Efficient method for launching in-gap solitons in fiber Bragg gratings using a two-segment apodization profile

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We theoretically demonstrate what is a new method for efficient launching of in-gap solitons in fiber Bragg gratings. The method is based on generating a soliton outside the grating bandgap. Then, the soliton is adiabatically coupled into the bandgap by using its particlelike behavior. We compare our method to a previously published launching scheme that is based on generating the soliton directly within the grating bandgap. When using low-intensity incident pulses, the transmission efficiency of our method is three times higher than that of the previously published scheme. © 2008 Optical Society of America

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Soliton propagation in one-dimensional periodic structures has been studied extensively in recent years [1–10]. These solitons, often referred to as Bragg solitons, propagate owing to the balance between grating dispersion and nonlinearity. One of the striking properties of Bragg solitons is their ability to propagate even when their central frequency is located within the forbidden band of the periodic structure. The first experimental observations of Bragg soliton propagation in fiber Bragg gratings (FBGs) were obtained for out-of-gap solitons [2,3]. Recently, the propagation of in-gap solitons has also been demonstrated experimentally [7].

One of the proposed applications for Bragg solitons is pulse compression [4,8]. In a recent experiment, a 12-fold compression was demonstrated for out-of-gap solitons [8]. One of the limitations of using out-of-gap solitons for pulse compression is that multiple solitons may be generated if the incident pulse power is too high. This problem can be overcome if one uses a compression scheme that is based on generating in-gap solitons [10]. In the case of in-gap solitons, the reflection from the bandgap may be used to maintain a single-soliton transmission for high incoming powers [10].

The in-gap soliton excitation scheme used in [7] and analyzed numerically in [9] is based on launching a high-intensity pulse with frequency components that overlap the bandgap of an apodized grating. As the incident pulse enters the grating, its maximum intensity is enhanced owing to the deceleration in its group velocity [10]. Near the end of the apodized section, the high-intensity part of the pulse shifts the bandgap away owing to nonlinearity and excites an in-gap soliton. However, the leading low-intensity part of the pulse is backreflected before a soliton is formed. Therefore, the maximum pulse-transmission efficiency of the grating is inherently limited. A similar effect occurs when the soliton exits the grating. Therefore, the pulse-transmission theoretically obtained in [9] was relatively low: in the range of 20%–30% [9].

In this work, we propose a new method for efficiently launching in-gap solitons. The method is based on generating a soliton with a cental frequency outside the grating bandgap. The formed soliton then penetrates the bandgap adiabatically. Since solitons under adiabatic perturbations behave like particles [11], there is no substantial loss in the soliton energy as it penetrates the bandgap. The soliton excitation was performed by using a two-segment apodization profile. In the first segment, the pulse spectrum is located outside the local grating bandgap. The pulse is decelerated as it enters the grating and hence its intensity is enhanced [10]. Since the frequency components of the incident soliton lie mostly outside the grating bandgap, the launching efficiency is very high. In the second segment, the excited soliton adiabatically penetrates the bandgap. The exit of the soliton out of the bandgap is also performed adiabatically to reduce backreflections from the grating end. The adiabatic changes in the grating parameters at both grating ends significantly improve the total transmission through the grating, especially when the intensity of the incident pulse is low.

We note that the second apodization segment can be replaced by a small chirp that could be obtained by creating a temperature gradient over parts of the grating [12]. In [10], we have demonstrated that chirped gratings can be used for in-gap soliton formation. The main difference between our two works is that in our current scheme, only a single soliton is generated, whereas in [10] multiple solitons were formed. In [10], we used the interaction between the solitons to enable the transmission of only the leading soliton. The disadvantage of using such a scheme is that the generation of multiple solitons decreases the efficiency of the soliton formation. In our current work, we eliminate the generation of multiple solitons by tuning the input pulse frequency close to the grating bandgap.

We compare our launching scheme to the one analyzed in [9]. In the comparison, we use input pulses that are similar to the ones used in [9]. In addition,

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we use a grating with the same length and the same maximum strength of the coupling coefficient. The comparison shows that when the minimal launching powers are used, the soliton in our scheme is generated with approximately twice the efficiency of the scheme in [9]. The difference between the methods is even more considerable at the grating output; there, the pulse-transmission efficiency of our method is over three times higher. We note that the efficiency of the scheme analyzed in [9] can be significantly improved if the input pulse power is increased. The efficiency of both schemes can also be further improved by optimizing the shape of the first apodization segment of the grating to reduce reflections at frequencies proximal to the grating bandgap.

