Brillouin frequency shifts in silica optical fiber with the double cladding structure

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Abstract: We report theoretical and experimental analysis on Brillouin frequency shift in silica optical fibers with the double cladding structures that are comprised of GeO_2-doped core, P_2O_5- and F-codoped inner cladding and silica outer cladding. The intrinsic Brillouin frequency shift was calculated for various fiber parameters utilizing boundary conditions for longitudinal acoustic waves. Optical fibers with different fiber parameters were fabricated and the Brillouin frequency shifts were measured in the wavelength region of 1.55 µm. We confirmed that the inner cladding in an optical fiber could provide a new degree of freedom in controlling the Brillouin frequency shift.

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measurement of strain and temperature [4]. In order to characterize SBS phenomena, the impacts of optical fiber materials on SBS have been reported and GeO$_2$-doped silica was found to be an optimal glass host for the core in terms of gain and optical loss [5]. Brillouin gain spectrum is, however, influenced by the geometric structures of optical fibers as well as material compositions. Among geometrical parameters, the core radius of an optical fiber would be one of the highest interests because the core will determine overall wave-guiding properties as well as Brillouin responses [6]. SBS is induced by parametric interaction among pump, Stokes, and acoustic waves in optical fibers [7]. Acoustic waves in cylindrical optical fibers could be guided in definitive modes such as longitudinal, torsional, and flexural modes [8,9]. Among them, the lowest longitudinal acoustic mode, $L_{01}$-mode, dominantly interacts with the input optical pump wave and gives rise to backscattered Stokes signal, which is down-shifted by the Brillouin frequency [6]. Safaai-Jazi et al. analyzed the acoustic modes in optical fibers with a GeO$_2$-doped core and pure silica cladding [10], where the relations between the core and cladding properties were assumed as; $V_{L_{CO}} < V_{L_{CL}}$, $V_{S_{CO}} = V_{S_{CL}}$, and $\rho_{CO} = \rho_{CL}$, where $V_{L_{CO}}$, $V_{L_{CL}}$, $V_{S_{CO}}$, $V_{S_{CL}}$, $\rho_{CO}$ and $\rho_{CL}$ are the longitudinal velocities, the shear velocities, and densities of the core and the cladding, respectively. In the simple core and infinite cladding structure, the Brillouin frequency shift was found to monotonically decrease as a function of the core radius [6], which has imposed significant restriction in optical fiber structures for SBS applications. The ability to control the Brillouin frequency shift ($\nu_B$) could generate novel features in current SBS applications, especially in dense wavelength division multiplexing (DWDM) devices where precise spectral control is emphasized.

In this letter, we report, for the first time to the best knowledge of the authors, the influence of inner cladding layer of an optical fiber on the acoustic waves and the Brillouin frequency shift, $\nu_B$, providing analytic understanding of non-trivial behavior of $\nu_B$ for various fiber parameters. The analytic relationship will endow a new degree of freedom to design novel fiber SBS devices.

![Fig. 1. The schematics of refractive index profile of the optical fiber with the matched inner cladding. $a$, $b$, and $c$ are the radii of core, inner cladding, and outer cladding, respectively.](image-url)

Structure of the fiber used in the analysis is schematically shown in Fig. 1. The fiber has three layers; the core is doped with GeO$_2$ while the inner cladding is co-doped with P$_2$O$_5$ and F to lower processing temperature and to match the refractive index to that of pure silica glass in the outer cladding. When the fiber is drawn at a sufficiently low speed, the density of each...
layer in optical fiber is dominantly affected by the thermal stress, which results from the differences in thermal expansion coefficients in the layers [11]. The calculated thermal stress profile is shown in Fig. 2 and the corresponding density distribution is shown in Fig. 3. The thermal stress and density were calculated for the optical fiber of which the concentrations of each layer were 3.36-mol% GeO₂-doped core, 2.12-mol% P₂O₅- and 1-mol% F-codoped inner cladding, and pure silica outer cladding. The relation between the stress and density is described in Ref. 12.

Fig. 2. The calculated thermal stress profile of optical fiber. \( \sigma_r, \sigma_\theta, \) and \( \sigma_z \) are the radial, circumferential, and axial thermal stress, respectively. Core radius \( a = 3 \, \mu m \), outer radius of inner cladding \( b = 6.32 \, \mu m \), and outer radius of outer cladding \( c = 62.5 \, \mu m \) [11].

Fig. 3. Corresponding density distribution. The density in the absence of volumetric stress is 2,220 kg/m³ [14].

