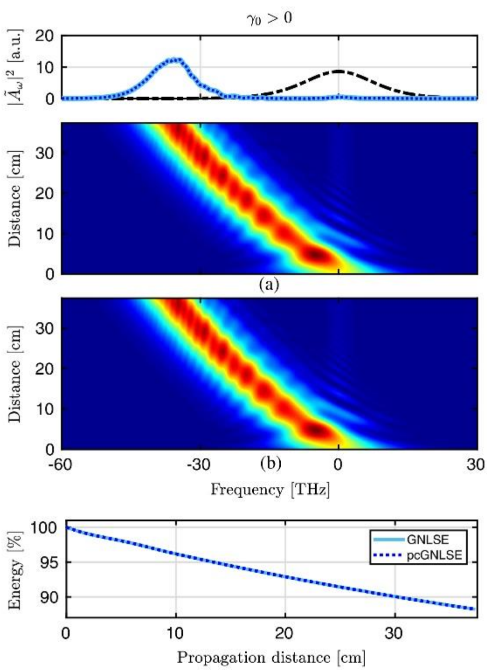
Quadratic term to the nonlinearity

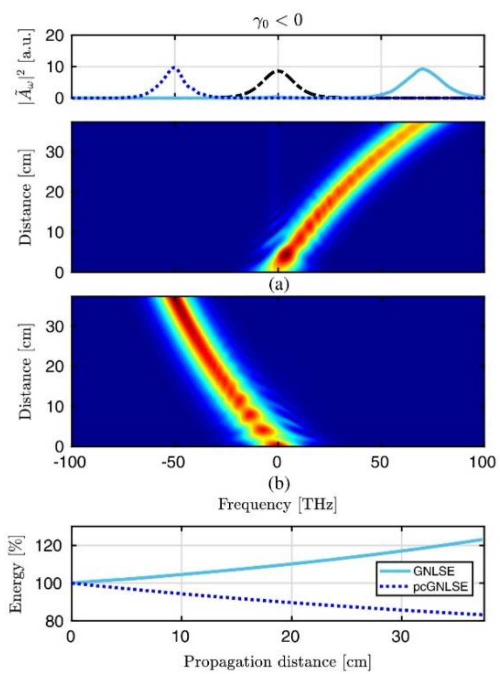
[J. Bonneti et al., J. Opt. Soc. Am. B **36**, 3139–3144 (2019)

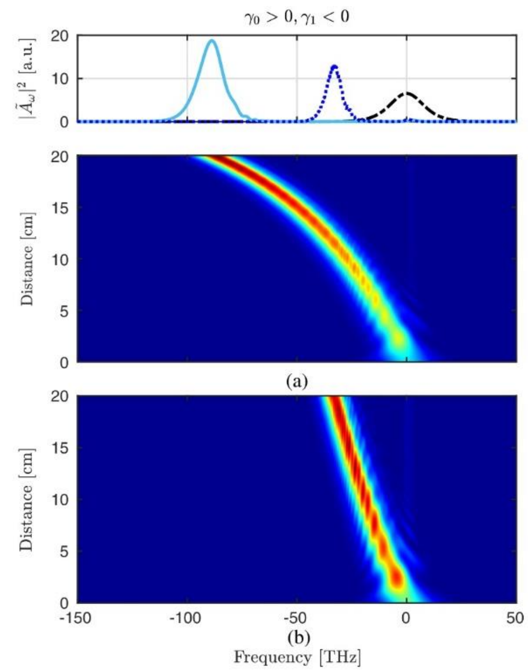
Photon conserving GNLSE (pcGNLSE)

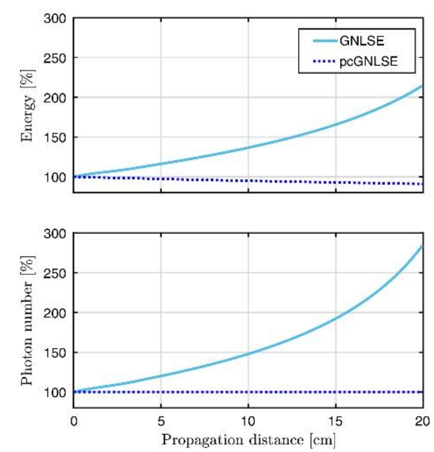
$$\frac{\partial \tilde{A}_\omega}{\partial z} = i\beta(\omega)\tilde{A}_\omega + i\frac{\bar{\gamma}(\omega)}{2}F(C^*B^2) + i\frac{\bar{\gamma}(\omega)^*}{2}F(B^*C^2)$$

$$+if_R\bar{\gamma}(\omega)^*F\left(B\int_0^\infty h_R(\tau)\ |B(t-\tau)|^2 d\tau - B|B|^2\right)$$