The propagation of light in nonlinear FBGs can be described by the following coupled-mode equations [10]:

$$\frac{i}{V_g}\frac{\partial \mathcal{E}_\pm}{\partial t} \pm i\frac{\partial \mathcal{E}_\pm}{\partial z} + \kappa(z)\mathcal{E}_\mp + \Gamma(|\mathcal{E}_\pm|^2 + 2|\mathcal{E}_\mp|^2)\mathcal{E}_\pm = 0, \quad (1)$$

where $\mathcal{E}_\pm$ is the envelope of the forward (+) and the backward (−) electric waves, V_g is the group velocity in the absence of the grating, $\kappa(z)$ is the grating amplitude, and Γ is the nonlinear coefficient. In our simulations, we used the split-step method described in [13] to solve Eq. (1) numerically. The fiber parameters were chosen as in [9]: $V_g = 2\times10^8$ m/s and $\Gamma = 6.4\ \mathrm{km}^{-1}\,\mathrm{W}^{-1}$.

The apodization at the grating entrance is shown in Fig. 1. The apodization is composed of two segments with lengths of L_1 and $L_2 = 1.5$ cm. The first apodization section is used to launch a soliton whose central frequency is outside the bandgap. The second apodization section is used to adiabatically couple the soliton into the grating bandgap. The apodization at grating end is a mirror image of the apodization at its beginning and is used to efficiently decouple the soliton out of the grating. The total grating has a length of $L = 10$ cm, where the uniform section of the grating has a length of $L - 2(L_1 + L_2) = 7$ cm and a coupling strength of $\kappa_0 = 2000\ \mathrm{m}^{-1}$. The apodization profile at the input of the grating is described by the following equation:

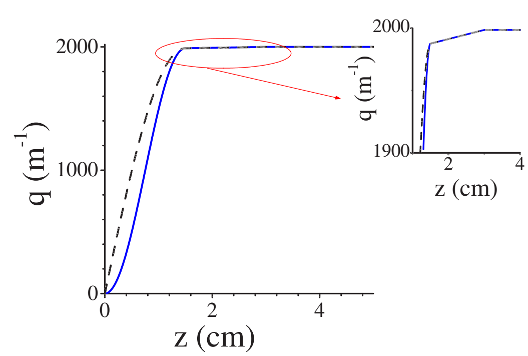

Fig. 1. (Color online) Coupling coefficient of the grating apodization. The inset shows a zoom around the second apodization segment.

$$\kappa(z) = \begin{cases} 0.5\,\eta\kappa_0(\cos(\pi z/(2L_1)) + 1), & 0 < z \le L_1 \\ \eta\kappa_0 + (1-\eta)\kappa_0(z - L_1)/L_2, & L_1 < z \le L_1 + L_2 \end{cases}, \quad (2)$$

where the parameter η fulfills $\eta < 1$. We assume an incident pulse with a hyperbolic-secant profile, a full width at half-maximum (FWHM) duration of $T_0 = 680$ ps, and a temporal frequency of $\Omega/V_g = 1990\ \mathrm{m}^{-1}$ [10]. The detuning is chosen to maximize the intensity enhancement of the pulse due to the slow-light effect as discussed in [10]. To efficiently launch an in-gap soliton, we use the parameter $\eta = 0.9945$ in Eq. (2). After penetrating the bandgap, at $z = L_1 + L_2$, the central frequency of the incident pulse is located within the local grating bandgap, defined in the linear regime, i.e., for $\Gamma = 0$ [10]. The detuning of the pulse from the edge of the local bandgap of the uniform region is equal to $10\ \mathrm{m}^{-1}$. For this value, 90% of the pulse energy overlaps with the local grating bandgap.

For the pulse duration and the grating parameters given above, the minimum peak power that is required for launching an in-gap soliton is approximately 270 W. Figure 2 shows the propagation of a pulse with such a peak power through the grating. The figure shows that a soliton is formed at $z = L_1$ and is decelerated as it penetrates the grating bandgap at $L_1 < z < L_1 + L_2$. The soliton in the uniform section of the grating has a peak power of 4 kW and a velocity of $0.018V_g$. The total energy of the soliton at $z = L_1 + L_2$ is approximately equal to 71% of the energy of the incident pulse, whereas the remaining 29% are backreflected as shown in the figure. After exiting the grating, the soliton energy diminishes to 63% of the initial pulse energy. The transmitted pulse at the grating output has a FWHM duration of 320 ps and a maximum power of 303 W.

