Atmospheric distributed Brillouin sensors utilizing all-glass optical fibers fabricated from rare earth garnets: LuAG

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**Abstract**

An all-glass optical fiber derived from single-crystal LuAG is investigated for its potential use in athermal Brillouin distributed strain sensors. Such sensor systems are comprised of fiber whose Brillouin frequency shift is independent of temperature, but not independent of strain. Bulk Brillouin spectroscopy measurements on the precursor LuAG crystal are performed to gain insight into the crystal-to-glass transition. Results suggest that both the mass density and acoustic velocity are reduced relative to the crystal phase, in common with the other rare earth aluminosilicates. Advantages of the LuAG derived fiber over other rare earth garnet-derived fibers for the sensing application are a stronger strain response and larger Brillouin gain with narrower Brillouin spectral width.

**Introduction**

Brillouin scattering, whether in the spontaneous or stimulated form, pervades a vast scientific range; from medical [1, 2], to geoscience [3], to optical systems applications [4]. It is known to be a very powerful tool in the optical [5] and acoustic [6] analysis of materials. This paper focuses on a subset of the optical systems technologies: that of optical fiber [7]. Firstly, Brillouin scattering can be a significant limitation in optical fiber systems since its effects most typically limit the available optical power [8], while possibly also causing other impediments such as enhanced system noise [9]. However, secondly it can also be a powerful tool in enabling distributed strain and temperature sensing systems [10, 11]. The approach to managing or handling Brillouin scattering certainly differs in the two cases, with the former typically seeking its suppression [12–16], while the sensor application embraces it and seeks its enhancement [17–20]. The scope of this paper is further refined to address the latter.

Excellent reviews of Brillouin-based distributed fiber sensors can be found in [17, 18]. While there are a number of technologies that can be utilized for distributed sensing purposes, including fiber grating-based technologies [21], Raman scattering [22], and Rayleigh scattering [23] (another excellent review of the last two in comparison with Brillouin scattering can be found in [24]), Brillouin scattering has the potential to offer relatively high spatial resolution distributed measurements of temperature and strain with excellent sensitivity [24]. Brillouin scattering-based systems also have the added advantage of relatively straightforward waveguide [14] and compositional-tuning [16] fiber design methodologies that can very significantly alter their interaction properties. As such, this enables the possibility of engineering an optical fiber for a particular application or system, rather than vice versa.

Distributed sensor systems based on Brillouin scattering work on the principle that the Stokes’ shift experienced by an optical wave due to interaction with a longitudinal acoustic wave is a strong function of the material’s (or, more specifically, the fiber’s) thermo-mechanical environment [25]. The environmental factors can be generalized to two: temperature and strain. It is widely known that silica-based optical fibers have a Brillouin frequency shift (BFS) that increases with both an increase in temperature and any application of strain.
(fiber stretch). To be clear, ‘silica based’ in this context means an optical fiber comprised mainly of silica. This Brillouin interaction is governed by the Bragg condition, \( \nu_s = V/\lambda = 2Vn_m/\lambda_0 \) where \( \nu_s \) is the BFS, \( V \) is the acoustic (longitudinal-wave) velocity, \( \lambda_0 \) is the acoustic wavelength, \( \lambda_0 \) is the vacuum optical wavelength, and \( n_m \) is modal index of refraction in the fiber (at \( \lambda_0 \)). In cases where the fiber acts as an acoustic waveguide \([26, 27]\) (or anti-waveguide \([16]\)), \( V \) is the phase velocity of the acoustic mode, which typically is very close to the material value in the core \([28]\).

In order to understand the dependencies of the BFS on environment, the derivative of the Bragg condition may be performed with respect to temperature and/or strain to obtain

\[
\frac{d\nu_s}{d(\varepsilon, T)} = \frac{d\left(\frac{2Vn_m}{\lambda_0}\right)}{d(\varepsilon, T)} = \frac{2}{\lambda_0} \left( n_m \frac{dV}{d(\varepsilon, T)} + V \frac{dn_m}{d(\varepsilon, T)} \right). \tag{1}
\]

