Pressure dependence of Brillouin frequency shift in bare silica optical fibers

Haidong Gu (顾海栋)[1], Huijuan Dong (董惠娟)[2*], Guangyu Zhang (张广玉)[1], Jun He (何 俊)[1], Ning Xu (徐 宁)[1], and Douglas. J. Brown[3]

[1]*School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China*
[2]*State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001, China*
[3]*Department of Electrical and Computer Engineering, University of New Brunswick, Fredericton,*
NB E3B 5A3, Canada
[*]*Corresponding author: dhj@hit.edu.cn*

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The effect of hydrostatic pressure (up to 28 MPa) on Brillouin frequency shift (BFS) within two types of bare, single-mode fibers is studied via Brillouin optical time domain analysis technique. Experimental results show a negative linear relation between pressure and BFS, with almost the same sensitivity in both types of fibers. The average value of experimental slopes is –0.742 MHz/MPa. This value is found to be well suited to theoretical analysis on the basis of data on bulk silica glass in previous reports. This preliminary evaluation may result in a new method for distributed pressure sensing along silica optical fiber.

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Stimulated Brillouin scattering (SBS) in silica optical fibers is attractive in a number of research fields, including amplifiers and distributed sensors[1−4]. However, SBS should be avoided in other fields, such as in long-distance fiber telecommunications[3,4]. Brillouin frequency shift (BFS) is one of the most important parameters in the study of SBS. Variations in BFS correspondence with changes in tensile strain and temperature along optical fibers have been widely investigated at atmospheric pressure[5−7]. However, to the best of our knowledge, no experiment or discussion on the effect of pressure on BFS within silica optical fiber has been reported.

Although a number of studies examined the behavior of BFS with pressure in bulk silica glass and other amorphous materials since the 1980s, they often focused on changes in sound velocity or on conformational properties in the materials under high pressure up to many gigapascal (GPa)[8,9]. By contrast, few reports focused on the intermediate pressure of dozens of megapascal (MPa) via quantitative analysis. No direct data have been obtained on the relation of pressure and BFS, either in bulk silica glass or in silica optical fibers. Furthermore, silica fiber as a hair-fine filament is drawn from molten silica glass, which exhibits moderate amounts of doping, and has likely been fabricated from synthetic silica[7]. However, whether silica fibers are similar to bulk silica glass in terms of BFS versus pressure has not been proven.

Therefore, in this letter, an experiment is conducted to measure BFS under pressure along two types of bare fibers via Brillouin optical time domain analysis (BOTDA). During pressurization, BFS is found to decrease linearly in both types of fibers with almost the same slope. In addition to obtaining the quantitative expression of this relationship, we analyze the experimental result by comparing the pressure dependence of the elastic modulus and the refractive index for bulk silica glass; consistent results are obtained.

Room-temperature (24°) experiment was performed on two types of bare, standard telecommunication single-mode fibers: Corning SMF28e$^+$ (fiber A) and G652.D fiber from YOFC in China (fiber B). Both fibers were 100-m-long and were connected in the same line as the test fibers. The effective group indexes of refractions (n) at 1550 nm were 1.468 for fiber A and 1.467 for fiber B.

The experimental arrangement to detect the BFS of the test fibers under pressure is illustrated in Fig. 1 and can be divided into two subsystems: the hydraulic system and the optical system of BOTDA[7].

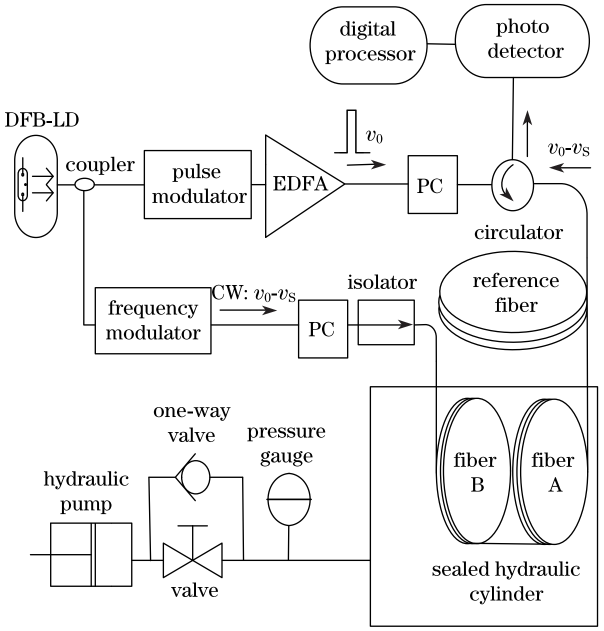

Fig. 1. Experimental arrangement for detecting BFS in test fibers under pressure. PC: polarization controller.

