High-repetition-rate soliton-train generation using fiber Bragg gratings

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Abstract: We propose a high-repetition-rate soliton-train source based on adiabatic compression of a dual-frequency optical signal in nonuniform fiber Bragg gratings. As the signal propagates through the grating, it is reshaped into a train of Bragg solitons whose repetition rate is predetermined by the frequency of initial sinusoidal modulation. We develop an approximate analytical model to predict the width of compressed soliton-like pulses and to provide conditions for adiabatic compression. We demonstrate numerically the formation of a 40-GHz train of 2.6-ps pulses and find that the numerical results are in good agreement with the predictions of our analytical model. The scheme relies on the dispersion provided by the grating, which can be up to six orders of magnitude larger than of fiber and makes it possible to reduce the fiber length significantly.

OCIS codes: (270.5530) Pulse propagation and Solitons; (320.5520) Pulse compression; (350.2770) Gratings; (230.6080) Sources; (060.4370) Nonlinear optics, fibers.

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1. Introduction

High-repetition-rate optical pulse sources are key components in designing high-speed fiber-optic communication systems. Recently, several soliton-pulse sources based on lithium niobate modulators have been proposed, and nearly transform-limited pulses at repetition rates of up to 15 GHz have been generated [1]. However, it is difficult to achieve repetition rates > 20 GHz by this electronic technique. An all-optical method, capable of generating soliton-like pulse trains at high repetition rates, makes use of modulational instability in optical fibers [2]. Pulse trains at repetition rates of up to 300 GHz have been generated by using such a method [3]. However, individual pulses contain a significant pedestal, leading to nonlinear interactions between neighboring solitons.

A novel all-optical technique which was proposed a few years ago makes use of adiabatic compression of a dual-frequency signal inside an optical fiber and has been used to generate a stable train of pedestal-free, non-interacting solitons [4-11]. It has been shown that a dispersion-decreasing fiber (DDF) can be used for adiabatic pulse compression and, in fact, is mathematically equivalent to a uniform fiber with distributed gain [5,6]. If the groupvelocity dispersion (GVD) inside a DDF decreases adiabatically, the soliton self-adjusts to preserve the balance between dispersion and nonlinearity, resulting in pulse compression and enhancement of peak power. Soliton pulse trains with a repetition rate of up to 200 GHz have been generated by using a DDF [6]. However, because of the relatively small GVD of optical fibers, this technique requires long fiber lengths (> 1 km). Moreover, fabrication of fibers with complex dispersion profiles usually involves splicing of several different fibers or drawing the fiber with an axially varying core diameter.

A more attractive solution consists of adiabatic compression of pulses in a highly dispersive nonlinear medium such as a fiber Bragg grating. Grating dispersion just outside the stop band is up to six orders of magnitude larger than that of silica fiber [12,13] and can be tailored simply by changing the grating profile. Indeed, a pulse-compression scheme based on a fiber grating with slowly decreasing dispersion was recently proposed [14]. Moreover, almost any grating profile can be manufactured using the state-of-the-art grating-writing techniques [15,16]. To change the dispersion along the grating length, one can vary the average refractive index, the period of the grating (chirped grating), or the index modulation depth. Experimental results on adiabatic soliton evolution in chirped fiber Bragg grating are reported in Ref. [17] elsewhere in this issue. In this paper we consider only changes in the index modulation depth but the theory is general.

We propose a high-repetition-rate soliton source based on adiabatic compression of a dual-frequency signal in a nonuniform fiber Bragg grating operating in transmission. As the signal propagates through the grating whose index modulation depth decreases along its length, it is reshaped into a train of solitons through adiabatic compression, as shown in Fig. 1. In Section II we develop a simple analytical model based on the nonlinear Schrödinger equation (NLSE) for optimization of the grating parameters required for generating high-quality, soliton-like, pulse trains. In Section III we demonstrate numerically that a soliton train at a 40-GHz repetition rate can be generated by this technique and find that the numerical results are in good agreement with the predictions of our analytical model. Finally, in Section IV we summarize our results.

