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Nonlinear matching of Solitons - Continued redshift between silica and soft-glass fibers.

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Abstract: We present an analysis of nonlinear coupling between fibers. We introduce the nonlinear coupling coefficient and investigate solitons coupling from one fiber into another. We will also present simulated supercontinuum from concatenated fiber systems.

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In the search for making a versatile broadband infrared (IR) supercontinuum (SC) source, the dynamics of soliton coupling between optical fibers is of great interest. Soft-glass fibers made from, e.g., ZBLAN or tellurite, are promising candidates as nonlinear fibers used in IR SC sources for broadening the spectrum of light beyond the material loss limit of silica around 2.5 μm. Generally, soft-glass fibers have zero dispersion wavelengths (ZDW) at longer wavelengths than silica fibers, and thus systems of concatenated silica and soft-glass fibers have been proposed to enable the use of Er/Yr based lasers for anomalous dispersion regime pumping [1–4]. In such concatenated systems, solitons redshift, by the soliton self-frequency shift (SSFS), initially in a silica fiber (fiber 1) until strong dispersion prevents further redshift [4]. Then, light is coupled into a soft-glass fiber (fiber 2) for further redshifting into the IR.

When coupling linear waves between optical waveguides, mode-field diameter matching is important to avoid loss of power. When coupling fundamental solitons between two nonlinear fibers however, soliton number preservation becomes an equally important matching requirement, placing restrictions not only on the group velocity dispersion of the fibers (β_2), but also on their nonlinearity $\gamma = n_2\omega/(cA_{\mathrm{ff}})$ [5, 6]. Here n_2 is the nonlinear refractive index of the fiber material, ω is the frequency, c is the speed of light in vacuum and A_{eff} is the effective area of the mode. There are two scenarios, in which nonlinear processes dominate further dynamics after coupling of light into fiber 2, and both are determined by the soliton number in fiber 2, N_2. (1) If $1/2 < N_2 < 3/2$ (Fig. 1 left panel, top left) the coupled light will continue propagation as a fundamental soliton in fiber 2. (2) If $N_2 > 3/2$ (Fig. 1, left panel, top right) a higher order soliton is generated, which will undergo soliton fission and possibly generate dispersive waves.

As a numerical example illustrating the nonlinear soliton matching (NLSM), we consider coupling between silica and soft-glass photonic crystal fibers (PCFs) with hole diameter d, pitch Λ, and 7 rings of air-holes. All fiber properties

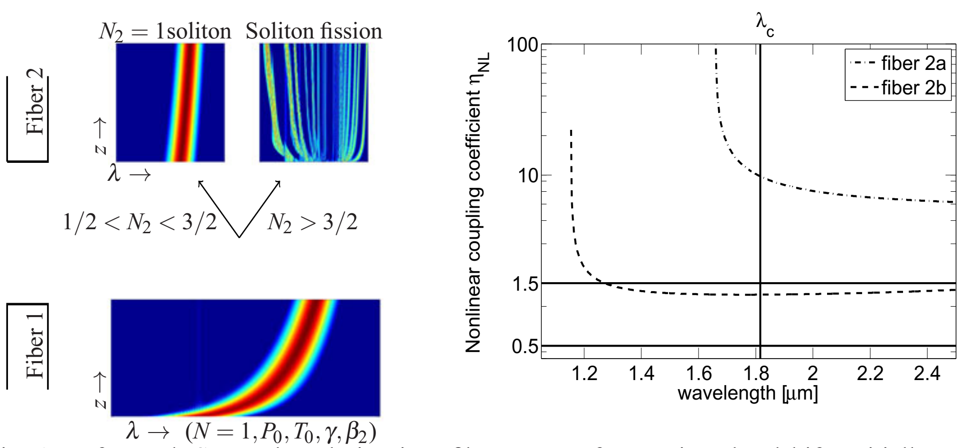

Fig. 1. Left panel: Spectral evolution in a fiber system for continued redshift: Initially an $N = 1$ soliton redshifts in fiber 1 (silica), and the output is coupled into fiber 2 (soft-glass). Right panel: Nonlinear coupling coefficient, η_{NL} for fiber 2a (dash dotted) and fiber 2b (dashed) with $\eta = 1$.

