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Parabolic pulse generation in a dispersion-decreasing solid-core photonic bandgap Bragg fiber

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ABSTRACT

We analyze the interplay of nonlinearity and dispersion in a dispersion-decreasing photonic bandgap Bragg fiber as a new platform for generating parabolic pulses. A suitably designed linearly tapered, low-index-contrast, solid-core Bragg fiber – amenable to fabrication by conventional modified chemical vapor deposition technology – is shown to yield stable parabolic pulses. The fiber design was optimized through a simple and accurate transfer-matrix formalism and pulse evolution was studied by the well-known split-step Fourier method. Our study revealed feasibility of generating parabolic pulses in such a dispersion-decreasing Bragg fiber of length as short as 1 m. We have also studied the effect of third order dispersion on generated parabolic pulse, which is an important deteriorating factor in such applications. The effective single-mode operation of the proposed device is achieved through appropriate tailoring of the outer cladding layers.

1. Introduction

Generation of a parabolic pulse through an optical fiber by exploiting complex interplay amongst the gain, nonlinearity and dispersive effects has drawn much attention in recent years because the use of such pulses are beneficial for high-power fiber lasers and amplifiers, supercontinuum generation, and all-optical signal regeneration [1–4]. Parabolic pulses are attractive because of their resistance to optical wave breaking [5,6], self-similarity in shape [2], and nearly linear chirp. Linearly chirped parabolic pulses are also useful in compressing short pulses from picoseconds down to femtoseconds [6]. Indeed, a variety of fiber-based techniques, active [1,2,6] as well as passive [7–11], have been proposed in the literature for generating parabolic pulses. One of the most widely discussed passive routes to obtain parabolic pulses relies on a suitably designed tapered fiber, which enables a hyperbolic dispersion-decreasing propagation of the launched seed pulse at the input [7,8]. In practice, such a fiber taper may not be easy to attain, although it can be approximated by concatenating two linear tapers of different slopes in their dispersion versus diameter curve. Since the input pulse evolves asymptotically to a parabolic pulse, the required fiber length is typically very long [7,8]. Alternative passive approaches that have shown parabolic pulse generation in shorter sample lengths of fibers involve hybrid combination of different fibers [9], or through propagation in a comb-like dispersion-decreasing profile [10] simulated by concatenation of a set of different fibers or more recently a tapered microstructured fiber [11].

Recently, there has been growing interest in solid-core Bragg fiber (SCBF) devices because of a wide design freedom afforded by such fibers for tailoring the dispersion and nonlinear characteristics useful for shifting the zero-dispersion wavelength towards shorter wavelengths [12], spectral broadening and supercontinuum generation [13,14], large mode area fibers [15], etc. Nonlinear pulse evolution has been studied in anti-resonant optical waveguide (ARROW) type solid-core bandgap fibers and a range of nonlinear effects were observed in the recent past [16,17]. In contrast to other varieties of microstructured fibers, one distinct advantage of solid-core photonic band gap Bragg fibers with low refractive index contrast is that such fibers are amenable to fabrication by the well-developed and mature technology of modified chemical vapor deposition. In this perspective, we investigate and present our first results on the feasibility of passive generation of parabolic pulses within a short, dispersion-decreasing, linearly tapered SCBF. Optimization of fiber design has been carried out numerically through a simple and accurate matrix method [18]. Feasibility of parabolic pulse generation in a tapered SCBF of length as short as 1 m is demonstrated. We have also studied the effect of third order dispersion on generated parabolic pulses.

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2. Optimization of fiber design

The schematic diagram of the refractive index profile of the proposed SCBF is shown in Fig. 1. In order to study propagation characteristics of such fibers, we have implemented a transfer-matrix approach, proposed originally to analyze leaky structures [18]. As our proposed SCBF is essentially a leaky structure having low-index contrast cladding bi-layers, propagation characteristics of this fiber can be studied accurately and easily by this method. As the scalar approximation is valid for a low-index contrast SCBF, the modal field can be written as:

$$\Psi(r, z, \phi, t) = \left[A_j J_m(k_j r) + B_j Y_m(k_j r)\right] \exp[i(\omega t - \beta z) \pm in\varphi], \qquad (1)$$

where $j = 1, 2 \ldots Q$, and $m, n = 0, 1, 2 \ldots$ and $k_j = [(n_j \omega / c)^2 - \beta^2]^{1/2}$, β is the propagation constant, n_j is the refractive index of the jth region and Q is the total number of regions in the structure. The finite number of cladding regions implies that the modes of the Bragg fibers are inherently leaky in nature, and hence the field in the outermost region should represent a purely outgoing wave. The eigenvalue equation is obtained by imposing this particular condition; the propagation constant and the leakage loss of the modes are calculated by solving this equation.

