

# Suppression of stimulated Brillouin scattering in optical fibers using fiber Bragg gratings

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**Abstract:** We propose a novel scheme for suppressing stimulated Brillouin scattering in optical fibers. The scheme makes use of a single or a sampled Bragg grating fabricated within the fiber used for transmitting intense Q-switched pulses. The grating is designed such that the spectrum of the Stokes pulse generated through stimulated Brillouin scattering falls entirely within its stop band. We show numerically that 15-ns pulses with 2-kW peak power can be transmitted through a 1-m-long fiber with little energy loss using this scheme. A sampled grating can be used for longer fibers but its coupling coefficient should be higher. The proposed scheme should prove useful for double-clad fiber lasers and amplifiers.

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## References and links

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## 1. Introduction

Stimulated Brillouin scattering (SBS) is a nonlinear process that can occur in optical fibers at relatively low input power levels [1]. It manifests as the generation of a backward-propagating Stokes wave, downshifted in frequency from the incident light by an amount equal to the acoustic-wave frequency and carrying most of the input power once the Brillouin threshold is reached. Although SBS has been studied extensively in the context of optical communication systems [2], it also impacts the performance of high-power fiber lasers and amplifiers designed to generate Q-switched pulses with high energies [3]-[5]. Even though fiber lengths and average power levels may not be very large in this case, the peak power of a Q-switched pulse can exceed 10 kW. Reducing the pulse duration to below 10-20 ns helps to some extent, as it raises the SBS threshold, but does not solve the underlying problem. The transient nature of SBS plays an important role for such short pulses and is studied by solving a set of three coupled nonlinear equations [6]-[8].

In this paper we propose a novel scheme for suppressing the SBS phenomenon occurring for high-energy Q-switched pulses. Our scheme makes use of a fiber Bragg grating (FBG) fabricated within the 'photosensitive' fiber for suppressing the SBS. The FBG is designed such that it is transparent to the forward-propagating optical pulses but the spectrum of the Stokes pulse generated through SBS falls entirely within its stop band. As a result, although the laser pulse is not affected by the grating, any Stokes radiation generated by it in the backward direction is reflected by the FBG such that it begins to propagate in the forward direction. Since this direction conversion occurs throughout the grating length, an SBS pulse cannot build up. We show through numerical simulations that, with a proper design of the FBG, almost entire pump energy remains in the forward direction and is transmitted through the fiber. For fibers longer than 1-m or so, it may hard to built the grating over the entire fiber length. We show that SBS can still be suppressed by using several shorter gratings or a *sampled* or *superstructure* grating [9]. Although the effects of SBS on nonlinear pulse propagation in a FBG have been discussed earlier [10], the pump pulse spectrum in this case was within the stop band of the grating; SBS cannot be suppressed under such conditions.

## 2. Theory

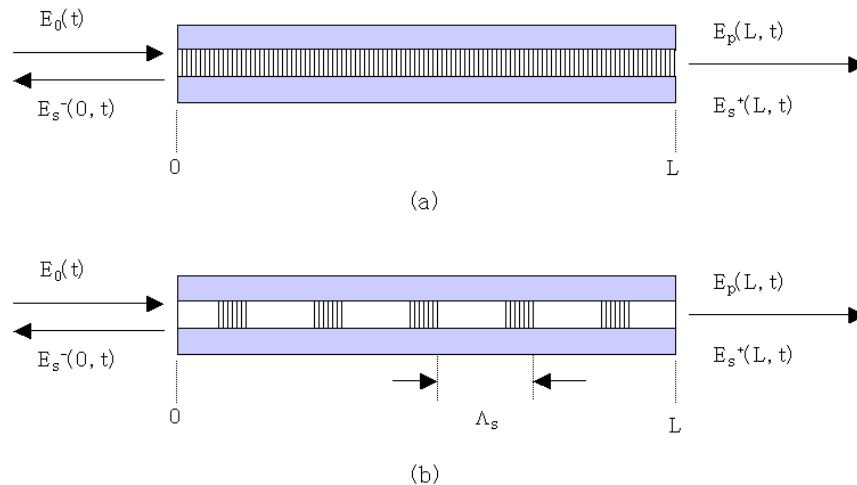


Fig. 1. Schematic of (a) a single and (b) a sampled FBG for suppressing SBS in optical fibers. The notation used in the paper is also shown.