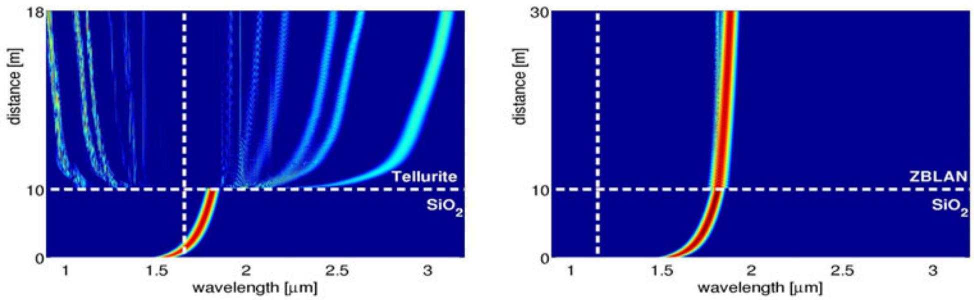

Fig. 2. Spectral Evolution in fiber 1 and fiber 2a (left panel) and fiber 1 and fiber 2b (right panel). Left panel: $\eta_{\rm NL} \gg 3/2$ and a higher order soliton undergoes soliton fission. Right panel: $1/2 < \eta_{\rm NL} < 3/2$, and a single fundamental soliton continues propagation. White vertical line marks $\lambda_{\rm ZD}$ of fiber 2.

are calculated using a commercially available finite-element tool and material dispersion taken from the literature. Fiber 1 is a PCF ($d = 3.3\ \mu$m and $\Lambda = 6.35\ \mu$m) made from fused silica and we investigate two different materials for fiber 2. Fiber 2a is a PCF ($d = 3.5\ \mu$m, $\Lambda = 4.38\ \mu$m) made from highly nonlinear tellurite and fiber 2b is a fluoride based ZBLAN PCF ($d = 3.3\ \mu$m and $\Lambda = 6.35\ \mu$m). In optical fibers the equation governing the dynamics is the generalized nonlinear Schrödinger equation (GNLSE) which we numerically. As initial condition we use a fundamental soliton with a central wavelength $\lambda_p = 1550$ nm, and FWHM pulse duration of $T_{\rm FWHM} = 50$ fs. After propagation in 10 m of fiber 1, simulation of the GNLSE shows that the soliton has redshifted to approximately $\lambda_c = 1820$ nm. We define the nonlinear coupling coefficient as [5],

$$\eta_{\rm NL}^2 \equiv N_2^2/N_1^2 = \eta(\gamma_2/|\beta_{22}|)/(\gamma_1/|\beta_{21}|) \tag{1}$$

which is given in terms of material parameters through the nonlinear coefficient γ_i, and fiber properties through β_{2i} for the i-th fiber, respectively ($i = 1,2$). In Eq. (1) the power coupling efficiency $0 \le \eta \le 1$, accounts for Fresnel reflection, mode field diameter mismatch and similar loss mechanisms. In the numerical treatment we take $\eta = 1$ [5]. In Fig. 1 right panel, we show $\eta_{\rm NL}$ for fiber 2a and 2b as function of wavelength. Notice that $\eta_{\rm NL}$ is singular at $\beta_{22} = 0$, thus $\eta_{\rm NL} \to \infty$ at $\lambda_{\rm ZD}$ of fiber 2. The black horizontal solid lines mark the band of NLSM, where continued SSFS of a stable fundamental soliton can be expected. We find that $\eta_{\rm NL} \gg 3/2$ for fiber 2a, and consequently we expect soliton fission will occur in fiber 2a after coupling from fiber 1. Simulation results for propagation in 10 m of fiber 1 and 8 m in fiber 2a are shown in Fig. 2 left panel. Here it is clearly confirmed that after a short distance of propagation in fiber 2a, soliton fission causes a breakup of the pulse, and generates multiple separated solitons. The central wavelength of the most redshifted soliton becomes approximately $\lambda = 3100$ nm in this case, and $\sim 18\%$ of the energy in the input soliton has been converted to this wavelength. If, on the other hand, the output from fiber 1 is coupled into fiber 2b, where the NLSM condition is satisfied so that $1/2 < \eta_{\rm NL} < 3/2$, a fundamental soliton will continue propagation and redshift. This is also confirmed by simulations shown in Fig. 2 right panel. Here it is shown that the fundamental soliton from fiber 1 continues stable redshift in fiber 2b, and the central wavelength increases to 1857 nm. In this case approximately 83% of the energy from the input pulse is converted to this wavelength.

In the presentation we will further present how the NLSM scheme can be used for optimum coupling of a broadband SC between silica and soft-glass fibers. Here we will focus on the importance of the bandwidth over which $\eta_{\rm NL} > 1/2$ for optimum coupling.

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