Our proposed SCBF consists of a pure silica-core surrounded by ten bi-layers of doped silica with an index contrast, $\Delta n = n_2 - n_3 = 0.016$ at $\lambda = 1.06$ μm. The core radius (d_1) is 6.1 μm and thickness of the bi-layers are $d_2 = 1.05$ μm and $d_3 = 2.01$ μm, respectively, chosen to satisfy the *quarter-wave stack condition* $k_2 d_2 = k_3 d_3 = \pi/2$ that minimizes the leakage loss in such a waveguiding structure. For this specific SCBF structure, we obtain through the matrix method the effective mode index n_{eff} ($=\beta/k_0$) and the corresponding field distribution $\Psi(r)$ associated with the fundamental mode, which is shown in Fig. 2. We use these to calculate the group velocity dispersion (GVD) parameter β_2, and the well-known nonlinear parameter γ for the SCBF using

$$\gamma = \frac{2\pi n'_2}{\lambda A_{\text{eff}}} \qquad (2)$$

where n'_2 is the nonlinear refractive index of silica ($\approx 2.4 \times 10^{-20}$ m^2/W) and A_{eff} is the effective mode area, defined as [19]

$$A_{\text{eff}} = \frac{2\pi\left[\int_0^\infty E^2(r) r dr\right]^2}{\int_0^\infty E^4(r) r dr} \qquad (3)$$

To investigate parabolic pulse generation, we assume that the SCBF is tapered along its length so that the propagating pulse experiences a decreasing dispersion during its propagation.

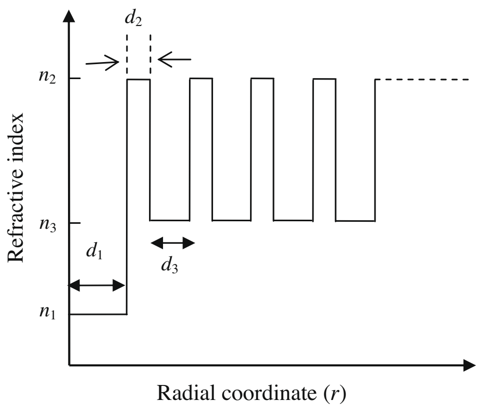

Fig. 1. Schematic diagram of the refractive index profile (RIP) of the proposed Bragg fiber.

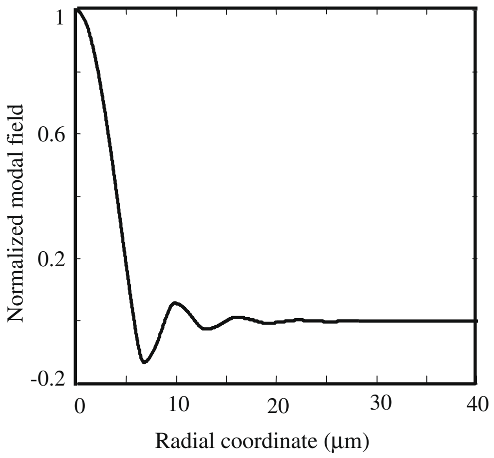

Fig. 2. Field distribution of the fundamental mode of the fiber.

A tapered fiber can be realized during its drawing from a preform [20] through a suitable control of the fiber draw speed or using a rig designed for fabricating tapered fibers through selective heating and pulling; the heat source could be an oxy-butane flame [21] or a CO$_2$ laser [22]. Due to tapering, the core and cladding thicknesses along the length of the tapered SCBF would vary uniformly for a given taper ratio assuming the taper to be linear. As expected, the dispersion of the SCBF decreases along the length of the fiber, as shown in Fig. 3. The GVD parameter is $\approx 5.9 \times 10^{-27}$ s^2/m at the input end, and it reduces to 0.48×10^{-27} s^2/m at the output end. The variation of nonlinear parameter (γ) along the tapered SCBF length is also shown in Fig. 3. The value of γ varied from $\approx$1.9–2.3 (W km)$^{-1}$ from the input end to the output end along the fiber length. The nominal effective area of the mode though would vary along the taper length, is $\approx$60 μm^2.