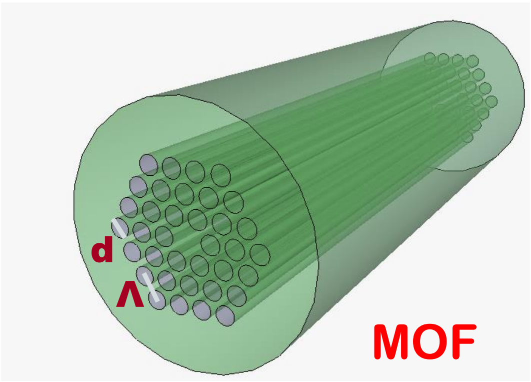


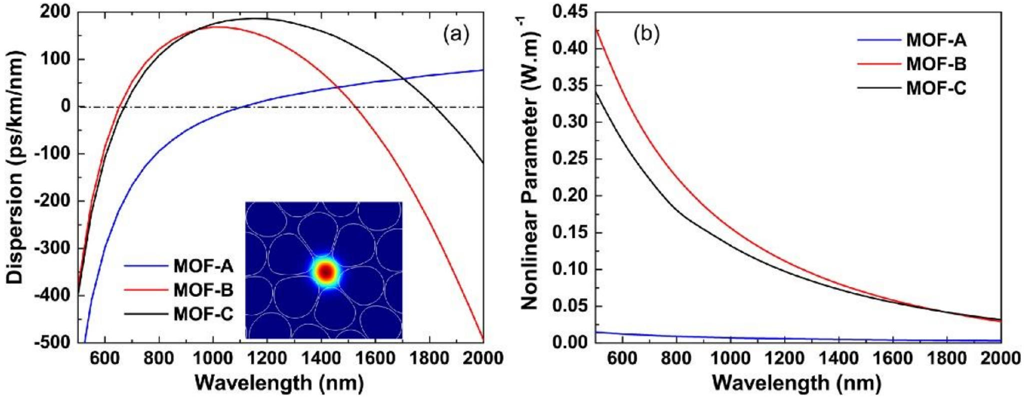


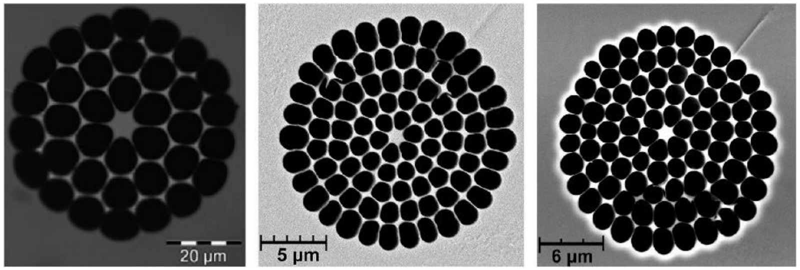
[J. Bonneti et al., J. Opt. Soc. Am. B **37**, 445-450 (2020)]

Microstructured fiber

- Dispersion properties can be tailored
- Enhanced nonlinearity due to tight modal confinement in the core.
- Effective area becomes frequency dependent