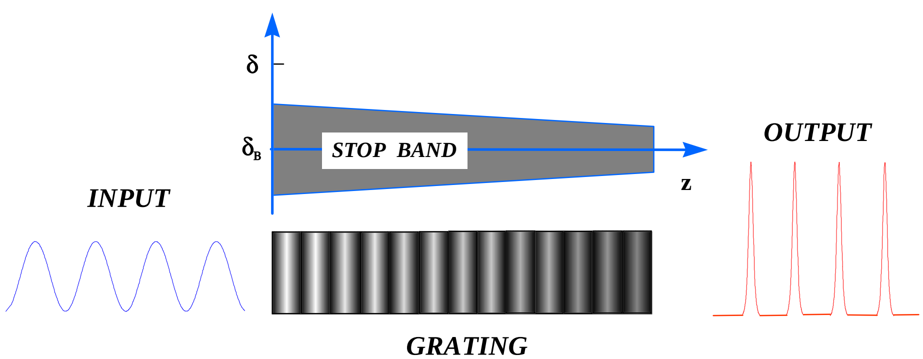

Fig. 1. Generation of a high-repetition-rate soliton train based on adiabatic compression in a nonuniform fiber Bragg grating. The stop-band width varies along the grating because of changes in the index modulation depth.

2. Analytical model

High-intensity pulse propagation through a fiber Bragg grating is governed by the nonlinear coupled-mode equations of the form [18]

$$i\frac{\partial E_+}{\partial z} + i\frac{1}{V}\frac{\partial E_+}{\partial t} + \kappa E_- + \Gamma_s |E_+|^2 E_+ + 2\Gamma_\times |E_-|^2 E_+ = 0, \quad (1)$$

$$-i\frac{\partial E_-}{\partial z}+i\frac{1}{V}\frac{\partial E_-}{\partial t}+\kappa E_+ +\Gamma_s|E_-|^2E_- +2\Gamma_\times|E_+|^2E_- = 0. \quad (2)$$

Here E_+ and E_- are the slowly varying amplitudes of forward and backward propagating waves, respectively, $V = c/n$ is the velocity of light in fiber, n is the average refractive index, $\kappa = \pi\eta\Delta n/\lambda_B$ is the coupling coefficient, Δn is the index modulation depth, η is the fraction of the energy in the fiber core, λ_B is the Bragg wavelength. Γ_s and $\Gamma_\times$ are the nonlinear parameters responsible for self- and cross-phase modulation such that $\Gamma_s = \Gamma_\times \equiv \Gamma_0 = 2\pi n_2/\lambda$, n_2 is the nonlinear refractive index, and λ is the signal wavelength. The nonlinear coupled mode equations have solitary-wave solutions, called Bragg solitons [19], that have been observed in recent experiments [20-22].

If the grating parameters are nearly constant over the spectral bandwidth of the pulse and the central frequency of the incident pulse is close to but outside the grating stop band, the nonlinear coupled-mode equations can be reduced to a simple NLSE having the form [23-25]

$$i\frac{\partial A}{\partial z}-\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial t^2}+\Gamma|A|^2A = 0. \quad (3)$$

Here A is the envelope of the Bloch wave associated with the grating, β_2 represents the GVD of the grating, Γ is the effective nonlinear coefficient, and t is the reduced time. The parameters β_2 and Γ are frequency dependent inside the grating and are related to the grating parameters through the relations [23-25]

$$\beta_2 = -\frac{1}{V^2}\frac{1}{\gamma^2 v^3\delta}, \quad \Gamma = \Gamma_0\frac{3-v^2}{2v}, \quad (4)$$

where $\delta = n/c(\omega - \omega_B)$ represents detuning of the incident signal from the Bragg frequency, $v = [1-(\kappa/\delta)^2]^{1/2}$, and $\gamma = (1-v^2)^{-1/2}$. We note that if the grating parameters κ or δ vary with z, both β_2 and Γ also vary along the grating length.

