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Ge-codoped fibers for mitigating stimulated Brillouin scattering in high power fiber amplifiers

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ABSTRACT

Rare-earth doped fibers for high power fiber amplifiers normally have a small refractive index difference between the core and inner cladding, but have a larger core diameter than conventional telecom fibers. We take advantage of this feature as well as the difference between the optical and acoustic waveguides and proposed several fiber designs to mitigate Stimulated Brillouin scattering (SBS) to produce higher output powers. The numerical modeling shows that an increase in SBS threshold by 3–6 dB can be achieved using Ge-codopant while maintaining diffraction limited beam quality. The key parameters that can affect the SBS performance are specified and optimal parameters for SBS suppression are obtained. The study also highlights the need to take into account the effects of minor refractive index profile variation in evaluating SBS performance.

1. Introduction

Stimulated Brillouin scattering (SBS) is a dominant nonlinear penalty in many applications such as optical transmission systems and high power fiber lasers and amplifiers. For telecommunication, it is desirable to transmit a large amount of optical power through optical fibers, while maintaining a high signal to noise ratio (SNR). However, as the optical signal power launched into an optical fiber increases, the launched power may exceed a certain threshold power (SBS threshold) and part of the optical signal power will then be reflected due to SBS, as a backward propagating signal. In an optical transmission system, SBS decreases the signal power level because a large amount of the signal power can be lost due to reflection back toward the transmitter. In addition, the scattering process increases the noise level at the signal wavelength. The combination of a decrease in the signal power and an increase in the noise thus reduce the SNR and lead to performance degradation. For high power single-frequency lasers and amplifiers, SBS limits the output power that can be achieved.

In recent years, significant efforts have been made in understanding of SBS effects in optical fibers resulting in new optical transmission fibers and gain fibers with reduced nonlinear optical effects [1–5]. In refs. [1] and [2], SBS is analyzed using the coupled mode theory and a simple formula for calculating the SBS threshold is derived. In refs. [4] and [5], gain fibers with increased SBS thresholds using Al/Ge co-doping were proposed and experimentally demonstrated. A similar design by another group [6] has claimed up to an 11 dB increase in SBS threshold compared to a reference fiber with the same optical effective area. Although these approaches can mitigate SBS effectively, they require multiple dopants, which can complicate fiber making processes. To overcome the issue, this paper explores an approach using Ge-doping and profile design to mitigate SBS for rare-earth doped gain fibers.

Although the framework in refs. [1–3] allows numerical modeling of SBS properties in optical fibers with an arbitrary refractive index profile, the design of an optical fiber that has improved SBS properties is subject to many practical constraints and the solution often is not obvious. In the case studied in the current paper, the gain fibers have a small refractive index delta difference between the core and inner cladding, but have larger core diameters than conventional fibers. By taking advantage of this feature and the difference between the optical and acoustic waveguide, we proposed fiber designs that can result in significant reduction of stimulated Brillouin scattering (SBS). An SBS threshold increase of 3–6 dB is predicted by numerical modeling. Even a higher SBS threshold increase is feasible for gain fibers with a large mode area. In the next section, we briefly summarize the theoretical equations used to evaluate the fiber SBS performance. In Section 3, we describe two approaches to reduce the overlap between the acoustic fields and the LP_{01} optical field. In one approach, we design a fiber to confine the fundamental longitudinal acoustic field to a smaller central region of the core than the LP_{01} optical field. In another approach, we push the fundamental longitudinal acoustic field out from the center of the core while keeping a large portion of the optical field in the center of the core. Brief conclusions and remarks are given in the final section, Section 4.

2. SBS formalism for optical fibers

We first lay out the formalism that describes the SBS properties of optical fibers [4] with emphasis to specific material properties essential to the study in the current paper. The threshold of SBS, P_{th}

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is affected by a few factors, $P_{th} \propto K A_{eff} \alpha_u / G(\nu_{max}, L) \bar{I}_u^{ao}$, where α_u is the acoustic attenuation coefficient for the acoustic mode of order u, A_{eff} is the optical effective mode area, $G(\nu_{max})$ is the effective gain coefficient at the peak frequency, K is the polarization factor, and $\bar{I}_u^{ao}$ is the normalized overlap integral between the electric and acoustic fields

$$\bar{I}_u^{ao} = \left(\int E_0 E_0^* \rho_u^* r dr d\theta\right)^2 / \int (E_0 E_0^*)^2 r dr d\theta \int \rho\rho^* r dr d\theta. \quad (1)$$

The SBS threshold depends on two parameters that are related to the fiber design: one is the optical effective area A_{eff}, and the other is the overlap integral $\bar{I}_u^{ao}$. To reduce the SBS effect, one can increase the optical effective area (thus reducing optical power density), and/or decrease the overlap integral. To capture the effects from both the optical effective area and the overlap integral, we define a figure of merit (FOM) by taking the ratio of the optical effective area over the overlap integral:

$$F = A_{eff} / \bar{I}_u^{ao}. \quad (2)$$

The figure of merit can be used to gauge the SBS improvement from one optical fiber to another (reference) optical fiber. In order to improve the SBS performance of an optical fiber, the figure of merit F should be designed to take a larger value than a reference fiber without the optimized performance in SBS. Specifically, the ratio of F for the fiber being designed to that of the reference fiber in dB unit is used to calculate how much the SBS threshold is improved.