Figure 1 shows schematically the two types of Bragg gratings considered in this paper for suppressing SBS. The grating is inscribed over the whole length of optical fiber in case (a) but an amplitude-sampled grating is used in case (b). The refractive index varies in both cases along the fiber length as

$$n(z) = \bar{n} + 2n_1(z) \cos(2k_B z) + n_2 |E(z)|^2, \quad (1)$$

where  $\bar{n}$  is the average refractive index of the fiber mode,  $n_1(z)$  represents local index change,  $n_2$  is the nonlinear Kerr coefficient,  $k_B = \pi/\Lambda$  is Bragg wave number, and  $\Lambda$  is the grating period. In the case of a sampled grating,  $n_1(z)$  is a periodic function with the sampling period  $\Lambda_s$ .

To describe the interplay between the SBS and Bragg processes, we use the notation of Ref. [9]. In our case, the optical field appearing in Eq. (1) can be written as (see Fig. 1)

$$E(z, t) = \text{Re}\{E_p(z, t) \exp[i(k_p z - \omega_p t)] + E_s^-(z, t) \exp[-i(k_s z + \omega_s t)] + E_s^+(z, t) \exp[i(k_s z - \omega_s t)]\} \quad (2)$$

It consists of a forward propagating pump  $E_p$  but the Stokes wave travels in both the forward and backward directions because of the coupling provided by the FBG. The backward propagating Stokes wave is coupled to the pump through the density variations of the form

$$\rho(z, t) = \rho_0 + \text{Re}\{\rho(z, t) \exp[i(k_A z - \Omega_B t)]\}. \quad (3)$$

The three frequencies and the three wave vectors satisfy the energy ( $\omega_p = \omega_s + \Omega_B$ ) and momentum ( $k_p = k_A - k_s$ ) conservation laws [1], where  $\omega_p$  and  $\omega_s$  are the frequencies at which the pump and Stokes pulse spectra are centered, respectively. The Brillouin shift  $\Omega_B = 4\pi\bar{n}(v_A/\lambda_p) = 2\pi v_B$ , where  $v_A$  is the acoustic speed in the fiber. Using Eqs. (1)-(3), the transient SBS process is governed by the following set of four nonlinear equations:

$$\frac{\partial E_p}{\partial z} + \frac{1}{v_g} \frac{\partial E_p}{\partial t} = -g_B^e E_s^- Q + i\Gamma(|E_p|^2 + 2|E_s^+|^2 + 2|E_s^-|^2)E_p \quad (4)$$

$$-\frac{\partial E_s^-}{\partial z} + \frac{1}{v_g} \frac{\partial E_s^-}{\partial t} = g_B^e E_p Q^* + i\delta E_s^- + i\kappa^* E_s^+ + i\Gamma(|E_s^-|^2 + 2|E_p|^2 + 2|E_s^+|^2)E_s^- \quad (5)$$

$$\frac{\partial E_s^+}{\partial z} + \frac{1}{v_g} \frac{\partial E_s^+}{\partial t} = i\delta E_s^+ + i\kappa E_s^- + i\Gamma(|E_s^+|^2 + 2|E_p|^2 + 2|E_s^-|^2)E_s^+ \quad (6)$$

$$\tau_A \frac{\partial Q}{\partial t} + Q = E_p E_s^{*-} + Q_0, \quad (7)$$

where  $v_g = c/\bar{n}$  is the group velocity and the coupling coefficient  $\kappa$ , the nonlinear parameter  $\Gamma$ , and the detuning parameter  $\delta$  are defined as

$$\kappa(z) = \frac{\pi n_1}{\lambda}, \quad \Gamma = \frac{2\pi}{\lambda} n_2, \quad \delta = k_s - k_B. \quad (8)$$

