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Enhancement of stimulated Brillouin scattering of higher-order acoustic modes in single-mode optical fiber

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The stimulated Brillouin scattering (SBS) process has been both considered a limiting factor for optical communication and utilized advantageously (in optical amplification, Brillouin lasers, and distributed strain-temperature sensing) in optical fibers. Owing to its wide range of applications, it is very important to design optical fibers with specific Brillouin gain spectra (BGS) having certain numbers of peaks corresponding to higher-order acoustic modes with certain frequencies, linewidths, and thresholds. A specific application is distributed, Brillouin-based fiber optic sensors, for which multiplex BGS can be potentially employed for simultaneous strain and temperature measurements. For this, the ratio of higher-order peaks relative to the main peak should be enhanced for simultaneous measurements.

SBS in optical fibers is due to the interaction of the laser beam with different acoustic modes supported by the fibers. Because of the solid-state nature of the glass materials, these modes are defined by the spatial distribution of the longitudinal, $V_L$, and shear, $V_S$, velocities and density, $\rho$, of the core and cladding materials. The studies of higher-order acoustic modes and their features in the BGS are limited either to the assumptions $V_{S1}=V_{S2}$ and $\rho_1=\rho_2$ (indices 1 and 2 refer to core and cladding, respectively) or to specific parameter sets of particular fibers under the undepleted regime. Considering the current advanced fiber fabrication technology, especially for microstructured fibers, a study of SBS of higher-order acoustic modes for a distribution of $V_{L1}$, $V_{S1}$, and $\rho$ involving pump depletion (e.g., pump-probe SBS amplification) and subnanosecond pulses is required.

Here we present a model of SBS in a pump–probe scheme, which includes exact solutions for acoustic modes in optical fibers with steplike variations of $V_L$, $V_S$, and $\rho$ in the core and infinitely thick cladding as well as the pump depletion and transient regime. We study the dispersion, relative gains, and the frequency shifts of these modes as a function of fiber and laser beam parameters. It is shown that the acoustic modes are leaky, where the attenuation due to leakage is a periodic function of acoustic frequency. Depending on fiber parameters and acoustic frequency, the leakage attenuation can result in a phonon lifetime of $\sim 20$ ns, which is comparable with the material phonon lifetime. We have found that fibers close to the cutoff of higher-order acoustic modes and under the saturation regime of pump–probe Brillouin scattering, where the pump is depleted by interaction with the fundamental acoustic mode, exhibit the maximum ratio of higher-order peaks relative to the main peak.

The model is based on two wave equations for the optical Stokes and pump fields, respectively, $E_z = (1/2)A_p(r,t)\exp i(\omega_d t - \beta z) + c.c.$ and $E_p = (1/2)A_p(r,t)\exp i(\omega_d t + \beta z) + c.c.$, coupled to an elastic wave equation for the acoustic field $E_p = (1/2)A_p(r,t)\exp i(\omega_d t + \beta z) + c.c.$ With the slowly varying envelope approximation and from energy–momentum conservation laws for the frequencies and propagation constants, $\omega_p = \omega_s + \omega_0$ and $\beta_p = \beta_s - \beta_0$, the equations for the optical fields can be written as