The derivatives of the acoustic velocity with respect to strain and temperature will be referred to as the strain-acoustic and thermo-acoustic coefficients (SAC and TAC), respectively. In equation (1), \( \varepsilon \) is the fractional strain. Similarly, the derivatives of the refractive index with respect to strain and temperature will be referred to as the strain-optic and thermo-optic coefficients (SOC and TOC), respectively. In silica, the SOC and TOC take on values of \(-0.262 \, \varepsilon^{-1} \) and \(10.4 \times 10^{-6} \, \text{K}^{-1} \), respectively \([29]\). Multiplying by the acoustic velocity of silica (5970 m s\(^{-1}\) \([29]\)) and using a nominal 1534 nm optical wavelength, the BFS dependencies on environment due to the change in index become approximately \(-2.0 \, \text{GHz} \, \varepsilon^{-1} \) and \(81 \, \text{kHz} \, \text{K}^{-1} \). Likewise, the SAC and TAC have values of 29.2 km/(s \( \varepsilon \)) and 0.555 m/(s K), respectively \([29]\). Again, multiplying by the refractive index of silica (1.444 at 1534 nm) and 2/\( \lambda_0 \), the BFS dependence due to the change in acoustic velocity is about 55 GHz \( \varepsilon^{-1} \) and 1.0 MHz K\(^{-1} \). With this simple calculation, it is clear that the change in the acoustic velocity (SAC and TAC terms), at least in fibers comprised mainly of silica, dominates the dependence of the BFS on environment. This change in acoustic velocity can be linked to a change in mass density and elastic moduli that accompany a change in temperature or the application of stress \([30–32]\).

In general an optical fiber installed along a structure (such as a bridge, pipeline, rail, etc) will be influenced simultaneously by both local changes in temperature and strain, and distinguishing the effect of one on the fiber from the other can be challenging. One approach is through the use of multiple Brillouin frequencies in a system. Ideally, the system would possess at least two Brillouin frequency components where both differ in either \( d\nu_s/dT \) or \( d\nu_s/d\varepsilon \), or both. Hence the two components would have measured BFS governed by

\[
\nu'_1(\varepsilon, T) = \nu'_{1,0} + \frac{d\nu'_1}{d\varepsilon} \varepsilon + \frac{d\nu'_1}{dT} \Delta T,
\]

\[
\nu'_2(\varepsilon, T) = \nu'_{2,0} + \frac{d\nu'_2}{d\varepsilon} \varepsilon + \frac{d\nu'_2}{dT} \Delta T. \tag{2}
\]

In equation (2) the superscript refers to the fiber or Brillouin component number (not squared values), and a ‘0’ on the subscript refers to a ‘rest state’ such as zero strain at room temperature. Implementing multiple BFSs in a single system can be accomplished in a number of ways. These might include utilizing multiple fibers \([33]\) or specialty fiber designs \([19, 34]\). In this way, equation (2) becomes a system of two equations with two unknowns: \( \varepsilon \) and \( \Delta T \). For a system in a distributed configuration (utilizing pulses, for example) these become functions of position along the fiber.

However, if knowledge of only one of temperature or strain is needed, another approach is to utilize a fiber with BFS that is immune to strain or temperature, respectively. This would then obviate the need for a pair of fibers, or Brillouin frequencies and, as such, permit a much simpler and more cost-effective system. An example where such a fiber might be useful would be measurement of fiber strain resulting from temporal structural changes along a bridge. In the case of strain sensing, the fiber should be immune to temperature changes (i.e., be ‘athermal’), and would therefore require, to first order, the use of a material that has \( dV/dT = 0 \) (if the refractive index response is assumed to be negligible). Previous work has shown such compositions are possible in a number of material systems including barium silicates \([35]\), aluminosilicates \([16]\), and rare earth aluminosilicates \([29]\). Simply put, mixing enough of a material with a negative TAC with silica (which has a positive TAC, see above) can give rise to a value of zero.

In the case of \( \text{Al}_2\text{O}_3 \), the deduced TAC values (for an effective bulk ‘glassy’ alumina) were found to be inconsistent with literature data for bulk sapphire \([36]\). It was surmised \([29]\) and later largely proven \([37]\) that this phenomenon can be linked to a thermal expansion mismatch between the fiber’s core and cladding. More specifically, an aluminosilicate core will have a coefficient of thermal expansion (CTE) larger than the surrounding pure silica cladding \([38]\). As the fiber temperature is increased, the tendency of the core to expand is restricted by the much larger (voluminous) cladding, and this can be likened to an applied pressure (stress) at an elevated temperature. With respect to its elastic properties, silica is known to be anomalous in that its acoustic velocity decreases with increasing pressure \([31, 39, 40]\). Hence, as the temperature is increased the acoustic
velocity tends to increase due to the positive-valued TAC of silica. However as the temperature is increased, the pressure on the core is increased, which tends to decrease the acoustic velocity of silica, therefore off-setting the TAC of silica. Notably, this represents an additional degree of freedom in the design of these fibers.