The fundamental soliton, by definition, obeys the following relation [26]

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\Gamma I_{in} T^2}{|\beta_2|} = \frac{E_S\Gamma}{2\sigma_{eff}}\frac{T}{|\beta_2|} = 1, \quad (5)$$

where $L_D = T^2/|\beta_2|$ is the dispersion length, $L_{NL} = (\Gamma I_{in})^{-1}$ is the nonlinear length, $I_{in} = |A|^2$ is the peak intensity of the pulse inside the grating, and T is a measure of the pulse width. For a pulse of the form sech(t/T), $T = T_{FWHM}/1.763$, where T_{FWHM} is the intensity full width at half maximum. The soliton energy $E_S = 2I_{in}T\sigma_{eff}$, where σ_{eff} is the effective core area. Note that the intensity inside the uniform fiber grating is enhanced with respect to that outside the grating by a factor $1/v$, i.e. $I_{in} = I_{out}/v$ [25].

We now consider soliton propagation in an axially nonuniform grating for which both β_2 and Γ are z dependent. Combining equations (4) and (5) we obtain the following condition for maintaining N=1 soliton in a nonuniform grating:

$$E_S\frac{\pi n_2}{\sigma_{eff}\lambda}\frac{T(z)}{|\beta_2^{eff}(z)|} = 1, \quad (6)$$

where β_2^{eff} is an effective GVD parameter defined to include the frequency dependence of both β_2 and Γ (see Eq. (4)) and is given by

$$\beta_2^{eff} = -\frac{2}{V^2(3-v^2)\gamma^2 v^2\delta}. \quad (7)$$

From Eq. (6) we find that if β_2^{eff} decreases adiabatically with z such that the soliton energy E_S remains constant, T must follow changes in β_2^{eff} to maintain the condition (5), while the peak intensity must increase. Note also that as β_2^{eff} decreases, the soliton accelerates, i.e. v increases with z. The soliton width at the end of the grating is given by

$$T(L) = T(0)\,\frac{\beta_2^{eff}(L)}{\beta_2^{eff}(0)}\,. \tag{8}$$

We next determine the constrains on the parameters of the grating, κ and L, for adiabatic compression of a short pulse inside the grating. Following Refs. [5,6], we reduce the NLSE Eq. (3) with z-dependent parameters β_2 and Γ to a standard NLSE with an effective gain. With the transformation

$$\xi = \frac{1}{T^2(0)}\int_0^z \beta_2(z')dz',\; F = T(0)\sqrt{\frac{\Gamma(z)}{\beta_2(z)}}\,A(z),$$

Eq. (3) becomes

$$i\frac{\partial F}{\partial \xi} + \frac{1}{2}\frac{\partial^2 F}{\partial \tau^2} + |F|^2 F = i\,g(\xi)\,F\,, \tag{9}$$

where $\tau = t/T(0)$ and assume β_2 is negative,

$$g(\xi) = \frac{1}{2\Gamma}\frac{\partial \Gamma}{\partial \xi} - \frac{1}{2\beta_2}\frac{\partial \beta_2}{\partial \xi} = -\frac{1}{2\beta_2^{eff}}\frac{\partial \beta_2^{eff}}{\partial \xi}\,. \tag{10}$$

The effective gain coefficient $g(\xi)$ takes into account axial variations of both β_2 and Γ.

Following Ref. [6], we define the total effective gain as

$$G_{eff}(\xi) = \exp\left(2\int_0^{\xi} g(\xi')\,d\xi'\right). \tag{11}$$

Using Eq. (11) it can be reduced to

$$G_{eff}(z) = \frac{\beta_2(0)}{\beta_2(z)}\frac{\Gamma(z)}{\Gamma(0)}) = \frac{\beta_2^{eff}(0)}{\beta_2^{eff}(z)}\,. \tag{12}$$

With the help of Eq. (8) and (12) the pulse width at the grating output can be written as

$$T(L) = \frac{T(0)}{G_{eff}(L)}\,, \tag{13}$$

where G_{eff} represents the factor by which the input pulse is compressed. Equations (12) and (13) show that the compression factor is determined by the ratio of the effective dispersion at the end points of the grating.

