Designing Dispersion- and Mode-Area-Decreasing Holey Fibers for Soliton Compression

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Abstract: We investigate numerically the adiabatic compression of solitons at 1.55 μm in holey fibers which exhibit simultaneously decreasing dispersion and effective mode area. Compression factors >10 are achieved for optimum fiber parameters.

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1. Introduction

Compression of soliton pulses propagating in optical fibers with decreasing dispersion is a well-established technique [1]. Very recently, a generalization of the technique for picosecond pulses has been suggested using tapered holey fibers [2]. This has been successfully demonstrated with femtosecond pulses at 1.06 μm [3].

Here, we investigate in more detail the idea of using dispersion- and mode-area-decreasing silica holey fibers and we analyze the required fiber design parameters. As a starting point, we show in Fig. 1(a) the dependence of dispersion D, dispersion slope Ds, and effective mode area A_{eff} on pitch Λ and air-filling fraction d/Λ of holey fibers with regular hexagonal geometry at 1.55 μm wavelength. We note that by appropriate fiber fabrication and/or tapering, a large variation of both D and A_{eff} can be achieved along the length of a single fiber.

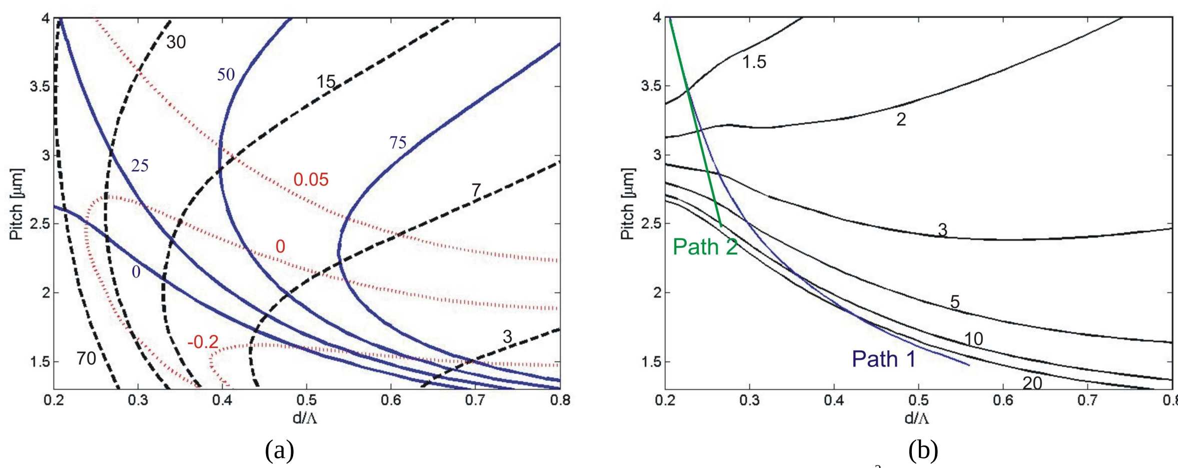

Fig. 1 Contour maps for (a) dispersion (blue solid) (ps/nm/km), dispersion slope (red dotted) (ps/nm²/km) and effective area (black dashed) (μm²), (b) adiabatic compression factors versus pitch Λ and d/Λ for holey fibers of hexagonal geometry at 1.55 μm wavelength.

2. Theory

For given fiber parameters and pulse energy, the width of a fundamental soliton is

$$\tau_0 = \frac{\lambda^3 D A_{eff}}{2\pi^2 c n_2 E_{sol}}, \quad (1)$$

where λ is the wavelength, n_2 is the nonlinear-index coefficient, and E_{sol} is the soliton energy. For adiabatic soliton compression in a low-loss fiber, E_{sol} stays approximately constant and the pulse width is proportional to the product of dispersion coefficient and effective area. Based on equation (1), we thus obtain the adiabatic compression factor, Fig. 1(b), corresponding to the map of fiber parameters, Fig. 1(a). Note that Fig. 1(b) is normalized to the top left corner of the figure which has the largest value of $D*A_{eff}$. A tapered fiber with parameters changing from that point to any other point on the map will result in compression of a soliton at 1.55 μm by the factor shown in the figure, provided that changes of fiber parameters over one local dispersion length are small. We performed numerical simulations of the generalized nonlinear Schrödinger equation using a standard split-step Fourier tool for two fibers with parameters following paths 1 and 2, respectively, as shown in Fig. 1(b).