Here, this work is continued with the development, for the first time to the best of our knowledge, of a new rare earth aluminosilicate glass fiber, derived from crystalline Lu$_2$Al$_2$O$_{12}$ (or LuAG). Like lanthanum [29], lutetium possesses a wide transparency window (away from any optically absorbing transitions) in the wavelength ranges of interest for most single-mode fiber-based systems (13XX nm or 15XX nm), making it suitable for the stated application. It also lies at the opposite end of the lanthanide series (relative to La) and may offer certain advantages associated with its larger molar mass, such as a reduced acoustic velocity (giving the acoustically guiding structures described later in the paper) or a higher Brillouin gain coefficient (BGC), thus warranting further investigation. Additionally, both doped and undoped crystalline LuAG can be obtained commercially, thereby enabling the use of a novel and relatively inexpensive fabrication method (molten core, described below). Fibers produced using this technique are simpler and less expensive [41] to make than conventional fabrication methods (such as chemical vapor deposition methods) since the need to fabricate an all-glass preform prior to fiber draw is removed. At the same time, these fibers gain access to a much wider range of available compositions and physical fiber characteristics, potentially enabling new approaches to systems technologies, and the added benefit of cost savings to those using them. The Brillouin-athermal fiber of the present study embodies many of these attributes.

Much similar work on lanthanum aluminosilicate fibers [29] has shown that CTE-assisted Brillouin-athermal lutetium aluminosilicate fibers are possible and, as hypothesized in the preceding paragraph, are found to offer some advantages over their lanthanum counterparts, including narrower Brillouin gain spectra (BGS), (implying a higher BGC), and a somewhat stronger strain response. As mentioned, the optical fiber is fabricated via the molten core approach [42, 43] starting with a solid crystalline rod of LuAG. As such, and unlike its lanthana counterpart [29], fabrication of the precursor core glass was therefore not done prior to the construction of the preform, and is therefore given the moniker ‘LuAG-derived fiber’ and is entirely glassy. The resulting fiber was analyzed for its thermal characteristics with respect to Brillouin-based distributed sensing. Lu$_2$O$_3$ seems to exhibit many of the same characteristics as do other sesquioxides studied to-date, namely reduction in mass density and acoustic velocity in the crystal-to-glass transformation (though the resultant glass contains silica, which the precursor crystal does not, dissolved into the core melt from the glass cladding during the draw process). This is investigated utilizing the acoustic velocity via a comparison with bulk acoustic velocity measurements on the precursor LuAG crystal [44].

Methods

Fiber fabrication

The LuAG-derived all-glass optical fibers were fabricated using the molten core approach where the core phase (crystalline LuAG, Scientific Materials, Bozeman, MT, USA) was sleeved inside a pure silica cladding tube (3 mm inner diameter by 30 mm outer diameter fabricated by Vitrocom, Mountain City, NJ, USA) and drawn into fiber at a temperature of about 2025 °C, where the cladding is sufficiently soft to draw yet the LuAG is above its melting point (~1980 °C). Inevitably during the draw process, some SiO$_2$ from the cladding glass dissolves into the LuAG melt yielding a lutetium aluminosilicate glass core in the fiber. Approximately 550 m of fiber was collected which was coated during the draw with a conventional telecommunications acrylate buffer. Several diameters of fiber were drawn during this single draw in order to provide differing sample for analysis, with core sizes ranging from about 6 μm to about 30 μm. Since time, temperature, and size affect the degree of clad dissolution into the molten core, each diameter of fiber possesses a different composition hence one draw of differing fiber core sizes offers a convenient way to assess multiple compositions, hence Brillouin and optical properties. The focus of this work is on the two fibers found to possess the smallest and largest lutetia and alumina concentrations, Fibers 1 and 2, respectively. If the core diameter is defined to be the radial diameter representing the full-width at half-maximum of the refractive index profile (RIP), the core diameters are 6.0 μm and 15 μm for Fibers 1 and 2, respectively. It will be shown that Fiber 2, with the lowest silica content, is approximately athermal.