To ensure that the compression remains adiabatic, we impose the condition that the gain coefficient g is small enough that little amplification occurs over one dispersion length, i.e.

$$gL_D << 1\,. \tag{14}$$

If $g(\xi)$ varies slowly with ξ, it can be averaged over the grating length. From Eq. (11), $G_{eff}(L) = \exp(2gL)$ for $z = L$. The condition (14) can thus be written as $\ln(G_{eff}) << L / L_D$ or, using Eq.(12), as

$$\frac{L_D}{2L}\ln\left(\frac{\beta_2^{eff}(0)}{\beta_2^{eff}(L)}\right) << 1. \tag{15}$$

We note that the simple theory developed in this Section is based on the assumption that the second-order dispersion of the grating is dominant, i.e. the impact of higher-order dispersion terms is negligible. This assumption is valid only for input signals whose wavelength is tuned close to a stop-band edge but remains far enough from the edges so that the third- and higher-order dispersion terms are small [13].

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3. Numerical simulations

We apply the results of the previous section to design a high-repetition-rate soliton source based on adiabatic compression of a dual-frequency signal in a nonuniform fiber Bragg grating whose index modulation depth Δn decreases along its length (see Fig. 1). Although the theory developed in Section 2 assumes that the input pulses are solitons, it allows to predict the width of compressed soliton-like pulses even if the input signal is sinusoidal and to provide conditions for adiabatic compression. As Δn decreases, grating stop band narrows, as shown in Fig. 1. The dual-frequency optical signal can be obtained from a laser operating simultaneously in two longitudinal modes or by using two distributed feedback semiconductor lasers, each operating in a single longitudinal mode. Coherent beating between the two modes generates a sinusoidally modulated optical signal such that

$$A(t,0) = A_0 \sin(\pi t/T_S), \tag{16}$$

where $T_S = (\Delta\nu)^{-1}$ is the modulation period for a mode spacing of $\Delta\nu$. We consider a fiber grating whose coupling coefficient is nonuniform with a functional form

$$\kappa(z) = \kappa_0 (1 - Cz), \tag{17}$$

where κ_0 is maximum coupling coefficient, and C is a constant. The effective dispersion parameter corresponding to this profile is given by

$$\beta_2^{eff}(z) = \frac{2\kappa^2(z)\,\delta}{V^2\,[2\delta^2 + \kappa^2(z)]\,[\delta^2 - \kappa^2(z)]}\,. \tag{18}$$

Figure 2 shows the axial variations of the coupling coefficient and the effective GVD as functions of z. Note that a linear variation of κ in Eq. (17) was chosen only for simplicity. In principle, κ can have any functional form as long as the conditions (6) and (15) are satisfied.

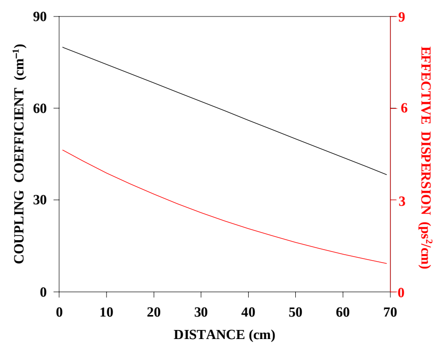

Fig. 2. Axial variations of $\kappa(z)$ (black line) and $|\beta_2^{eff}(z)|$ (red line) inside the grating.