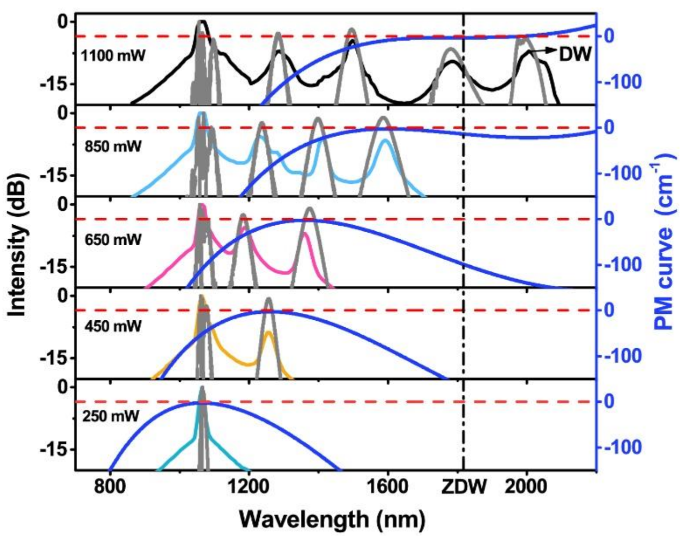






50µm 15µm 20µm

Manipulation of dispesive wave

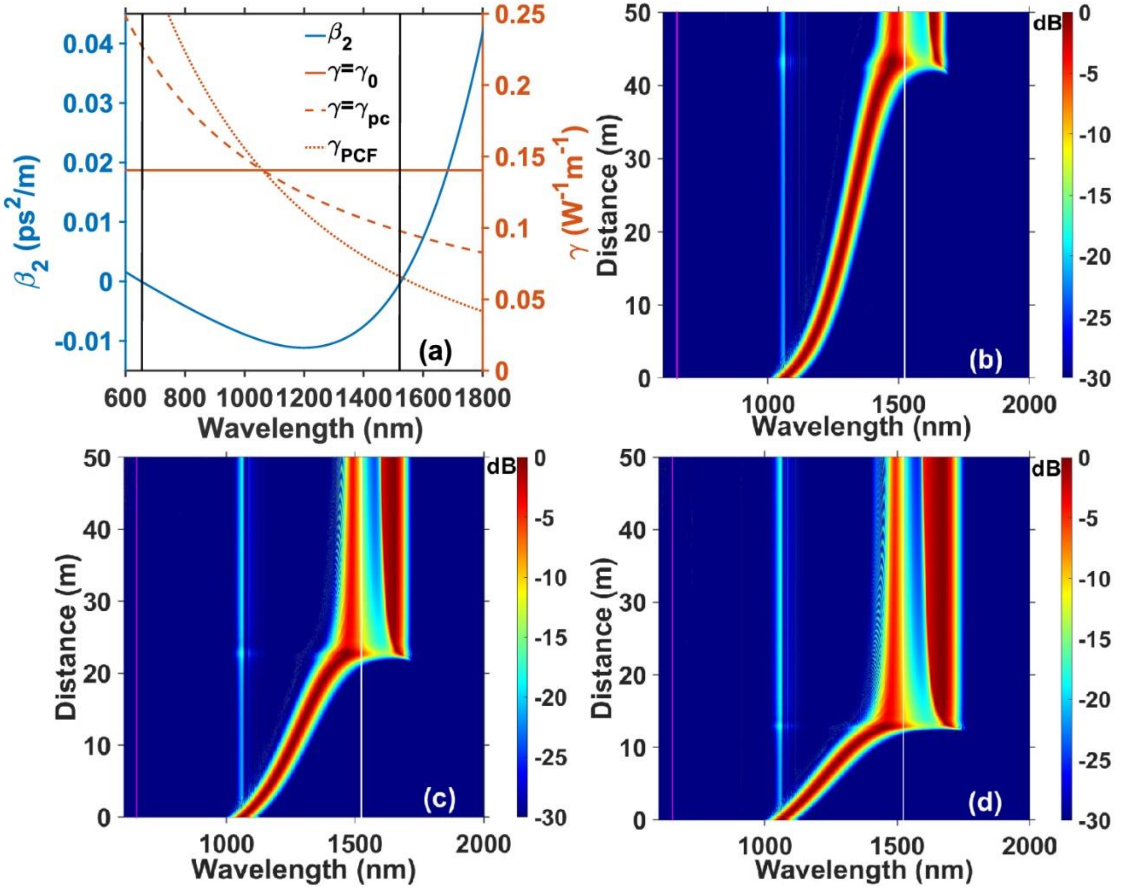


S. Bose et al., Appl. Opt. **59**, 9015-9022 (2020)

Spectral evolution of the fundamental soliton

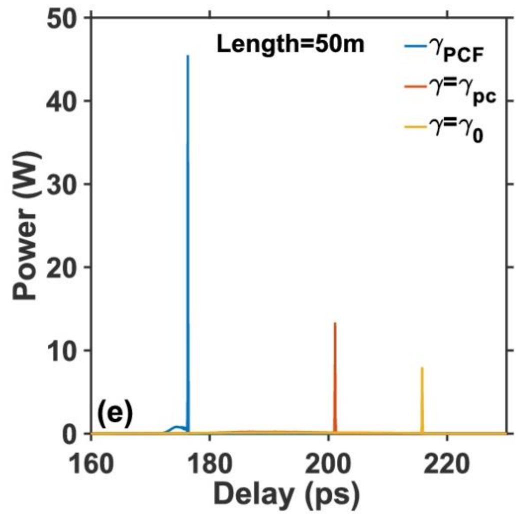
- Dynamic interplay between the higher order nonlinear and dispersion terms on the shaping of the Raman soliton
- Raman induced frequency shift (RIFS) suppression through specral recoil
- Non-solitonic radiation (NSR)
- Standard GNLSE overestimates the RIFS for most PCFs