Optical fiber measurements

Compositional profiles of the drawn fibers were measured using energy dispersive x-ray (EDX) spectroscopy on a Hitachi-6600 scanning electron microscope. The RIPs were measured transversely at 950 nm through the side of the fiber using a spatially resolved Fourier transform interferometer (Interfiber Analysis, Sharon, MA, USA) [45]. The attenuation spectrum is measured by launching white light into the fiber and is normalized to a cutback measurement at 1534 nm.
Detailed descriptions of the experimental apparatus used to measure various characteristics of fabricated test fibers can be found in detail elsewhere [28, 46, 47]. In short, the BGS is measured utilizing a heterodyne approach. A narrow line-width laser source (<100 kHz spectral width) operating at a wavelength of 1534 nm is amplified and launched through a circulator into the fiber under test (FUT). Backscattered light in the case of the LuAG-derived fibers, comes from spontaneous Brillouin scattering from longitudinal acoustic waves, Rayleigh scattering, and Fresnel reflection at the splice point between the FUT and apparatus. The Fresnel reflection was at an adequate power level to serve as the local oscillator signal in the heterodyne system. The collected Brillouin back-scattered and reflected local-oscillator light is preamplified, optically filtered, and then sent to a fast detector which is attached to an electrical spectrum analyzer, which subsequently displays the BGS.

The thermal dependence of the BFS was measured by immersing the fiber in a heated water bath whereas the strain response was measured by hard-epoxying the fiber at two ends to fixtures. One of those fixtures is mounted on a linear translation stage whereby a strain of measurable quantity can be applied to the fiber. In order to measure the SOC and TOC of the fiber, a ring laser is constructed with the FUT forming part of the cavity (~2 m). This fiber is then either strained (as described above) or heated, and from measurements of the resulting change in the free spectral range (FSR) of the ring laser, the desired coefficient can be determined [35, 47]. This measurement requires the FUT to operate mainly on a single mode, since coupling between waveguide modes can lead to undesirable FSR hops.

### Results

Two LuAG-derived fibers with different core compositions are discussed in more detail here as examples. A summary of their basic measured properties can be found in Table 1. Figure 1 shows SEM end-images and figure 2 provides the measured attenuation spectra for both fibers. Several features can be seen in the spectra, and these can easily be attributed to other rare earth elements present in the starting LuAG as well as OH absorption near 1400 nm. For example the wide features at the long-wavelength end can be attributed to Er3+ and that at the short end to either Yb3+ or Er3+. While these impurities contributed to excess loss in the fibers, they are not present in a quantity that will significantly alter the Brillouin characteristics. Fiber 1 generally has lower loss than Fiber 2 and this can probably be attributed to the core possessing a greater quantity of high-purity silica originating in the cladding. In other words, the starting core material was more diluted with a material of lower loss in Fiber 1. For completeness, it is worth noting that prior results on YAG-derived optical fibers yielded attenuation values of about 0.12 dB m−1 so lower losses are certainly possible [42]. The measured RIPs for the two fibers are shown in figure 3. Given the slight ellipticity of the fiber cores, the RIPs shown are the azimuthal.

### Table 1. Summary of physical properties of the LuAG-derived fiber.

| Value                                      | Fiber 1 | Fiber 2 |
|--------------------------------------------|---------|---------|
| Optical wavelength (nm), Brillouin         | 1534    | 1534    |
| scattering measurements                    |         |         |
| Core diameter (µm)                         | 6.0     | 15      |
| ∆n (<10−3)                                 | 83.3    | 108     |
| Mode index, n₄ (1534 nm); room temp.       | 1.5108  | 1.5444  |
| and zero strainb                           |         |         |
| Mode field diameter, (1534 nm); room temp.| 4.20    | 6.30    |
| and zero strain, LP₀₁ mode (µm)³           |         |         |
| Attenuation coefficient (dB m⁻¹) at        | 1.42    | 1.52    |
| 1534 nm                                    |         |         |
| ν₄ (GHz)                                   | 11.347  | 11.574  |
| ∆ν (MHz)                                   | 50      | 65      |
| V (m s⁻¹) (acoustic mode value)            | 5761    | 5748    |
| [Al₂O₃] mole%                              | 7.70    | 11.3    |
| [Lu₂O₃] mole%                              | 5.60    | 7.90    |
| Thermal coefficient (MHz K⁻¹)              | 0.269   | 0.065   |
| TOC (10⁻⁸ K⁻¹)                             | c       | 10.2    |
| Strain coefficient (GHz ε⁻¹)               | 27.9    | 19.5    |
| p₁₂ − ν₄(ν₄ − ν₄(ν₄ + p₁₂) (dimensionless)| c       | 0.123   |
| gb (10⁻¹¹ m W⁻¹, peak value)               | 0.44 (0.63) | 0.40   |