To test the validity of our simple analytic model, numerical simulations were performed using the nonlinear coupled-mode equations. As an example, we consider propagation of a 40-GHz sinusoidal signal with T_S = 25 ps and I_{out} = 7.04 GW/cm^2 through a 70-cm-long apodized fiber grating. The κ profile is given by Eq. (15) with κ_0 = 80 cm^{-1}, δ = 160 cm^{-1}, and C is chosen such that G_{eff} =5. Since $gL_D \approx 0.1$ for this choice of parameters, the adiabatic-compression condition (14) is reasonably well satisfied. Figures 3 and 4 show pulse shapes and spectra respectively at the input (upper plot) and output (lower plot) ends of the grating. These results show that the 12.5-ps sinusoidal pulses evolve and compress by a factor of about 4.8 to become 2.6 ps soliton-like pulses. This behavior is in good agreement with the prediction of our simple analytic theory. We note that each pulse in the generated train contains a very small pedestal which is not visible on a linear scale. The origin of the pedestal may be related to the fact that the compression is not perfectly adiabatic, resulting in an asymmetric spectrum, as seen in Fig. 4. The time-bandwidth product for each pulse in the train is found to be about 0.34 (FWHM), while it is 0.315 for a soliton, which means that the pulses are very close to transform-limited. Finally, we note that in this example the ratio between the soliton separation and soliton pulse width is 9.6. Since pulses are widely separated, neighboring solitons practically do not interact with each other [27].

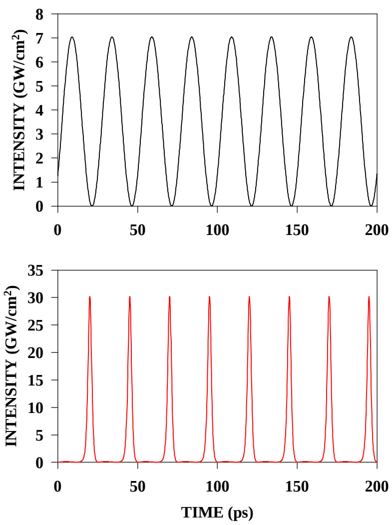

Fig. 3. Input sinusoidal signal (upper plot), and soliton train generated at the grating output (lower plot).

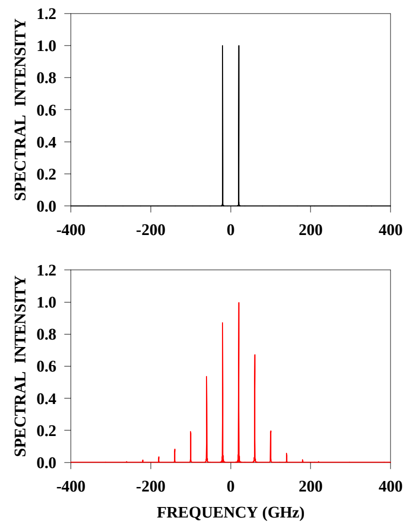

Fig. 4. Input dual-frequency signal spectrum (upper plot) and output spectrum of the soliton train (lower plot).

4. Conclusions

In this paper we have proposed a high-repetition-rate soliton-train source based on a nonuniform fiber Bragg grating. In our scheme, a dual-frequency signal is reshaped into a train of soliton-like pulses as it is compressed adiabatically during its propagation in a fiber grating with a nonuniform coupling coefficient. We develop an simple analytical model to predict the width of compressed soliton-like pulses and to provide conditions for adiabatic compression. We demonstrate numerically that a 40-GHz train of 2.6 ps solitons can be generated using a fiber grating with linearly decreasing coupling coefficient. Higher repetition rates can be achieved using stronger and longer gratings or other types of photonic crystals. Since the proposed scheme relies on the dispersion provided by the grating, which is many orders of magnitude larger than that of silica fibers, the device length can be reduced significantly, compared to fiber-based devices. However, note that the intensities required when silica-fiber gratings are used are very large (~10 GW/cm^2). The required intensity can be scaled down using a medium with high nonlinearity. For example, the nonlinear coefficient of As_2S_3 chalcogenide fibers is 100 times larger than that of standard silica fibers [28] and, therefore, the peak intensity of 7 GW/cm^2 used in our numerical example in Section III will scale down to 70 MW/cm^2 (peak power ~ 10 W) if such fibers are used.

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