3. Results and discussion

The evolution of an input seed pulse inside the dispersion-decreasing SCBF was modeled by solving the following nonlinear Schrödinger equation (NLSE) through the symmetrized split-step Fourier method [19]:

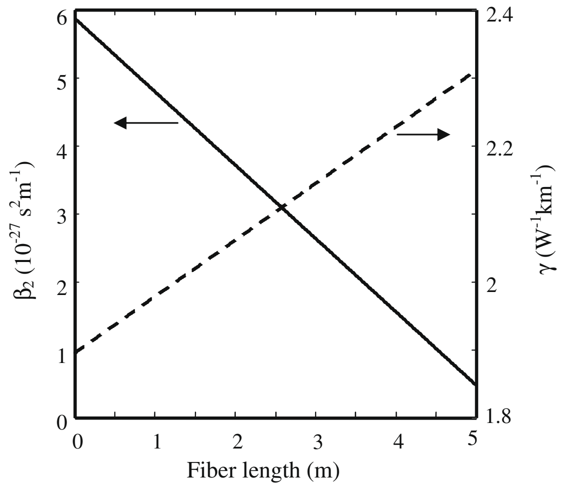

Fig. 3. Variation of the GVD parameter (solid curve) and the nonlinearity parameter (dashed curve) along the fiber length.

$$\frac{\partial u}{\partial z}+\frac{\alpha}{2}u+i\frac{\beta_2(z)}{2}\frac{\partial^2 u}{\partial t^2}-i\gamma(z)|u|^2u=0 \tag{4}$$

where u is the slowly varying pulse envelop and α is the loss parameter. The parameters $\beta_2(z)$ and $\gamma(z)$ are the longitudinally varying GVD and nonlinear parameters, respectively. Eq. (4) with varying dispersion can be written, through simple transformations as an equation with a varying gain term.

A sample tapered SCBF with optimum parameters obtained in Section 2 and of length 1 m was chosen for numerically investigating the evolution of the seed pulse in it. We assume that a Gaussian seed pulse with a peak power of 2 kW, and temporal width (FWHM) 200 fs is launched into the input end of the tapered SCBF. The shape of the output pulse (solid curve) after 1 m is compared with the input pulse (dashed curve) in Fig. 4(a). A fitted exact parabolic pulse (dotted curve) is also given in this figure for comparison. The frequency chirp accumulated across the pulse at the output end is also shown in Fig. 4(a). Fig. 4(b) shows the output pulse on a logarithmic scale. The evolution of the input pulse to a parabolic form is evident from this figure.

We have also studied the effect of third order dispersion (TOD) on the generated pulse quality as this was found to be the most important parameter affecting the quality of generated parabolic pulse [8]. The output pulses at the output of the fiber without (solid) and with (dashed) TOD are shown in Fig. 5. As can be seen from the figure, there is no observable degradation in the pulse quality except a slight shift in the pulse. This is attributed to the relatively short length of the fiber required in our case for the generation of the pulse. Moreover, one can optimize the design further to achieve smaller TODs, which would eventually facilitate realization of parabolic pulses with longer fiber lengths.