* Value at the core center.
* Calculated from the RIPs.
* Value could not be measured.
averages. The graded-index shape is observed and results from the dissolutional and diffusional processes inherent to the molten core process [42]. The mode field diameter and mode area (Petermann II method) calculated from the RIRs are also provided in table 1.

EDX analysis resulted in Lu2O3 and Al2O3 concentrations (at the center of the core) as they are listed in table 1. Not only has there been considerable dilution of the starting material by SiO2, but also some redistribution of the alumina relative to lutetia has occurred such that the starting ratio of 5Al2O3:3Lu2O3 has not been maintained at any given point. To illustrate this, figure 4 provides the measured molar ratio of lutetium to aluminum (both, of course, forming sesquioxides) for Fiber 2. Over the range from core center outward to a distance of about 5 μm the molar ratio of Lu to Al is uniform, and just under 0.7, in contrast to the ratio in LuAG of 0.6. In the region of the core between about 5 and 10 μm the molar ratio of Lu to Al steadily decreases, due to alumina occupying a region slightly wider than the lutetia. Coarsely integrating the compositional profiles in cylindrical coordinates for the total number of ions gives a Lu to Al ratio of about 0.6, thus satisfying a ‘conservation of ions’ principle. This suggests that during fiber formation, while silica migrated inward towards core center, there was a contemporaneous (albeit slight) outward migration of alumina.

Figure 5 provides the BGC spectra measured for both fibers (measurement of the peak value of the BGC is described later in the paper). Knowledge of the BGC enables the calculation of the Brillouin gain for a given pump power and fiber length. The peak near 11.0 GHz originates in the apparatus (all fibers in the apparatus are SMF-28-like). It can be seen that Fiber 1 (11.347 GHz) has significant structure in its spectrum. Peaks on the blue
side of the spectrum (namely the small peak near 11.45 GHz), can be attributed to higher-order acoustic waveguide modes (HOAMs) [27]. It should be noted that, as will be shown, the longitudinal acoustic velocity of the core is less than that of the cladding, thus rendering the optical fiber an acoustic waveguide [48]. Excitation of HOAMs generally leads to an increase in the range of acoustic frequencies excited by Brillouin scattering and hence a commensurate decrease in the gain coefficient [27]. Peaks on the red side of the spectrum can be attributed to Brillouin scattering involving higher order optical modes [35], in principle due to the mode mismatch between the apparatus fiber and the FUT that gives rise to their excitation. The fit shown in figure 5 is one comprised of 4 Lorentzian components, the strongest being peaked at 11.347 GHz, with a 50 MHz spectral width. Fiber 2 (11.574 GHz), on the other hand, is well-represented by a single Lorentzian function, suggesting excitation of primarily the fundamental optical mode. Additionally, HOAMs are not observed in the Fiber 2 spectrum suggesting good spatial overlap between the fundamental optical and acoustic modes. This can be partly explained by a far better mode matching at the splice point, in addition to a reduced SOC (the quantity $p_{12} = -\nu_{\text{Poison}} (p_{11} + p_{12})$ is listed in table 1 for Fiber 2; the SOC is this quantity multiplied by $-n_{\text{Si}}^2 / 2$ [49]) relative to silica [50]. The reduced SOC lowers the susceptibility of the fiber to bend-induced refractive index changes that can lead to mode coupling [29]. The SOC for Fiber 1 could not be measured due to the excitation of multiple optical modes leading to deleterious apparatus FSR instabilities. The BFS for both fibers was found to increase linearly with increasing applied strain. Those values are also listed in table 1.
Next, the thermal response was investigated. The BFS was measured at several different temperatures increasing from room temperature, with the slope of the line representing the thermal coefficient. It was found that the BFS increased in a simple and well-defined linear fashion for both fibers, and as the fiber was heated, the spectra narrowed, consistent with silica [25]. It should be noted that some materials, such as B₂O₃, can have Brillouin spectral widths that increase with increasing temperature [51]. Rather than to show the simple linear dependence of the BFS on temperature, figure 6 shows the measured BGS of Fiber 2 (the athermal example) at room (21.5 °C) and elevated (94 °C) temperatures, along with Lorentzian fits. The spectral width has reduced significantly; from 65 MHz to 56 MHz at 94 °C. Fiber 2 had the lower thermal coefficient (\(d\nu_a/dT\)) of 0.065 MHz K\(^{-1}\). When compared to fibers comprised mainly of silica with thermal coefficients in the range of 1.1–1.2 MHz K\(^{-1}\) (at 1534 nm) [25, 46], this coefficient has been reduced to very close to zero for the LuAG-derived fiber. While Fiber 2 is not fully athermal, a slight increase in the lanthana and alumina concentrations in the fiber can further ‘zero’ the thermal coefficient. This is discussed later in the paper. A drawback to this composition is the reduction of the strain coefficient, roughly a factor of ~2.6 X relative to conventional Corning SMF-28 [47]. The TOC of Fiber 2 is found to be similar to that of silica, while that of Fiber 1 could not be measured (for the same reason the SOC could not be measured). Due to noise in measured spectra, the
uncertainty in the peak BFS is approximately ±1 MHz, giving an uncertainty of about 22% in the Fiber 2 thermal coefficient. While this seems large, it results mainly from the near-zero thermal coefficient. This uncertainty drops to ~5% for Fiber 1 due to the much larger thermal coefficient.