$$ (\hat{T}_j + \hat{P}_j)A_j = \hat{N}_j \quad (j = s, p). \quad (1) $$

Here $\hat{T}_{s,p} = \nabla^2 + (n^2 k_{s,p}^2 - \beta_{s,p}^2) + c.c.$ are the transverse operators, $\hat{P}_{s,p} = 2i\beta_s \rho_0 \partial_t - 2i\omega_s \rho_0 (n/c)^2 \partial_\rho$ are the longitudinal propagation operators, and $\hat{N}_s = -(\gamma/2\rho_0 c^2)\omega_s^2 A_p A_{p,x}$, $\hat{N}_p = -(\gamma/2\rho_0 c^2)\omega_s^2 A_p A_{s,x}$ are the nonlinear operators that describe the interaction between the acoustic and the optical fields, where $\nabla^2_s$ is the transverse Laplacian, $n(x,y)$ is the refractive index profile, $\gamma$ is the electrostrictive coefficient, $\rho_0$ is the average density, and $c$ and $k_{s,p}$ are the speed of light and wavevectors, respectively. We consider silica fibers with GeO2-doped cores, where $n_1$, $V_{L1}$, $V_{S1}$, and $\rho_1$ change linearly with doping $\Delta (V_{L1} < V_{L2}$ and $V_{S1} < V_{S2})$. We use Waldron’s expressions for the vectorial elastic wave equation for the axially symmetric displacement field $\mathbf{u}$, consider the boundary conditions for $\mathbf{u}$ and stress tensor...
By examining the displacement fields, we note that the acoustic wave can be well approximated as a scalar field, in terms of change in the density, by $E_\eta / \rho_0 = \nabla \cdot \mathbf{u} = i \beta_\eta \mathbf{u}_z$. In the dispersion method (Ref. 11 and references therein) the acoustic field $A_\eta$ is expanded as $A_\eta = \sum \alpha_\eta(x,z) F(\eta) r$, where $F(\eta)$ are the longitudinal components of LR\eta. Considering single-mode fibers with optical fields $A_\eta = \alpha_\eta(x,z) F(\eta)$, where $F$ is the transverse optical mode satisfying $\hat{T} F = 0$, a dynamic equation for the amplitudes $\alpha_\eta$ is

$$\left( \partial_t + \Gamma_\eta \right) \alpha_\eta = - \left( i \gamma / 2 + 64 \pi \omega_0 \right) \alpha_\eta \int_0^\infty F^2 F^* \cdot dx, \quad (2)$$

where $\Gamma_\eta = \Gamma_\eta' / 2 - i \omega_\eta$ is the detuning term in which $\omega_\eta$ is the Brillouin frequency, $\Gamma_\eta' = 1 / \tau_\eta$ (where $\tau_\eta$ is the phonon lifetime corresponding to the $\eta$th mode) represents the attenuation of the acoustic mode $\eta$ due to absorption. However, for $V_{S1} \neq V_{S2}$ there is another attenuation mechanism that is due to the leaky nature of the acoustic modes. This attenuation is a periodic function of the acoustic frequency [Fig. 1(b)], and its magnitude and period increase as the core radius decreases. Also, decreasing doping increases the period and reduces the magnitude of the attenuation. For comparison, the attenuation due to absorption is of the order of $2 \times 10^4 \text{ m}^{-1}$ for the acoustic frequency 10 GHz. As a result, BGS at different Brillouin frequencies broadens, since the effective phonon lifetime for each mode is $1 / \tau_{\text{eff}} = 1 / \tau_\eta + 1 / \tau_{\text{leak}}$, where $\tau_{\text{leak}}$ is the phonon lifetime due to leakage of the modes into the transverse directions.

For the steady state ($\partial_r a_\eta = 0$) and undepleted ($\partial_r a_\eta = 0$) regime, the gain spectral profile has the form

$$g_\eta(\omega_\eta) = \sum g_\eta 1 / (\Gamma_\eta' / 2)^2 + (\Gamma_\eta' / 2)^2 + (\Omega_{\text{B}_\eta} - \omega_\eta)^2$$

which is a sum of different Lorentzian functions of centers $\Omega_{\text{B}_\eta}$ and linewidth $\Gamma_\eta' / 2$, with the gain coefficient $g_\eta = \gamma / 2 \omega_0 \omega_\eta^2 / \omega_\eta^2$, where $\omega_\eta$ is the phonon frequency. From Eqs. (1) and (2), we obtain

$$[\partial_r + (\tilde{n} c / \eta)] \alpha_\eta = \alpha_p \sum \eta g_\eta w_\eta(x,t),$$

$$[\partial_r - (\tilde{n} c / \eta)] \alpha_\eta = \alpha_s \sum \eta g_\eta w_\eta(x,t), \quad (3)$$

where $w_\eta(x,t) = (\Gamma_\eta' / 2)^2 \int_0^\infty \exp(\Gamma_\eta' / 2 - \gamma t) q_\eta q_\eta^* \cdot dx$ and $\tilde{n}$ is the averaged refractive index. Equations (3) are obtained similarly for the Brillouin interaction of different optical modes in free space.