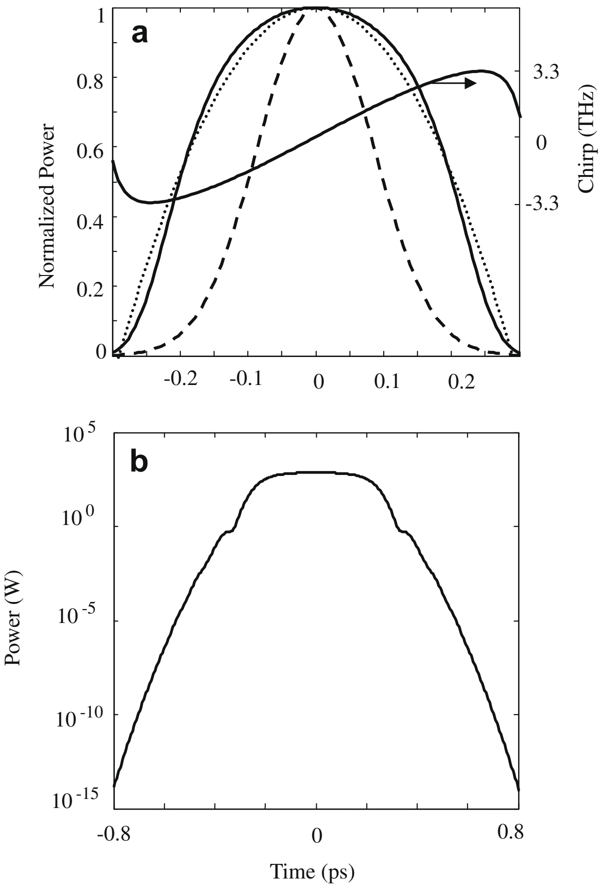

Fig. 4. (a) Output (solid), ideal parabolic (dotted) and input (dashed) pulses along with the frequency chirp after propagation through 1 m length of the designed tapered Bragg fiber; and (b) output pulse shape plotted on a logarithmic scale.

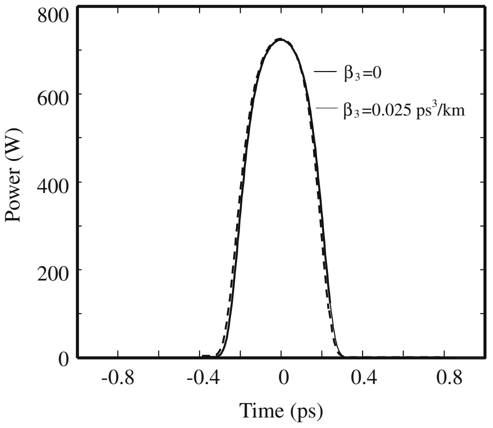

Fig. 5. Output pulse shapes after 1 m propagation without (solid) and with (dashed) the inclusion of the TOD.

Another important issue to be addressed regarding the proposed fiber design is the differential loss between the fundamental mode and the first higher-order mode. As our proposed fiber is inherently multimode in nature and the device length is short, it is essential to ensure that higher-order mode discrimination is achieved well within the short length of fiber. For our design, the leakage losses for fundamental mode and first higher-order mode were found to be 0.07 and 19.7 dB/m, respectively. The differential loss can be further enhanced by modifying the last few cladding bi-layers. This is based on the observation that the modal field of first-higher-order mode penetrates more into outer cladding layers compared to that of the fundamental mode. The modal field of the first higher-order mode is shown in Fig. 6. The field oscillations extending into last bi-layers can be seen from the figure. To achieve high differential loss between these modes, we have doubled the thicknesses of the last two bi-layers, making them anti-reflecting. Although this would enhance the radiation loss of both the modes, the loss now experienced by the first higher-order mode would be much higher. With this modified cladding, the leakage losses for the fundamental mode and first higher-order mode were found to be 0.74 and 58.4 dB/m, respectively. Hence, the first higher-order mode would get stripped-off within ~34 cm of propagation.

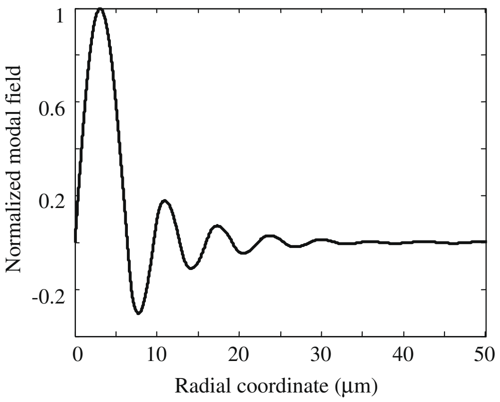

Fig. 6. Modal field distribution of the first-higher-order mode of the proposed dispersion-decreasing Bragg fiber.