The Brillouin gain (or more specifically the BGC, \( g_B \)) is an important characteristic from the perspective of a distributed sensing system. More specifically, any reduction in \( g_B \) may have an adverse effect on signal-to-noise ratio, possibly necessitating more optical power. Depending on system architecture, this may then lead to other unwanted parasitic effects, such as other nonlinear fiber impairments (e.g., self-phase modulation). Knowing the attenuation, exact (and effective) lengths, splice losses, mode diameters, etc, \( g_B \) for a FUT can be estimated from measurements of the BGS. More specifically, the strength of the backscattered Brillouin signal (spontaneous scattering) can be calculated in the regime of low gain (~0 dB)\(^{52} \). Satisfying this condition requires utilizing short fibers (~2 m were used here) with moderate pump power. Measurement of the strength of this scattering can therefore disclose \( g_B \) for an optical fiber. Rather than measure actual scattered power (which requires careful tracking of power through the measurement system), the scattered power of the FUT is instead compared with that of a control fiber (with known BGC). A \( \text{P}_2\text{O}_5 \)-doped silica fiber was selected since its BGS is far from both the apparatus and the FUT spectra (minimal spectral overlap). To implement the measurement, a segment of the control fiber was spliced to the apparatus, then a segment of roughly the same length was attached to that, and the resultant aggregate BGS was measured (that utilizing Fiber 2 is given in figure 7). In figure 7 the strength of the peak near 11.8 GHz (FUT) relative to that at 10.1 GHz (control fiber, known \( g_B \)) allows for the estimation of \( g_B \) for the FUT. Full details of the approach can be found elsewhere\(^{29, 35} \), and the results of the measurement can be found in table 1. The measured \( g_B \) for Fiber 1 was reduced somewhat due to the excitation of multiple optical and acoustic modes. In order to estimate the material value, the Fiber 1 spectrum was numerically integrated and then a single-Lorentzian function (\( \nu_L \) and \( \Delta \nu \) as in table 1) was normalized to that. This calculation suggests that the material value for \( g_B \) in the center of the core (value in parenthesis in table 1) is ~40% larger than the measured value.