In Eqs. (4)-(7), the SBS process is governed by the photon-phonon coupling coefficient  $g_B^e = \tau_A g_1 g_2$  with  $g_1 = \pi n_0^3 p_{12} / 2\lambda \rho_0$ , and  $g_2 = \pi n_0^5 p_{12} \epsilon_0 / \lambda v_A$ , where  $n_0$  is the core index,  $\rho_0$  is the average density,  $p_{12} = 0.286$  is the longitudinal elasto-optic coefficient for silica fiber,  $\tau_A$  is the phonon lifetime,  $Q = \rho / (i g_2 \tau_A)$  is the normalized amplitude of the acoustic wave, and

$Q_0 = f(z, t)/(ig_2)$  describes thermal fluctuations leading to SBS. We assume that the Langevin noise source  $f(z, t)$  is a Markovian Gaussian random process such that

$$\langle f(z, t) \rangle = 0, \quad \langle f(z, t) f^*(z', t') \rangle = F \delta(z - z') \delta(t - t'). \quad (9)$$

The diffusion coefficient  $F$  associated with this random process is found from thermodynamic arguments to be  $F = 2kT\rho_0 / (\tau_A v_A^2 A_{eff})$ , where  $k$  is the Boltzmann constant,  $T$  is absolute temperature, and  $A_{eff} = 50 \mu\text{m}^2$  is the effective core area of the fiber [11]. The influence of the Bragg grating on the acoustic wave is neglected in Eqs. (4)-(7) for simplicity. This is justified in practice for relatively weak gratings required here.

We solve Eqs. (4)-(7) numerically using the same finite-difference method used earlier for studying pulse propagation in a nonlinear FBG [12]. This method uses the characteristics associated with Eqs. (4)-(6) and solves them on a two-dimensional grid using an implicit fourth-order Runge-Kutta scheme, while combining the results at the grid points. In the geometry of Fig. 1, a single pump pulse at a wavelength of  $\lambda_p = 1.06 \mu\text{m}$  with the amplitude  $E_0(t)$  is incident at  $z = 0$ . The boundary conditions in this case are  $E_p(0, t) = E_0(t)$ ,  $E_s^-(L, t) = 0$ , and  $E_s^+(0, t) = 0$ , where  $L$  is the fiber length. For numerical simulations, we use  $\bar{n} = 1.45$ ,  $n_2 = 2.6 \times 10^{-20} \text{ m}^2/\text{W}$ ,  $v_A = 5.96 \text{ km/s}$ , and  $g_B = 4Z_0 g_B^e / \bar{n} = 4.9 \times 10^{-11} \text{ m/W}$ ; these parameters are appropriate for typical silica fibers.