The acoustic velocity, then, can be estimated from Eq. (1) [12].

\[
V_A = \sqrt{E(1-\nu)/(1+\nu)(1-2\nu)\rho} \tag{1}
\]

where \( V_A \) is the acoustic velocity, \( \rho \) is the density, \( \nu \) and \( E \) are the Poisson’s ratio and the Young’s modulus, respectively. In the range of dopant concentration in this study, \( \nu \) and \( E \) are found to be nearly the same as that of pure silica. Therefore, the density of each layer plays a dominant role to alter the acoustic response such as value of \( V_A \). In double cladding
fiber structure, the acoustic mode analysis, initially proposed by Safaai-Jazi et al. [10], has to include the inner cladding boundary as below:

\[
\Phi^{(0)} = \begin{cases} 
A_n J_n (u_1 r), & \text{for } r < a \\
B_n J_n (u_2 r) + C_n Y_n (u_2 r), & \text{for } a < r < b \\
D_n K_n (w_3 r), & \text{for } r > b 
\end{cases}
\]  

(2)

where \( \Phi^{(0)} \) is the zero-order solution of acoustic scalar wave equation, \( n \) is an integer, \( a \) and \( b \) denote the radii of core and inner cladding, respectively. Here indices 1, 2, and 3 denote the core, the inner cladding, and the outer cladding, respectively. \( u_1, u_2 \) and \( w_3 \) are expressed as,

\[
u_i = 2 \pi f \left[ \left( \frac{1}{V_{L_i}} \right)^2 - \left( \frac{1}{V} \right)^2 \right]^{1/2}, \quad i = 1, 2
\]  

(3)

\[
w_3 = 2 \pi f \left[ \left( \frac{1}{V} \right)^2 - \left( \frac{1}{V_{L_3}} \right)^2 \right]^{1/2}
\]  

(4)

where \( V_{L_i} \)'s are the longitudinal velocities at individual layers. \( f \) is the acoustic frequency, that is, Brillouin frequency shift, \( \nu_B \). \( V \) is the phase velocity of the longitudinal acoustic mode given by [13],

\[
V = \frac{\lambda}{2 n_1 f}
\]  

(5)

where \( n_1 \) is the refractive index of core, and \( \lambda \) is the optical wavelength. For acoustic \( L_{01} \) modes, \( \nu_B \) can be obtained by solving the characteristic equation for the \( L_{01} \) mode obtained from the continuity of \( \Phi^{(0)} \) and \( \partial \Phi^{(0)} / \partial r \) at the boundaries [10].

\[
\left\{ u_2 J_1 (u_2 a) - u_1 J_0 (u_2 a) \right\} \left[ w_3 J_0 (u_2 b) K_1 (w_3 b) - u_2 J_1 (u_2 a) K_0 (w_3 b) \right] - \left\{ u_2 Y_1 (u_2 a) - u_1 Y_0 (u_2 a) \right\} \left[ w_3 J_0 (u_2 b) K_1 (w_3 b) - u_2 J_1 (u_2 a) J_1 (u_2 b) K_0 (w_3 b) \right] = 0
\]  

(6)

Fig. 4 shows the dependence of \( \nu_B \) on the core radius \( a \), for different inner cladding radii. Here we have assumed that the acoustic velocity at the inner cladding is lower than that of core such that \( V_{L_1} = 5.691 \text{m/s}, V_{L_2} = 5.677 \text{m/s}, \) and \( V_{L_3} = 5.759 \text{m/s}, \) respectively. The acoustic velocity of outer pure silica cladding was calculated from Eq. (1) using elastic properties, such as Poisson’s ratio \( \sigma = 0.17, \) density \( \rho = 2.22 \times 10^3 \text{kg/m}^3, \) and Young’s modulus \( E = 6.85 \text{GPa} \) [14]. The acoustic velocities of core and inner cladding were obtained using each density of Fig. 3. Note that \( \nu_B \) increases as the core increases, which is completely opposite to the previous results where inner cladding has not been included in the analysis [6]. Furthermore, it is found that \( \nu_B \) does depend on the dimension of the inner cladding. When the acoustic velocity of inner cladding is, however, higher than that of the core, \( \nu_B \) shows monotonic decrease as a function of the core radius, consistent to the previous results.
The behavior of $v_B$ is analyzed for various acoustic velocities at the inner cladding, and the results are shown in Fig. 5. Here the inner cladding radius was 6.32 µm, and the acoustic velocities of the core and the outer cladding were 5,691 m/s and 5,759 m/s, respectively. The slope in the $v_B$ increases for a higher inner cladding acoustic velocity and the sensitivity of $v_B$ with respect to the core radius change gets significantly higher.