Measurements of the acoustic velocity also were performed on the same single crystalline \( \text{LuAG} \) used to fabricate the \( \text{LuAG} \)-derived all-glass fibers. Brillouin scattering measurements were performed with a six-pass Sandercock-type\(^{33} \) tandem Fabry–Pérot interferometer using a Torus (Laser Quantum) diode-pumped solid state laser (\( \lambda = 532.0 \text{ nm} \)) as a light source. Measurements were performed in a 90.07° symmetric/platelet scattering geometry with plate spacing of 4.5 mm. Sound velocities, \( V \), were determined from the frequency shift using the following relationship\(^{44} \):

\[
V = \Delta \nu \lambda_0 / 2 \sin (\theta / 2),
\]

where \( \nu \) is the measured Brillouin shift, \( \lambda_0 \) is the incident laser wavelength, \( \theta \) is the external scattering angle. A representative Brillouin spectrum is shown in figure 8. Characteristic of the spectrum is a high-velocity peak at 7143 m s\(^{-1} \) corresponding to the longitudinal-wave velocity and a low-velocity peak at 4144 m s\(^{-1} \) corresponding to the transverse wave velocity. Sound velocity versus crystallographic orientation, collected by changing the crystal orientation through movement of the \( \chi \)-circle of the Eulerian cradle, showed little or no

\[\text{Figure 7. Normalized Brillouin gain spectrum for a control P}_2\text{O}_5 \text{-doped fiber (main peak near 10.1 GHz, g}_B \sim 0.72 \times 10^{-11} \text{ m W}^{-1} \text{)} spliced to a segment of LuAG-derived fiber (peak at 11.574 GHz). The small features include the apparatus signature (near 11 GHz) and higher-order acoustic modes in the control fiber (~10.3 GHz, 10.6 GHz, and 11.1~11.2 GHz).}\]
change in the acoustic velocity, suggesting that bulk LuAG is highly isotropic. This high degree of acoustic isotropy, demonstrated in figure 9, is typical of many garnet-structured oxides [54, 55]. Given the negligible anisotropy, the elastic constants of LuAG can be calculated by averaging the measured acoustic velocities over several non-symmetric directions. The single-crystal elastic moduli can then be related to the aggregate moduli through the following equations:

\[ C_{11} = K + 4G/3 = \rho V_p^2, \quad C_{44} = G = \rho V_s^2, \quad C_{42} = K - 2G/3 = \rho \left( V_p^2 - 2\rho V_s^2 \right) \]

assuming the equality:

\[ 2C_{44} = C_{11} - C_{12}, \]
where \( \rho \) is the mass density of the sample taken from the manufacturer’s website to be 6710 kg m\(^{-3}\) \cite{56}. The results of this calculation are provided in table 2.

**Discussion**

An objective of this work, the fabrication of a Brillouin-athermal all-glass optical fiber from a rare earth garnet, namely Lu\(_3\)Al\(_5\)O\(_{12}\) (LuAG), was, for the most part, successful. Fiber 2 has a composition that balances the positive- and negative-valued thermal influences on the acoustic velocity giving rise to an optical fiber Brillouin frequency that has (almost) no thermal dependence. Fiber 1, on the other hand, has a composition that leads to a stronger thermal dependence (since it has more silica), but that is still greatly reduced relative to high-silica-content fibers due to the presence of significant quantities of lutetia and alumina. Performing a simple linear extrapolation from the two compositions of this study (those of Fibers 1 and 2, the latter being nearly athermal), increasing the lutetia-alumina content of Fiber 2 by 5.7% will result in a fully Brillouin frequency athermal fiber. However, there are clear hurdles to utilizing these materials in next-generation distributed sensing systems.

First, these fibers are multimode with large \( \Delta n \). Fibers with lower numerical apertures can potentially be fabricated if other lower-index materials are utilized or incorporated in the process. Alternatively, if a low-SOC fiber can be developed, such as seems to be characteristic of those with rare-earth aluminosilicate cores \cite{29, 50}, a single mode version may not be necessary if it can robustly propagate the fundamental (or any other) optical mode. This reduction in the SOC, however, derives partly from a small, but negative, \( \rho_{12} \) Pockels SOC. This characteristic tends to provide a significant reduction to the BGC; yet another drawback to the use of these materials. In particular, the BGC is roughly 5–6 X smaller in Fiber 2 than in conventional GeO\(_2\)-doped Corning SMF-28 \cite{57}. However, in this case, the LuAG-derived fiber has the clear advantage over its lanthanum aluminosilicate \cite{29} and bariosilicate \cite{35} fiber counterparts, with \( g_b \) being approximately 50% and >20 times larger at the athermal fiber compositions, respectively. Long term goals for this work is the similarity of the various rare earth sesquioxide silicates in some of their Brillouin and other material properties. For example, they universally seem to possess low (and negative) photoelastic constants and tend to have large refractive index values.