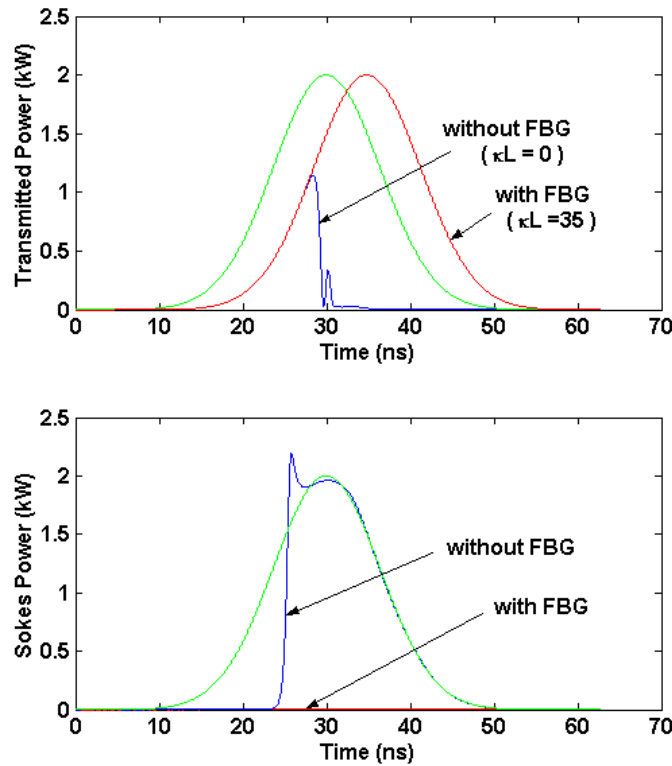


Fig. 2. Pump (top) and Stokes (bottom) pulses at the fiber output when 15-ns pump pulses with 2-kW peak power are launched into 1-m-long fiber. Green curves show the input pump pulse for comparison, blue curves show the no-grating case, while red curves show the improvement realized using a 1-m-long FBG with  $\kappa L = 35$ .

### 3. Simulation results and discussion

We first consider a single FBG fabricated over the whole 1-m-long fiber with  $\kappa L$  in the range of 0 to 30. When  $\kappa L = 30$ , the spectral bandwidth of FBG is only 1.98 GHz. The Bragg wavelength is chosen such that the stop band is shifted from the pump frequency by the Brillouin shift  $\nu_B = 16.3$  GHz in the 1.06- $\mu\text{m}$  region so that the Stokes waves falls exactly in the center of the stop band ( $\delta = 0$ ). The pump pulse is taken to be Gaussian in shape with a full width at half maximum (FWHM) of 15 ns and a peak power of 2 kW. Figure 2 shows the pump (top) and Stokes (bottom) pulses at the fiber output. Green curves show the input pump pulse for comparison. In the absence of the FBG (blue curves), transmitted pump pulse develops a substructure and contains only 20% of the input energy, the remaining energy appearing in the Stokes pulse. In contrast, when a FBG with  $\kappa L = 35$  is used (red curves), transmitted pump pulse maintains its shape (except for a small delay) and contains almost 100% of the input energy. Clearly, SBS is virtually suppressed by the grating. In fact, the Stokes pulse carries less than 0.1% of the pump energy in the forward direction and virtually no energy in the backward direction.

In general, the grating needs a minimum value of  $\kappa$  before it is strong enough to suppress the SBS totally, and this minimum value increases with the pump peak power  $P_0$ . Figure 3 show the fraction of pulse energy transmitted as a function of  $\kappa$  for three different values of  $P_0$  under the same operating conditions. As seen there, although any grating would help, one needs  $\kappa L > 20$  for transmitting 100% of the pump energy when  $P_0 = 1$  kW but this value increases to 30 for  $P_0 = 2$  kW. Moreover,  $\kappa L = 150$  is needed for  $P_0 = 10$  kW. Note that  $\kappa$  is only  $1.5 \text{ cm}^{-1}$  even in the last case. Since such values of  $\kappa$  can be realized in practice, 15-ns pulses with 10-kW peak power can be transmitted with our scheme. We have verified that the required value of  $\kappa L$  decreases for shorter pulses because of an increase in the SBS threshold. We have included the effects of Kerr nonlinearity within the FBG in our analysis because it affects the SBS process to some extent.

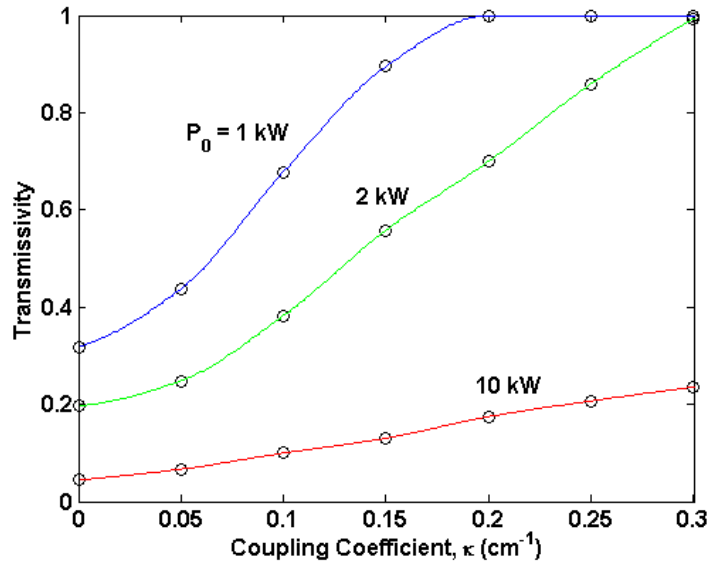


Fig. 3. Fraction of pulse energy transmitted as a function of  $\kappa$  for three values of peak power when a single 1-m-long grating is used for SBS suppression.