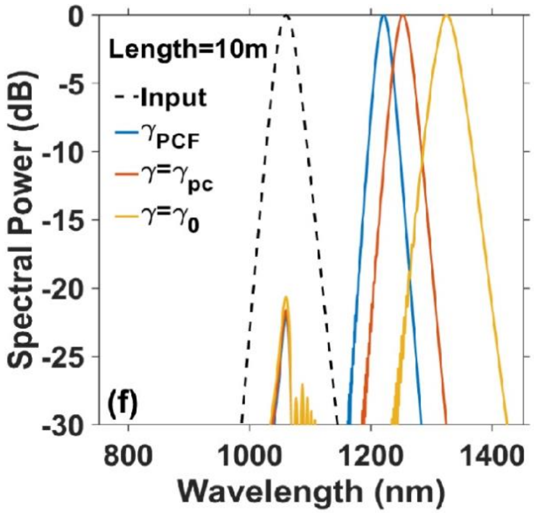
$$A(0,t) = \sqrt{P_0}\mathrm{sech}(T/t_0)\ t_0 = 20fs;\ P_0 = 180W$$

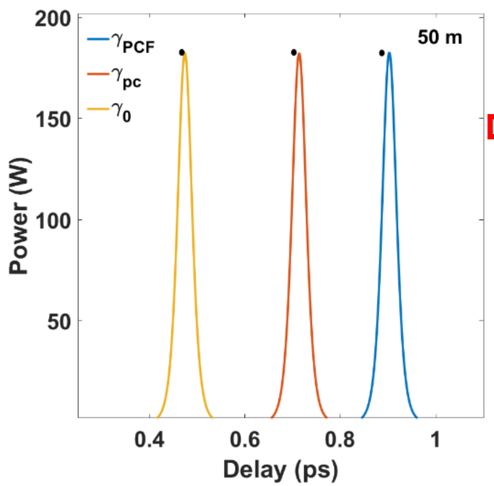


Numerical experiment

- The temporal and spectral shift are recorded for three different nonlinear profile
- Variation of peak power of the soliton are observed
- Compare with an analytical expression







In absence of HOD and Raman terms

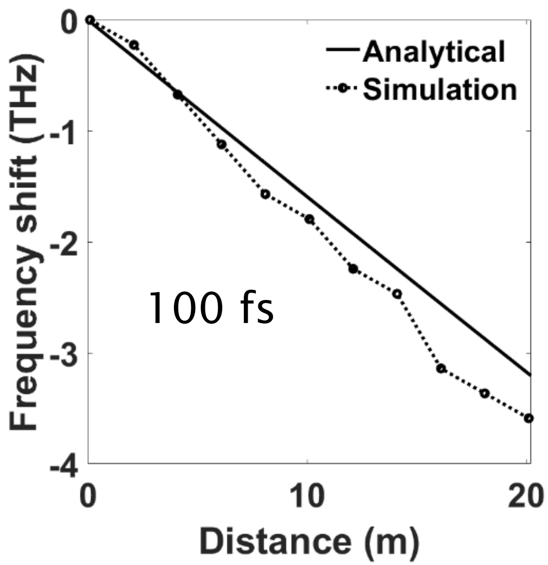
$$T = \frac{a+2}{3}\frac{\beta_2 z}{\omega_0 t_0^2} \qquad a = \frac{\gamma_1 \omega_0}{\gamma_0}$$