A small hydraulic system was used to apply pressure on the test fibers. As illustrated in Fig. 1, the pressure is produced by a hydraulic pump, and hydraulic oil is pumped though a one-way valve to a sealed hydraulic cylinder, which contains the test fibers. Pressure was measured with a commercial pressure gauge, and a hand valve was employed to release pressure as necessary. The bare test fibers were connected to the coated fibers, which passed through two holes on the cylinder cover, and these holes were sealed with the use of epoxy.

Two branches of light waves from distributed feedback laser diode (DFB-LD), each with wavelengths of 1 552 nm, were launched to each end of the optical loop system. One branch was generated to a narrow pulse wave as pump light (ν_0). The pulse was preset to have a 50-ns pulse width (corresponding to a resolution of 5 m) and a 100-μs repeat period. The pump light was amplified to approximately 300 mW by erbium-doped fiber amplifier (EDFA). The other branch was set to be a continuous wave (CW) as a probe light lower than 2 mW; it was downshifted by $\nu_{\rm S}$ from ν_0. ν_0 was constant, whereas $\nu_{\rm S}$ varied from approximately 10 to 11 GHz. These two lights counter-propagated through the fiber core in opposite directions. When the frequency difference of the two lights approached BFS ($\nu_{\rm B}$) as they met each other at a certain point in the fiber, the probe light would achieve gain. Furthermore, as $\nu_{\rm S} = \nu_{\rm B}$, a peak appeared in the probe light; therefore, the gain signals or $\nu_{\rm B}$ can be measured with stepping of $\nu_{\rm S}$ with an interval of 2 MHz. The average time was set as 2^{14}.

Gain signal as a function of position along the fiber was detected by a photo detector and sent to a digital processing system. The position (distance (z) from pump light end) function is

$$z = (c \cdot t)/(2n), \tag{1}$$

where t is the time from launching to receipt for a certain pulse of pump light, and c is the vacuum velocity of the incident light. This set-up allowed us to test the pressure dependence of BFS for any point in the fibers.

Pressure increased gradually up to 28 MPa with 4 MPa gains at each step in intervals of 15 min. The experiment reveals double peaks in the Brillouin gain spectrum for each point of fiber A and one peak in the spectrum of fiber B; this difference may be attributed to different doping or refraction index profiles[10]. As pressurization occurred, the center frequencies of these peaks became notably lower. Figure 2 presents an overview of the variations in BFS with pressure for both types of fibers.

In order to avoid coincidental and accidental results, the averaged value of 30 test points along each type of fiber was considered as the result. In addition, the measurements were repeated three times; pressure was pumped and released for three cycles. The average values of the three tests are plotted in Fig. 3.

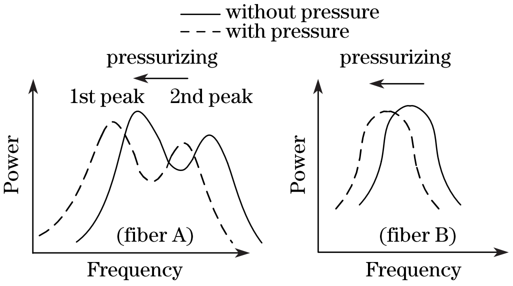

Fig. 2. Overview of the variations in BFS with pressure for a certain point in the test fibers.

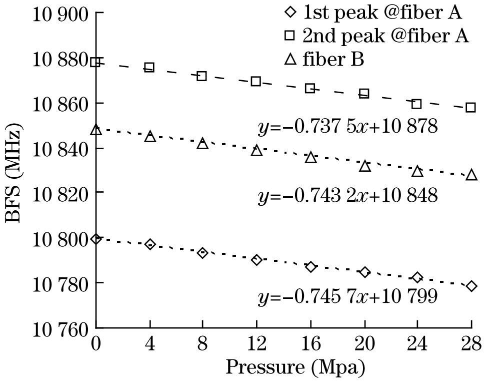

Fig. 3. Pressure dependence of BFS in bare silica optical fibers.