4. Conclusion

We have demonstrated through a numerical study the feasibility of generating parabolic pulses in a tapered, all-solid, silica-core, Bragg fiber of length as small as 1 m. The designed SCBF consisted of bi-layers of doped silica with a relatively low-index contrast and is thus amenable to fabrication by the well-known MCVD technique of fiber fabrication. The effect of TOD is found to be negligible on the generated pulse quality. Effective single-mode operation is achieved by modification of last two bi-layers.

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References

[1] M.E. Fermann, V.I. Kruglov, B.C. Thomsen, J.M. Dudley, J.D. Harvey, Phys. Rev. Lett. 84 (2000) 6010.
[2] V.I. Kruglov, A.C. Peacock, J.D. Harvey, J.M. Dudley, J. Opt. Soc. Am. B 19 (2002) 461.
[3] S. Boscolo, S.K. Turitsyn, IEEE Photon. Technol. Lett. 17 (2005) 1235.
[4] F. Parmigiani, C. Finot, K. Mukasa, M. Ibsen, M.A.F. Roelens, P. Petropoulos, D.J. Richardson, Opt. Exp. 14 (2006) 7617.
[5] D. Anderson, M. Desaix, M. Karlsson, M. Lisak, M.L. Quiroga-Teixeiro, J. Opt. Soc. Am. B 10 (1993) 1185.
[6] K. Tamura, M. Nakazawa, Opt. Lett. 21 (1996) 68.
[7] T. Hirooka, M. Nakazawa, Opt. Lett. 29 (2004) 498.
[8] A.I. Latkin, S.K. Turitsyn, A.A. Sysoliatin, Opt. Lett. 32 (2007) 331.
[9] C. Finot, L. Provost, P. Petropoulos, D.J. Richardson, Opt. Exp. 15 (2006) 852.
[10] B. Kibler, C. Billet, P.A. Lacourt, R. Ferriere, L. Larger, J.M. Dudley, Electron. Lett. 42 (2006) 965.
[11] N. Vukovic, N.G.R. Broderick, F. Poletti, Parabolic pulse generation using tapered microstructured optical fibers, Advances in Nonlinear Optics, Article ID 480362, Open Access Article Distributed Under Creative Commons Attribution License, vol. 2008, Hindawi Publishing Corp., 2008, pp. 1–10.
[12] F. Brechet, P. Roy, J. Marcou, D. Pagnoux, Electron. Lett. 36 (2000) 514.
[13] S. Dasgupta, B.P. Pal, M.R. Shenoy, J. Lightwave Technol. 25 (2007) 2475.
[14] H.T. Bookey, Sonali Dasgupta, B. Nagaraju, B.P. Pal, A. Sysoliatin, J.E. McCarthy, M. Salganskii, V. Khopin, A.K. Kar, Opt. Exp. 17 (2009) 17130.
[15] S. Février, R. Jamier, J.-M. Blondy, S.L. Semjonov, M.E. Likhachev, M.M. Bubnov, E.M. Dianov, V.F. Khopin, M.Y. Salganskii, A.N. Guryanov, Opt. Exp. 14 (2006) 562.
[16] A. Fuerbach, P. Steinvurzel, J.A. Bolger, A. Nulsen, B.J. Eggleton, Opt. Lett. 30 (2005) 830.
[17] A. Fuerbach, P. Steinvurzel, J.A. Bolger, B.J. Eggleton, Opt. Exp. 13 (2005) 2977.
[18] K. Thyagarajan, S. Diggavi, A. Taneja, A.K. Ghatak, Appl. Opt. 30 (1991) 3877.
[19] G.P. Agrawal, Nonlinear Fiber Optics, third ed., Academic, San Diego, CA, 2001.
[20] V.A. Bogatyrev, M.M. Bubnov, E.M. Dianov, A.S. Kurkov, P.V. Mamyshev, A.M. Prokhorov, S.D. Rumyantsev, V.A. Semenov, S.L. Semenov, A.A. Sysoliatin, S.V. Chernikov, A.N. Guryanov, G.G. Devyatykh, S.I. Miroshnichenko, J. Lightwave Technol. 9 (1991) 561.
[21] B.P. Pal, P. Roy Chaudhuri, M.R. Shenoy, Fiber Int. Opt. 22 (2003) 97.
[22] P. Pal, W.H. Knox, Opt. Exp. 15 (2007) 13531.