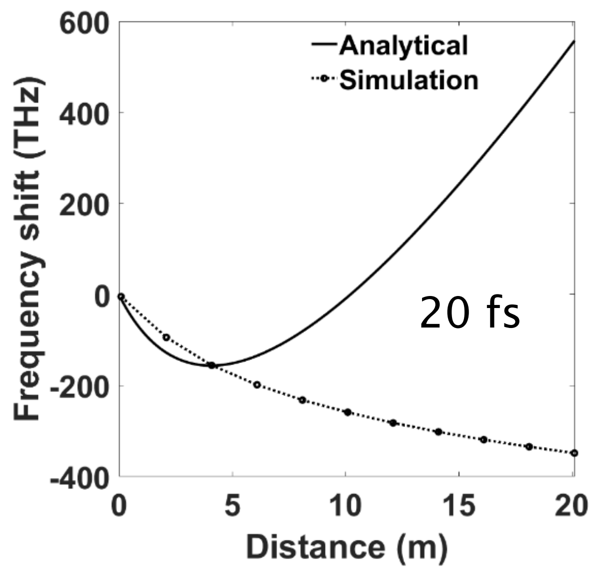
Linale et al., Opt. Lett. **45**, 4535-4538 (2020)

Comparison with analytical theory

- The analytical expression is based on the moment method
- RIFS in the presence of propagation losses, self-steepening, and dispersion slope

$$\Omega_{tot} = -\omega_0\left[1-\left(\sqrt[3]{\frac{5\omega_0 {T_0}^4}{8T_R|\beta_2|z_{eff}+5\omega_0 T_0^4}}\right)\right]-\frac{|\beta_2|}{\beta_3}\left[\sqrt[4]{\left(1+\frac{32T_R\beta_3}{15T_0^4}z_{eff}\right)}-1\right]+\frac{8T_R|\beta_2|}{15T_0^4}z_{eff}$$