![Graph showing the effect of inner cladding radius on Brillouin frequency shift](image1)

In order to verify these numerical results, three types of optical fibers with the refractive index matched inner cladding were fabricated to experimentally measure the Brillouin frequency shift. All parameters of optical fibers were same except for the core radius. The core was doped with GeO$_2$ and the inner cladding was co-doped with P$_2$O$_5$ and F. The inner cladding radius was 6.35 µm and the relative refractive index difference, $\Delta$, was 0.35%. The core radii of fabricated fibers were 4 µm, 4.7 µm, and 5.2 µm.

![Graph showing the effect of acoustic velocity in inner cladding on Brillouin frequency shift](image2)

Here we have assumed the inner cladding radius, $b = 6.32$ µm, the core acoustic velocity $V_{L1} = 5,691$ m/s, and outer cladding acoustic velocity $V_{L3} = 5,759$ m/s.
It is known that a slight strain as small as 0.0001 results in the Brillouin frequency shift change as much as 5.941MHz. Furthermore, temperature change of 1 degree induces a Brillouin frequency shift change of about 1.36MHz in a 250-µm acrylate microjacketed fiber [5]. In order to minimize the Brillouin frequency shift change due to applied strain and temperature, all fibers were drawn at the same conditions, such as 21 m/min low drawing speed for mechanical strain-free optical fibers. The Brillouin frequency shifts of all fibers were measured at the same room temperature of 25°C. Therefore, Brillouin frequency shift change due to strain and temperature could be neglected because uniform strain and temperature were applied to all fibers.

To measure the Brillouin frequency shift of the fabricated optical fibers, a pump and probe technique was used [5]. The Brillouin gain spectra (BGS) of test fibers were obtained at the wavelength of 1.55µm. The resolution of the measurement was 100kHz.

As shown in Fig. 6, the measured Brillouin frequency shifts clearly showed increase from 10.7149, 10.7168, and to 10.7194GHz for the increasing core radii of 4.05, 4.70, and 5.18 µm, respectively. The measurement confirms the effect of inner cladding as discussed in Fig. 4 and Fig. 5 contrast to previous results [6]. Theoretical fitting gave estimation of the acoustic velocities of 5,694, 5,676, and 5,759m/s at the core, the inner cladding, and the outer cladding, respectively showing a good agreement with the experimental results. The deviation from the theoretical fitting could be attributed to contribution from torsional modes or flexural modes of acoustic wave. Small-applied strain and temperature changes during measurement also could cause the deviation.

![Fig. 6. Measured Brillouin frequency shifts for three different core radii. Theoretical curve assumes the estimation of the inner cladding of }3,5\mu m, the core acoustic velocity of }V_{c1} = 5694m/s, the inner cladding acoustic velocity }V_{c2} = 5676m/s and the outer cladding velocity }V_{c3} = 5759m/s.

Brillouin spectra of the test fibers are shown in Fig. 7. Measured BGS data were fitted with Gaussian function. Due to time-variant Rayleigh scattering from unmodulated probe signal, absolute magnitude of the Brillouin gain was not measurable and the intensity of the Stokes wave was normalized to the maximum. The Brillouin bandwidths (Δνg) were found to increase from 20.62, to 22.25, and 23.44MHz for the increasing core radii of 4.05, 4.70, and 5.18µm.
Fig. 7. The Brillouin gain spectra of test fibers. The Brillouin frequency shift ($\nu_B$) and Brillouin bandwidth ($\Delta\nu_B$) are 10.7149GHz and 20.6164MHz for 4.053µm core radius, respectively. $\nu_B$ =10.7168GHz, $\Delta\nu_B$ =22.2530MHz for 4.701mm core radius and $\nu_B$ =10.7194GHz, $\Delta\nu_B$ =23.4422MHz for 5.182mm core radius.

In conclusion, we analytically investigated the effect of the inner cladding on Brillouin frequency shift. Thermal stress across the double cladding structure optical fiber induced local distribution of longitudinal acoustic waves and densities, which in turn affected the behavior of Brillouin frequency shift. It was both theoretically and experimentally shown that the Brillouin frequency shift could be fine-tuned by the inner cladding adding a new degree of freedom to design SBS optical fiber devices. Brillouin gain bandwidths were also found to be affected by the fiber structures and further analysis is being undertaken by the authors.

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