The optical field and longitudinal acoustic field are governed by similar scalar wave equations [4], which were derived from the formalism in ref. [1] starting with the Eq. (15) of ref. [7]. The two equations can be written in the same form for the fundamental optical mode and the acoustic mode by factoring out the azimuthal variation that are involved in the SBS,

$$\frac{d^2 f_o}{dr^2} + \frac{1}{r}\frac{df_o}{dr} + k_o^2\left(n_0^2(r) - n_{oeff}^2\right) f_o = 0, \quad (3a)$$

$$\frac{d^2 f_a}{dr^2} + \frac{1}{r}\frac{df_a}{dr} + k_a^2\left(n_a^2(r) - n_{aeff}^2\right) f_a = 0, \quad (3b)$$

where the subscript 'o' stands for the optical field and subscript 'a' stands for the acoustic field. For an optical mode, f_o is the optical field distribution, $n_o(r)$ describes the refractive index as a function of the radial position, and k_o is the optical wave number, which is linked to the optical wavelength by $2\pi/\lambda$. For a longitudinal acoustic mode, $f_a(r)$ is the acoustic field distribution and the acoustic refractive index is defined as

$$n_a(r) = V_{clad} / V_L(r), \quad (4)$$

and

$$k_a = \frac{2\pi}{\lambda / \left(2 n_{oeff}\right)} = \frac{2\pi}{\lambda'} \quad (5)$$

where λ' is the acoustic wavelength.

In practice, the optical refractive index profile is often described by the optical delta profile. Similarly, we can also define the delta for the acoustic refractive index so that each optical refractive index profile is also associated with a corresponding acoustic delta profile that describes the acoustic behavior of longitudinal acoustic field. Using the index definitions for the optical and acoustic waves, we can describe the optical delta profile and acoustic delta profiles using the following equations:

$$\Delta_o = \frac{n_o^2(r) - n_{oc}^2}{2 n_o^2(r)} \times 100\% \quad (6a)$$

$$\Delta_a = \frac{n_a^2(r) - n_{ac}^2}{2 n_a^2(r)} \times 100\% \quad (6b)$$

where subscript "o" stands for optical wave and a stands for acoustic wave, and "c" denotes the index for the cladding.

The optical refractive index of the core as a function of the GeO_2 doping concentration is described by the following equation

$$n_o(w_{GeO2}) = n_o\left(1 + 1.0 \times 10^{-3} * w_{GeO2}\right), \quad (7)$$

where w_{GeO2} is the mole percent of the GeO_2 dopant. It is clear that the GeO_2 doping contribute to the increase of the refractive index from that of pure silica. The role of the GeO_2 doping on the longitudinal acoustic velocity takes the following form

$$V_L(w_{GeO2}) = 5944 \times \left(1 - 7.2 \times 10^{-3} * w_{GeO2}\right), \quad (8)$$

where the longitudinal acoustic velocity is in the unit of m/s. Using Eq. (8), the acoustic refractive index can be expressed by

$$n_a(w_{GeO2}) = 1 + 7.2 \times 10^{-3} * w_{GeO2}. \quad (9)$$

Eqs. (7) and (9) show that GeO_2 increases both the optical and acoustic refractive index.

It can be found that for the same amount of Ge-doping level, the increase of acoustic refractive index is about seven times of that of the optical refractive index. This means that a small change in the optical refractive index value can have a much greater effect to the acoustic index profile. Therefore, it is possible to incur a small change in the optical refractive index profile that is not sufficient to significantly alter the optical field but enough to cause a major change of the acoustic fields. In addition, the acoustic wavelength is about 3 times shorter than the optical wavelength (See Eq. (5)). Therefore, an optical fiber, which is optically single-moded at a particular wavelength, for example $\lambda = 1.55$ μm, may be highly multi-moded acoustically because the acoustic wavelength corresponding to Brillouin frequency is around 0.55 μm, which is quite small compared to typical optical fiber dimensions. In the case of spontaneous Brillouin scattering at relatively low launch powers, the incident optical field is Brillouin scattered by each of the acoustic modes and Brillouin gain spectrum shows peaks corresponding to optical field interaction with each of the acoustic modes. When the power exceeds the SBS threshold, for a well designed fiber, one of the acoustic modes becomes dominant while the other acoustic modes, which have much smaller acoustic–optic overlapping, do not survive the mode competition, leading to the onset of stimulated Brillouin scattering.

To mitigate undesirable SBS, the coupling between the optical and acoustic mode field(s) needs to be reduced. This can be done via engineering the optical and acoustic index profiles of the optical fiber.

3. SBS mitigation approaches in gain fibers using profile design

Unlike ref. [4], we only use GeO_2 dopant in the core to manipulate the SBS property of the fiber. In our modeling, we have ignored the refractive index contribution of the rare-earth doping materials as they are usually doped uniformly across the core and therefore have little effect to the SBS property. In order to reduce the SBS effect or increase the SBS threshold, the optical fiber in at least one region of a silica-based core should have a higher amount of up-dopant (for example, Ge), than the adjacent core region. Since Ge increases the optical refractive index, while decreasing the acoustic velocity (or increasing acoustic index as indicated in Eq. (9)), by utilizing different amounts of Ge within the core, one can design optical fibers with a depression (dip) in the optical delta profile, which has a corresponding depression in the acoustic delta profile. Two schemes have been developed to alter the radial distribution of acoustic modes relative to the optical field. In one approach, we can design an optical fiber so that optical field remains extended while acoustic fields become more tightly confined in one region of the core to reduce the overlap between the optical and acoustic fields. In another