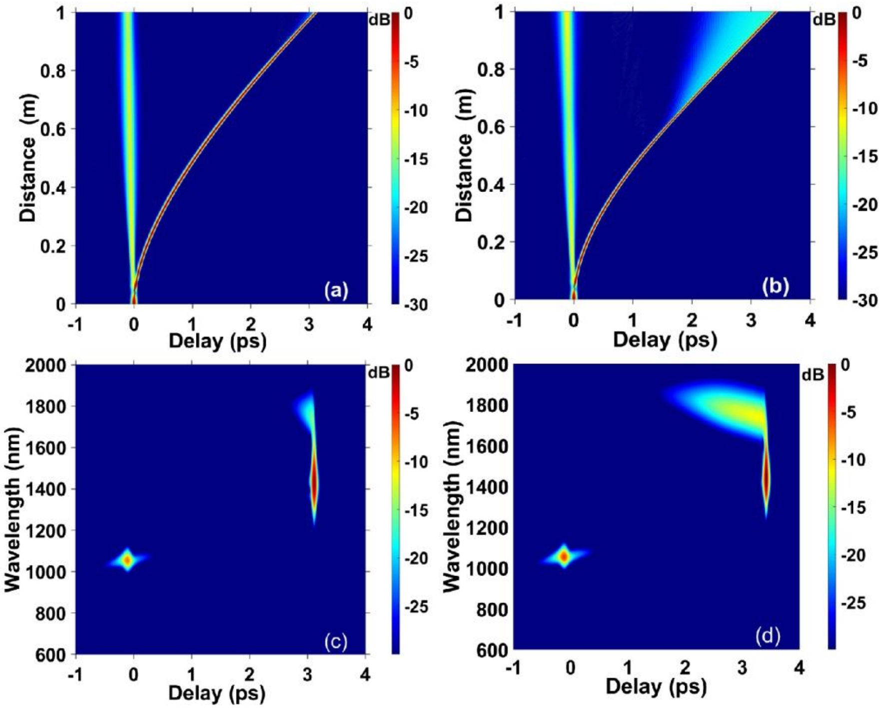
It matches well with long pulses

R. Kormokar et al.,J. Opt. Soc. Am. B 38, 466-475 (2021)

Pulse evolution of the higher order soliton

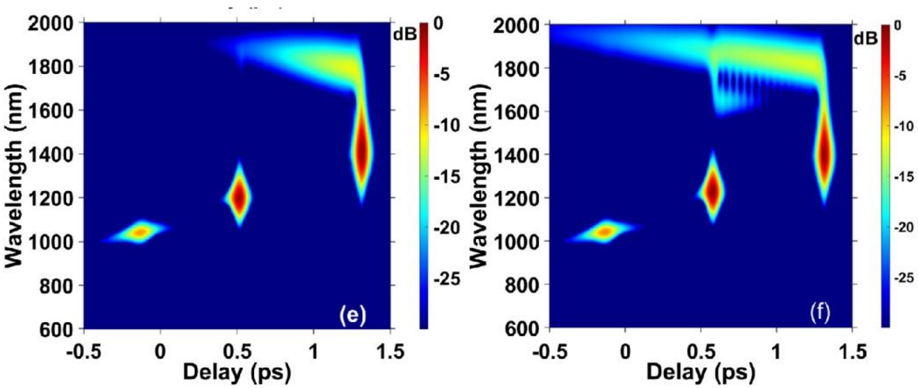
- Second-order soliton undergoes fission and splits into two fundamental solitons of different widths

- Significant changes in the spectrogram



$N = 2;\ P_0 = 715W$

Additional spectral feature at 1620 nm due to the trapping of the NSR

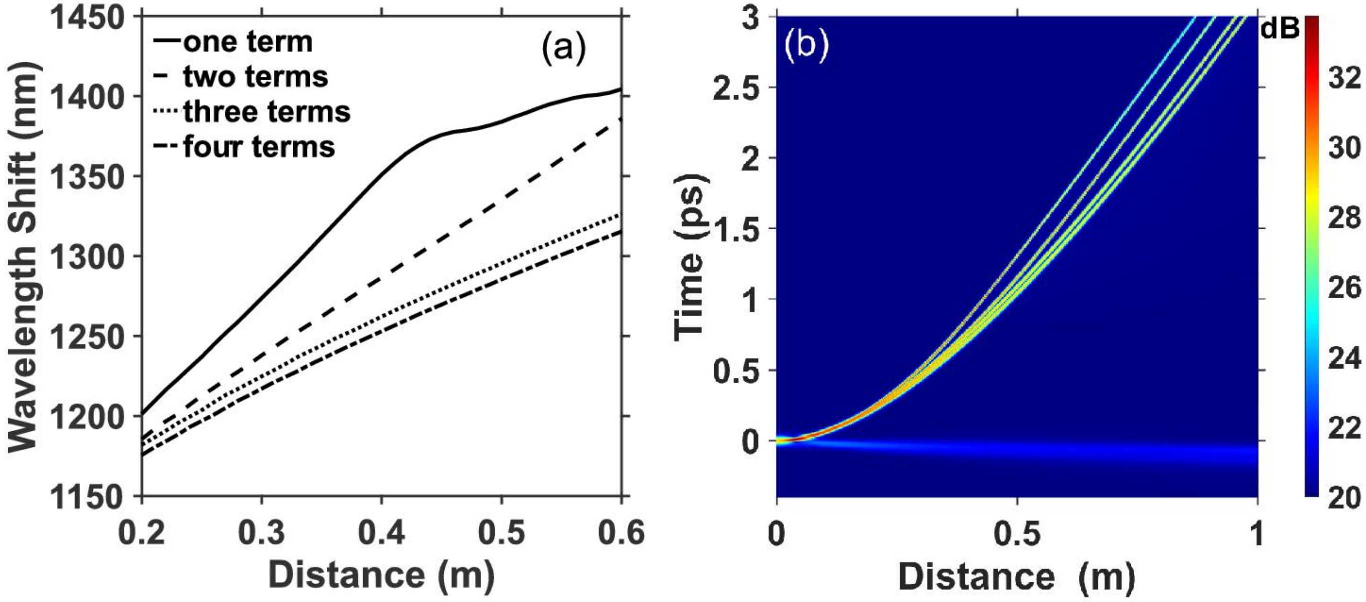


$N = 3;\ P_0 = 1610\ W$

Wavelength shift

$$\gamma(\omega) = \gamma_0 + \gamma_1(\omega - \omega_0) + \gamma_2/2!\,(\omega - \omega_0)^2 + \gamma_3/3!\,(\omega - \omega_0)^3 + \ldots\ldots\ldots$$

An important question is how many terms should be retained in the Taylor expansion of $\gamma(\omega)$?