3. Simulations and Results

For Path 1 from Fig. 1(b), both D and A_{eff} are decreasing by a factor of ~10 from the top left corner of the map to a point close to D=0. Fig. 2(a) shows the simulated propagation of a 400 fs soliton (dispersion length ~5 m) at fiber input through 50 m of low-loss holey fiber with the corresponding profiles for D and A_{eff}. After ~20 m of fiber, the observed width deviates from the analytic expression (1). A closer analysis reveals that two effects prevent further compression at this point: (i) As the pulse broadens spectrally and the fiber parameters change, a zero-dispersion wavelength is found close to the soliton wavelength towards the fiber end and thus the soliton starts to shed energy into dispersive waves [4]. (ii) The large decrease in A_{eff} (increase of nonlinearity) leads to temporal broadening by Raman soliton self-frequency shifting (SSFS). In order to avoid these limiting factors, holey fiber parameters have to be chosen in the top left area of the map, Fig, 1(a), with an endpoint near the line of zero dispersion slope Ds=0.

Path 2 of Fig. 1(b) represents such a choice. Here, D decreases by a factor of ~5 and A_{eff} by a factor of ~2.5 along the fiber. The corresponding simulation results, Fig. 2(b), closely follow the analytic approximation (1), which suggests that the soliton compression is indeed adiabatic. A small SSFS is still observed in the corresponding spectrum but no dispersive waves are generated. A 400 fs soliton pulse is compressed down to 33 fs, a compression factor of ~12. The adiabaticity of the soliton compression is further confirmed by the fact that simulations using paths with the same end points as Path 2 but alternative routes in between yield very similar performances.

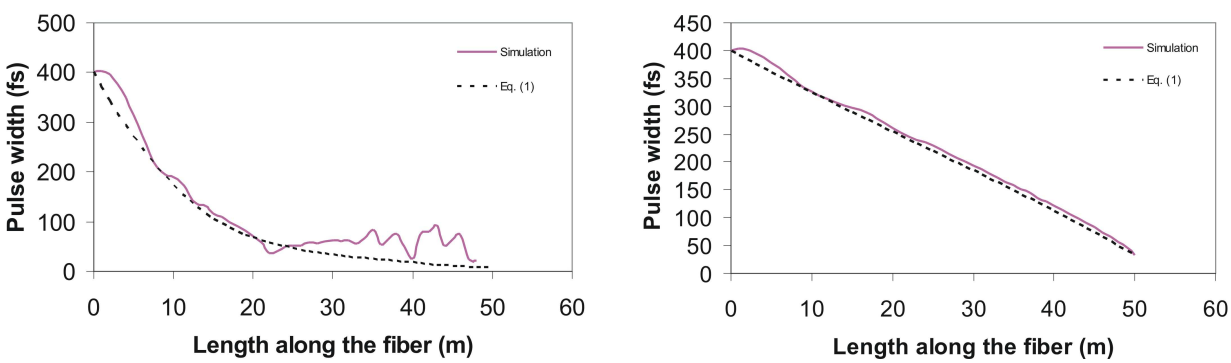

Fig. 2. Simulated pulse widths (FWHM) in fibers with dispersion and effective area profiles along (a) Path 1 and (b) Path 2 of Fig. 1. In both cases the fiber parameters decrease with a constant rate of variation along the 50 m length of fiber.

4. Conclusions

We have investigated adiabatic compression of femtosecond solitons in silica holey fibers of decreasing dispersion and effective mode area. These parameters are directly related to the structural design parameters Λ and d/Λ. A compression factor of 12 has been obtained for low-loss fibers in the adiabatic regime. Minimizing the fiber length required for adiabatic compression and nonadiabatic compression in much shorter fibers is currently under investigation.

References

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