We compared our launching method to that used in [9]. In that work, the grating had only a single-segment apodization with a half-period cosine profile [9], which can be described by Eq. (2) with $\eta = 1$. Beside using $\eta = 1$ in Eq. (2), we used the same grating and pulse parameters that were used in the example

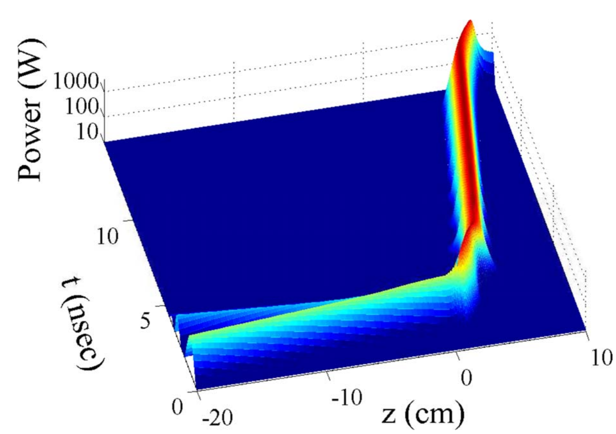

Fig. 2. (Color online) Formation and propagation of an in-gap soliton obtained using the launching method described in this Letter. The scale in the z axis is logarithmic.

given in Fig. 2. To launch a soliton, we had to increase the peak power of the pulse to 300 W. Figure 3 shows the propagation of the pulse inside the grating. The differences between the two excitation schemes can be understood by comparing between Figs. 2 and 3. In Fig. 3, the reflection at the beginning of the grating is much more significant than in Fig. 2. The total energy of the soliton inside the grating is equal to approximately 35% of the energy of the incident pulse. The peak power of the formed soliton is equal to 1.37 kW, and its velocity is equal to $0.052V_g$. As the pulse exits the grating, its energy is diminished to only 20% of the incident pulse energy. Hence, at the output of the grating, the transmission efficiency of our scheme is over three times higher than the result obtained by using the scheme in [9]. The transmitted pulse in Fig. 3 also has a long duration with a temporal FWHM of 1.18 ns and a relatively low peak power of 36 W.

In both the excitation schemes described in Figs. 2 and 3, the total pulse-transmission efficiency can be increased by changing the apodization profile of the first grating segment ($0<z<L_1$). In [10], a quarter-period sine apodization profile was used (Fig. 1, dashed curve). The reflection of the incident pulse for such a profile is lower than that obtained for a half-period cosine profile. Therefore, by using a quarter-period sine profile, the launching efficiency can be improved for both launching schemes. Assuming that the nonlinearity can be neglected, the dependence of the reflection on the grating profile can be qualitatively understood by analyzing the result in Eq. (18) in [14]. This equation indicates that in our apodization profiles, the maximum contribution to the reflectivity is obtained at the end of the apodization section, where the group velocity is minimal. To reduce the reflection from this region, the grating strength should be changed at the end of the apodization section as slowly as possible. As can be seen in Fig. 1, in a quarter-period sine profile, the grating amplitude changes more slowly at the end of the apodization than in a half-period cosine apodization profile with

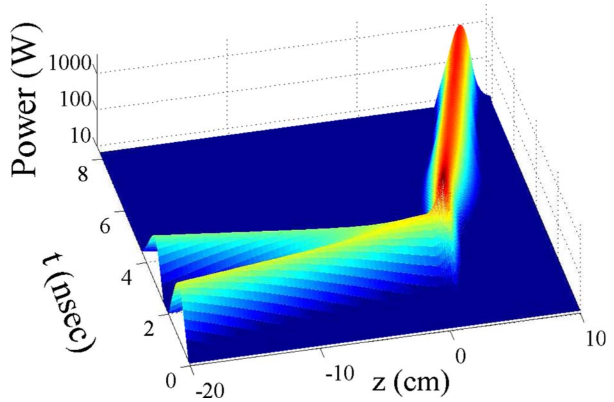

Fig. 3. (Color online) Formation and propagation of an in-gap soliton obtained using the launching method described in [9]. The scale in the z axis is logarithmic.

the same length. Thus, the linear reflection of a quarter-period sine profile is smaller for frequencies proximal to the grating bandgap.

Using a quarter-period sine apodization profile instead of a half-cosine profile reduces the minimum peak power required for soliton formation to 250 W for $\eta=0.9945$ and to 270 W for $\eta=1$. When the minimum input peak power is used, the transmission efficiencies that are obtained are higher than obtained in Figs. 2 and 3 and are equal to 70% and 23% for $\eta=0.9945$ and $\eta=1$, respectively. The transmission can be further improved by optimizing the apodization profile.

To reproduce our result in an experiment, it is required that the grating be written with high accuracy. In our numerical simulations we examined the soliton propagation when white Gaussian noise was added to the coupling coefficient. We found that when the noise did not change the effective slope in $L_1<z<L_1+L_2$ (calculated by using linear regression) by more than 10%, the propagation characteristics were not significantly altered.

In conclusion, we have demonstrated a novel method for efficient launching of in-gap solitons. The method is based on exciting a Bragg soliton outside the grating bandgap. Then, by using the tendency of solitons to adjust to adiabatic perturbations in the grating parameters, the Bragg soliton is coupled adiabatically into the bandgap. When the minimal launching powers are used, the pulse-transmission efficiency is three time higher in our method than in the method described in [7,9].

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