Figure 2 shows the SBS gain coefficient $g_{1-3}$ for the interaction of the optical mode with acoustic modes $LR_1-LR_3$ as a function of the core radius for different GeO\text{2} concentrations. In comparison, the gain is lower for $V_{S1} \neq V_{S2}$ than for $V_{S1}=V_{S2}$ except for LR2 and LR3 modes at some small core radii [Figs. 2(b) and 2(c)]. The shift in the maximum of $g_1$ to larger core radii for smaller dopings [Fig. 2(a)] is due to the spreading of the optical mode in the transverse directions. For the steady-state and undepleted regime of SBS the exponential growth of the Stokes power is $\exp(g_\eta |\alpha_p|^2 L)$, where $|\alpha_p|^2$ is the pump power and $L$ is the interaction length. Using $g_{1-3}$ in Fig. 2, the threshold power for different modes can be estimated as $|\alpha_p|^2 = 2 \pi g_\eta J_\eta$, and hence the parameter set for the lowest or highest threshold powers of LR1-LR3 modes can be identified.
The Brillouin frequencies of LR₁–LR₃ modes are shown as a function of the core radius for various GeO₂ concentrations in Fig. 3(a). The separation of $\Omega_{B1}$, $\Omega_{B2}$, and $\Omega_{B3}$ is reduced for larger core radii, resulting in merging of higher-order peaks into the main Brillouin peak. Smaller core radii, however, result in a bigger separation of the Brillouin frequencies, which is advantageous for those applications that require distinct Brillouin peaks. An important practical aspect of Fig. 3(a), which can be used for simultaneous strain and temperature sensing, is that for a large core radius, 3.0 μm, the slopes of the Brillouin frequency versus doping are almost the same for LR₁ and LR₂, 72.0, and 71.5 MHz/wt. % respectively, whereas for a small core radius, 1 μm, they are different, 76.0 and 69.0 MHz/wt. %, respectively [Fig. 3(b)]. As a result, LR₁ and LR₂ modes of small-core-radius fibers (close to the cutoff of LR₂ mode) have different sensitivities to variation of the refractive index and the speed of sound, which change linearly with doping. Thus, the parameter regime close to the cutoff region of LR₂ or LR₃ modes is preferable for simultaneous strain and temperature measurements.

We note that the parameter set $R=1.5 \mu m$ and doping $\Delta=6$ wt. %, which are in the vicinity of the cutoff region of the LR₃ mode, result in the maximum relative gain of LR₂/LR₁ mode $g_{1-3}=0.21$. However, this ratio is valid for the undepleted regime and can be improved significantly by choosing values of pump and probe powers and interaction length resulting in pump depletion. Although the developed transient model is applicable to sub-10-ns pulses, to demonstrate the depletion effect and have distinctive peaks in BGS we choose a 30 ns pulse with a large cw base, since shorter pulses result in broadened and merged peaks. Comparing curves 1 and 3 in Fig. 4, obtained by solving Eqs. (3) for the same pump and probe powers but different interaction lengths of 1 and 800 m, it is evident that there is an improvement of the ratio of LR₂ to LR₁ peaks from 0.27 to 0.67 for the longer interaction length. For curve 4, we kept the interaction length as 800 m but reduced the pulse and its base powers. Comparing the peak ratio of LR₂ over LR₁ for curves 4 and 3, which are 0.21 and 0.67, respectively, indicates a higher ratio for a higher probe power. This is expected, since the exponential growth of the Stokes power is valid for the undepleted regime only, whereas for large values of the pump powers or long fibers the pump depletes considerably, resulting in saturation. Because values of $g_{1-3}$ are different, there is a parameter set close to the saturation growth regime of LR₁ mode, but the exponential growth regime of higher-order modes results in the enhancement of the peak ratio of the LR₂ over the LR₁ mode.

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Fig. 3. Brillouin frequencies of (solid) LR₁, (dashed) LR₂, and (dotted) LR₃ modes as a function of (a) core radius and (b) doping. The labels 1, 2 and 3 in (a) refer to the same dopings as Fig. 2, and the core radii in (b) are as indicated.

Fig. 4. (a) Pump power loss versus frequency of a fiber with $R=1.5 \mu m$ and $\Delta=6$ wt. % for a 20 mW pump. The probe beam contains a 100 mW (peak power) pulse and 50 mW cw base (curves 1–3) and a 10 mW pulse and 5 mW cw base (curve 4). The interaction lengths are (1) 1 m, (2) 400, and (3–4) 800 inside an 800 m fiber.

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