Managing nonlinearity in optical fiber for high-power lasers

Ming-jun Li

proper choice of dopants and their spatial profiles in optical fibers can significantly reduce stimulated Brillouin scattering, which should enable superior laser systems.

High-power lasers have many applications in materials processing, aerospace, and the military. Optical fibers offer many advantages as gain media in such lasers, including high gain efficiency, large gain window, high power output, diffraction-limited beam quality, compactness, and reliability. However, the small core and long interaction length of fibers enhance nonlinear effects such as stimulated Brillouin scattering (SBS), stimulated Raman scattering, and the optical Kerr effect, all of which can limit output optical power.

Among these effects, SBS is the most significant because of its low threshold. SBS results from the interaction of an optical wave with an acoustic wave through electrostriction, in which an electric field causes compression of a material. As shown in Figure 1, the resulting density variations form an index grating that scatters the incident light backward through Bragg diffraction. The frequency of the scattered light downshifts because of the Doppler effect associated with the grating, which moves at the acoustic velocity.

One well-known way to reduce SBS is to make fibers with large mode area (LMA) by lowering the core numerical aperture (NA) and increasing the core diameter. For example, lowering the NA to 0.05 and increasing the core diameter to 30µm increases the effective area by a factor of 10 compared with a standard single-mode fiber with NA of 0.12 and core diameter of 8µm. However, even with this low NA, the fiber supports multiple modes when the core size is larger than 20µm. Achieving single-mode operation then requires modal discrimination techniques such as bend loss. But for large core size, bending deforms the mode field distribution and reduces the mode area. The practical core diameter for LMA fibers is limited to about 25µm.

To understand other factors that affect SBS, we have developed a model using a so-called coupled-mode formulation. The threshold, \( P_{th} \), of SBS is affected by the following factors:

\[
P_{th} \propto \frac{K A_{eff} \alpha_u}{G(v_{max}) T_u},
\]

where \( \alpha_u \) is the acoustic attenuation coefficient for the acoustic mode of order \( u \), \( A_{eff} \) is the optical effective mode area, \( G(v_{max}) \) is the effective gain coefficient at the peak frequency \( v_{max} \), and \( K \) is the polarization factor. \( T_u \) is the normalized overlap integral between the electric field, \( E_0 \), and acoustic density variation, \( \rho \), given by

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Designs aimed at minimizing the SMS effect may use dopants other than GeO$_2$.

Table 1. Different dopants in silica have varying effects on optical and acoustic refractive indices.

<table>
<thead>
<tr>
<th></th>
<th>GeO$_2$</th>
<th>P$_2$O$_5$</th>
<th>TiO$_2$</th>
<th>B$_2$O$_3$</th>
<th>F$_2$</th>
<th>Al$_2$O$_3$</th>
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</thead>
<tbody>
<tr>
<td>Optical refractive index</td>
<td>↑</td>
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<tr>
<td>Acoustic Refractive index</td>
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According to these equations, the SBS threshold can be raised by increasing not just the mode area but also the acoustic loss, or by decreasing the overlap integral or the maximum gain coefficient. The acoustic loss can be changed by glass composition design. The overlap integral can be controlled by design of the refractive index and acoustic velocity profiles of the fiber.

In a fiber with a simple step-index profile using GeO$_2$ doping, the fundamental optical and acoustic modes have very similar field distributions, so the overlap integral is about 1. However, the overlap can be reduced by using more sophisticated profile designs that affect the optical and acoustic fields differently. The basic concept in designing a fiber with low SBS is to locate the optical and acoustic fields in different regions of the core to minimize their interaction, as shown in Figure 2. The design in Figure 2(a) confines the acoustic field to the central portion of the core, whereas the design in Figure 2(b) pushes the acoustic field toward the edge of the core.

SBS can also be reduced by selecting other dopants in the core and the cladding, because different dopants have varying effects on optical and acoustic properties. Table 1 lists some common dopants that can be used in making silica glass-based fibers. The acoustic refractive index is defined as $n_a(r) = \frac{V_{L,\text{Silica}}}{V_L(r)}$, where $V_L(r)$ is the longitudinal acoustic velocity in the core region, and $V_{L,\text{Silica}}$ is the longitudinal acoustic velocity of pure silica glass. Among the dopants listed in Table 1, the first dopants increase both the optical and acoustic indices, whereas the last dopants have opposite effects on these indices.

Two approaches can be used to manipulate dopants for reducing SBS. One is to design a fiber structure that guides the optical wave but anti-guides the acoustic wave. This is accomplished, for example, by choosing a core dopant such as Al$_2$O$_3$ to increase the optical index but decrease the acoustic index or by choosing a cladding dopant such as F to decrease the optical index but increase the acoustic index. The resulting profiles are shown schematically in Figure 3(a). Because the acoustic wave is not guided in the core region, the interaction between the optical and acoustic waves is reduced. SBS suppression using this approach has been demonstrated.

The second design approach uses different core dopants to change the optical and acoustic field distributions to reduce their overlap. An example using two doping regions in the core is shown in Figure 3(b). Here, the first core region is doped with GeO$_2$ and the second with Al$_2$O$_3$. The optical refractive index profile is stepped, but the acoustic index profile has a W shape. The optical field is confined to the composite core region, whereas the acoustic field is confined only to the first core region. As a result, the overlap integral is significantly reduced. Numerical modeling indicates that an SBS threshold increase of over 6dB is possible using this approach.

To demonstrate the second design concept, a fiber was made using GeO$_2$ and Al$_2$O$_3$ co-doping. Figure 4 shows the measured SBS power of the fiber compared with a step-index fiber made with GeO$_2$ only. The SBS threshold is increased by about 6dB.

In summary, the SBS effect can be reduced by using different profiles of glass composition to minimize the overlap between the acoustic and optical fields. The proposed designs are suitable for making single-mode high-power fiber lasers. We
expect that with proper SBS management, single-mode and narrow-frequency fiber lasers with output power greater than 2kW will be possible in the near future.

The author would like to thank Xin Chen, Stuart Gray, Jeffrey Demeritt, Anping Liu, Boh Ruffin, Donnell Walton, Ji Wang, and Luis Zenteno for their technical contributions.

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Ming-jun Li is a senior research associate with Corning Incorporated. His research work focuses on new fibers for different applications. He holds 22 U.S. patents, has published one book chapter, and has authored and co-authored over 90 technical papers for journals and conferences. He has also served as a technical committee member for APOC (Asia-Pacific Optical and Wireless Communications) and ITCOM, and has written numerous papers for these and other SPIE conferences.

References