Figure 3 indicates that the BFS of the test fibers decreases linearly and negatively with pressure; the slopes are –0.7457, –0.7375, and –0.7432 MHz/MPa for the first peak, the second peak of fiber A, and the peak of fiber B, respectively. Notably, the slopes were almost equal not only between the double peaks of fiber A but also between the two types of fibers. In order to form a mathematical formulation, the temperature was assumed to remain constant; the relationship between pressure and BFS can be expressed by

$$v_{\rm B}(p) = v_{\rm B}(0) + k_{\rm p} \cdot p, \tag{2}$$

where $\nu_{\rm B}(p)$ is the BFS of the fiber under pressure p, and $\nu_{\rm B}(0)$ is the BFS of the same fiber without pressure (at atmospheric pressure). For a standard, single-mode optical fiber, a typical value for $\nu_{\rm B}(0)$ is approximately 11×10^3 MHz, when ν_0 is approximately 1 550 nm. $k_{\rm p}$ is the pressure proportionality coefficient. For our tested fibers, $k_{\rm p}$ is approximately –0.742 MHz/MPa, a value obtained from averaging the values of the above three slopes.

$\nu_{\rm B}$ is known to be proportional to the local longitudinal acoustic velocity ($V_{\rm a}$) and effective refractive index (n) in fiber or in bulk glass[5,8]:

$$v_{\rm B} = 2nV_{\rm a}/\lambda, \tag{3}$$

where λ is the vacuum wavelength of the incident light.

From Eq. (3), the pressure relative coefficient ($c_{\rm p}$) of the BFS ($\nu_{\rm B}$) can be given by

$$\begin{aligned} c_{\rm p} &= v'_{\rm B}(p)/v_{\rm B}(0) \\ &= V'{}_{\rm a}(p)/V_{\rm a}(0) + n'(p)/n(0), \end{aligned} \tag{4}$$

where $\nu'_{\rm B}(p)$ is the differential of $\nu_{\rm B}$ by pressure p. The same forms denote n and $V_{\rm a}$.

For fibers, the relation of pressure and $\nu_{\rm B}$ is linear, i.e., $v'_B(p) = k_{\rm p}$. Thus,

$$c_{\rm p} = k_{\rm p}/v_{\rm B}(0). \tag{5}$$

Therefore, according to Fig. 3, $c_{\rm p}$ is -0.691×10^{-4}, -0.678×10^{-4}, and -0.685×10^{-4} MPa^{-1} for the first peak, the second peak of fiber A, and the peak of fiber B, respectively. Their average value is -0.685×10^{-4} MPa^{-1}.

For bulk silica glass, the right-hand terms of Eq. (4) can be evaluated as follows. From Fig. 4 in Ref. [9], the longitudinal velocity decreased linearly from 5 960 m/s at no pressure to 5 520 m/s at 1 GPa, with a slope of –0.440 m/(s·MPa), i.e.,

$$V_{\mathrm{a}}'(p)/V_{\mathrm{a}}(0) = -0.738 \times 10^{-4}\ \mathrm{MPa}^{-1}. \tag{6}$$

According to the experimental work in Ref. [11], the refractive index of vitreous silica increases linearly with pressure with a slope of 0.92×10^{-5} MPa^{-1}, i.e., $n'(p) = 0.92 \times 10^{-5}$ MPa^{-1}. $n(0)$=1.46. Therefore, the following is obtained as

$$n'(p)/n(0) = 0.063 \times 10^{-4}\ \mathrm{MPa}^{-1}. \tag{7}$$

Equations (6) and (7) are substituted into Eq. (4), we have

$$c_{\mathrm{p}} = -0.675 \times 10^{-4}\ \mathrm{MPa}^{-1}. \tag{8}$$

This value is in excellent agreement with our experimental result (-0.685×10^{-4} MPa^{-1}) listed above, which proves that silica optical fibers seem to be similar to bulk silica glass in terms of the pressure dependence of BFS. In addition, the variation in sound velocity is clearly the main origin of the pressure proportionality coefficient of the BFS.

The linear relationship between pressure and BFS in optical fibers can be valuable in detecting pressure along the fibers through calibration of k_{p}. If the fiber composition is uniform, the slope k_{p} is actually the same for all points along the fiber. However, k_{p} in this letter refers to bare fiber. Our research on coated or jacketed fiber is ongoing.

In conclusion, the experimental study on the pressure dependence (up to 28 MPa) of BFS in bare silica optical fibers is represented. The sensitivity of BFS to hydrostatic pressure within fibers is proven to be almost the same as that in bulk silica glass. The pressure proportionality coefficient k_{p} is measured as –0.742 MHz/MPa when ν_0 is approximately 1 550 nm. The quantitative linear relation between pressure and BFS may be of interest as a positive reference to design distributed pressure sensing. It may also aid in the design of submarine fiber telecommunications.

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