We consider the case of a sampled FBG because such gratings may be easier to fabricate for longer fibers. As an example, we use a sampled FBG consisting of 4-cm-long samples over 1-m-long optical fiber with 10-cm sampling period. Figure 4 shows the fraction of pulse energy transmitted as a function of  $\kappa_s$  under the same operating conditions. As one may expect, the sampled grating is not as effective as a single long grating for the same value of  $\kappa$ . Nevertheless, almost 100% of pulse energy can be transmitted when  $P_0 = 1$  kW using a grating with  $\kappa = 0.8$  cm<sup>-1</sup>. For larger peak powers, one may have to increase both the coupling coefficient for a sampled grating  $\kappa_s$  and the sample length  $L_s$ . Noting that the effective grating length for a sampled grating with  $N_s$  periods is  $N_s L_s$ , a simple design rule would be  $\kappa_s N_s L_s > \kappa L$ . We have verified numerically that the phases of individual gratings do not have to be matched precisely for the proposed technique to work. Also, individual gratings need not be equally spaced although  $\kappa$  should be increased to improve their effectiveness.

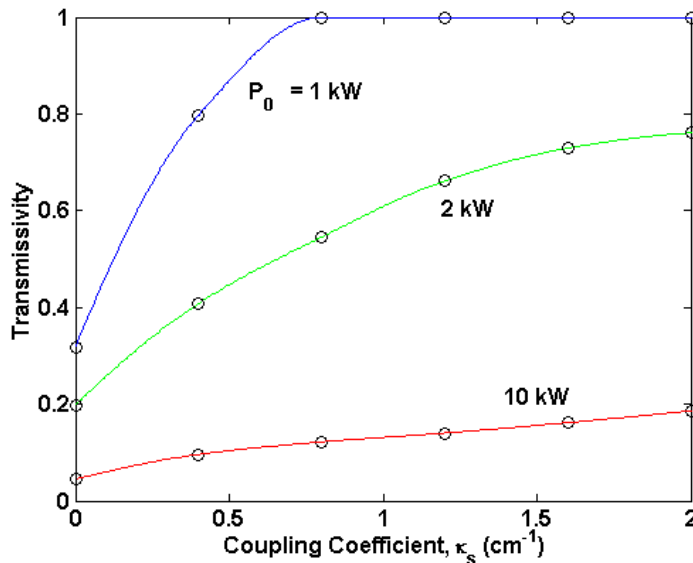


Fig. 4. Same as in Fig. 3 except that a sampled grating is used for SBS suppression. The grating consists of 4-cm-long samples with 10-cm spacing.

#### 4. Conclusion

In conclusion, we have proposed a novel scheme for suppressing SBS in optical fibers. It consists of fabricating a single or sampled FBG in the core of the fiber in which the intense pump pulse needs to be transmitted. Numerical simulations for a 1-m-long fiber show that 15-ns pulses with peak powers ~10 kW can be transmitted as long as the coupling coefficient of the FBG exceeds a certain minimum value. The same conclusion should hold for other pulse widths and fiber lengths. The proposed technique may prove useful for high-power fiber lasers and capable of generating Q-switched pulses with energies of 10  $\mu$ J or more.

We briefly address the issue of the practical implementation of this scheme. Fabrication of long FBGs has become possible with recent advances, and gratings longer than 10 m have been fabricated in undoped fibers [13]. The same technique can be adopted for doped fibers. For longer fibers, one can fabricate multiple gratings along the fiber.

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