RIFS as a function of distance for N=2

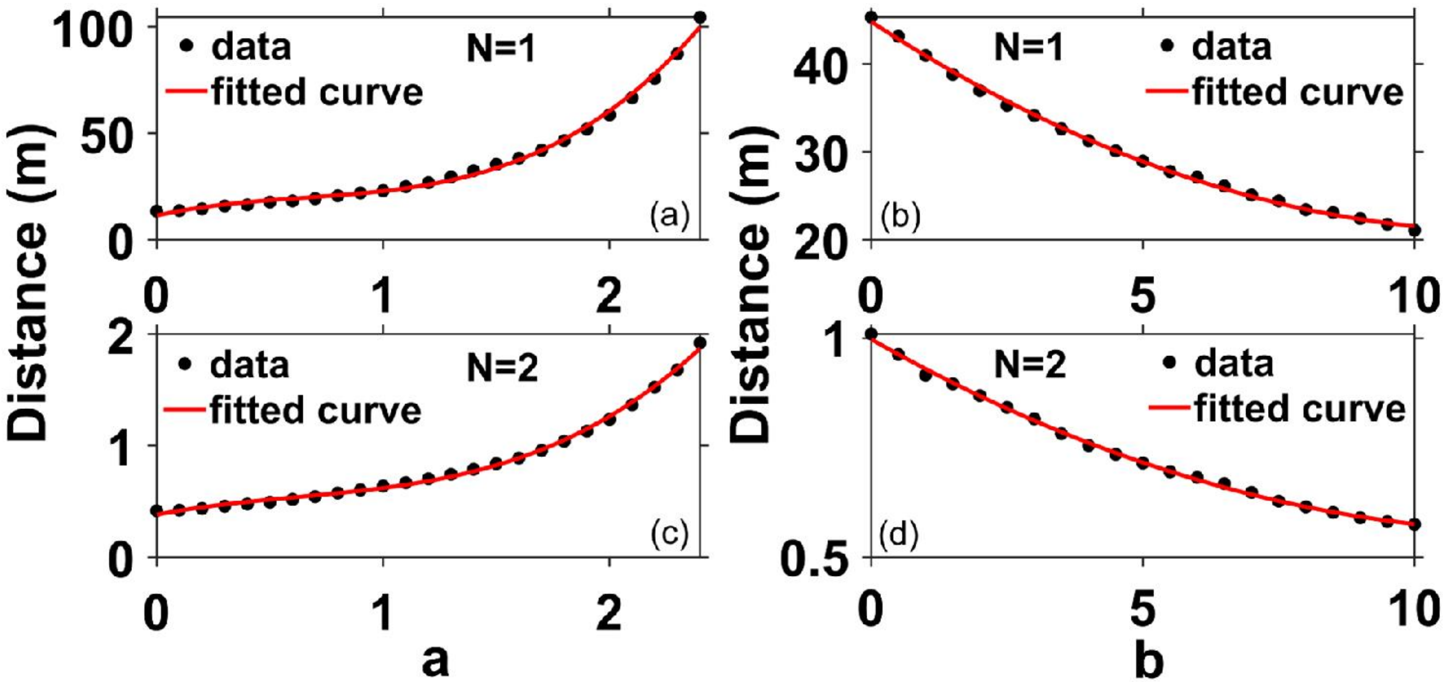
bose@iqo.uni-hannover.de

Effect of higher order nonlinear terms

$$\gamma(\omega) = \gamma_0 \left(1 + a(\omega - \omega_0)/\omega_0 + b(\omega - \omega_0)^2/2\omega_0^2\right)$$

dimensionless

$$a = \frac{\gamma_1 \omega_0}{\gamma_0} \qquad b = \frac{\gamma_2 \omega_0}{\gamma_0}$$



The length scale is reduced by a factor of 50 when we switch from *N* =1 to *N* =2 soliton

S. Bose et al., Opt. Lett. **46**, 3921-3924 (2021)

Summary

- Results are true for any high-confinement optical waveguide, including tapered fibers and suspended-core fibers
- The frequency dependence of $\gamma(\omega)$ in such fibers cannot be replicated using the conventional GNLSE based on the self-steepening effect
- To ensure the conservation of the photon number, we used the recently proposed modified GNLSE to reveal the importance of few-cycle solitons in a nonlinear waveguide
- Numerical simulations reveal that the rate of RIFS (along the fiber's length) is influenced by higher-order nonlinear terms
- Solitons are used to design a wavelength-tunable optical source

Thank you very much for your attention!