Comparing table 1 in this work and table 1 in \cite{29}, both lanthanana- and lutetia-possessing glass fibers acted very similarly with similar silica content, despite being at opposing ends of the lanthanide series.

However hidden in this similarity are some significant differences. For example, the acoustic velocity may be calculated from the Bragg condition, giving rise to the values in table 1 for both fibers. Simple additive models may be utilized to calculate the relative contributions to the measured velocity by each of the constituent oxides. This routine has been described in detail elsewhere \cite{58}, and is somewhat simplified in the present case since both the optical and acoustic modes are confined tightly to the center of the core due to the high index \cite{16}. As such, the measured properties of the waveguide largely take on the characteristics of the material in center, and a full waveguide analysis \cite{46, 47} becomes unnecessary. Utilizing the common theme that the density of the material drops by about 17% in going from bulk crystal to glassy phase \cite{16}, the density of Lu\(_2\)O\(_3\) is estimated to be 7928 kg m\(^{-3}\) and its acoustic velocity (longitudinal) is subsequently found to be about 3660 m s\(^{-1}\) from the fiber data. Combining this with the data for alumina used in \cite{29}, the acoustic velocity of bulk glassy Lu\(_3\)Al\(_5\)O\(_{12}\) is extrapolated to be 5340 m s\(^{-1}\). This represents a significant reduction in the acoustic velocity relative to bulk.

**Table 2.** Single-crystal and aggregate elastic properties, aggregate sound velocities and density of LuAG bulk sample. Uncertainties are provided in the parentheses.

| Parameter                  | Value     |
|----------------------------|-----------|
| Mass density \( \rho \) (kg m\(^{-3}\)) | 6710*     |
| Shear velocity \( V_s \) (m s\(^{-1}\)) | 4418(8)   |
| Compressional velocity \( V_p \) (m s\(^{-1}\)) | 7143(15)  |
| Bulk modulus \( K \) (GPa) | 189(2)    |
| Shear modulus \( G \) (GPa) | 115(1)    |
| \( c_{11} \) (GPa)       | 342(4)    |
| \( c_{12} \) (GPa)       | 112(2)    |
| \( c_{44} \) (GPa)       | 115(1)    |

* From manufacturer’s website.
LuAG (about 25% below the measured bulk value of 7143 m s$^{-1}$). Given the work in [16, 59], one would have expected a smaller reduction (but a reduction nonetheless) in the range of about 13%. In that case, the aggregate Lu$_3$Al$_5$O$_{12}$ constituent would have a ‘glassy’ acoustic velocity larger than silica, rendering an acoustic anti-waveguide, rather than a waveguide as was observed here. This demonstrates the clear utility in the characterization of oxides (among others) across the Periodic table.

One feature of the LuAG-derived fibers that provides them with an advantage over those with lanthanum aluminosilicate cores is the stronger strain response (19.5 GHz ε$^{-1}$ for the former compared with 16.4 GHz ε$^{-1}$ for the latter). A significant reduction in the strain response has unfortunately thus far accompanied these athermal fiber compositions, which clearly leads to reduced system sensitivity. A second feature is a narrower spectral width. In particular, the Brillouin spectral width of Lu$_2$O$_3$ is found to be about 20% narrower than La$_2$O$_3$. Considering that a distributed sensor system is typically looking for small changes in the peak value of BFS, system sensitivity to small changes in the peak BFS in narrow linewidth systems (coupled with small ΔT or Δε) could be limited by a broad spectral width, making it difficult to distinguish small environmental changes. The effect of spectral linewidth becomes less meaningful in narrow-pulse distributed systems, wherein a broad spectral content of the measurement (pump) pulse (approximately comparable to Δν or broader) will convolve with the intrinsic linewidth and broaden the spectrum of the interaction [17].

Conclusion

For the first time to the best of our knowledge, an all-glass optical fiber derived from single-crystal LuAG was produced and investigated for its potential use in athermal distributed strain sensors. An athermal composition was found to exist and a fiber was produced to within ~5% of that specification. Bulk Brillouin spectroscopy measurements on the precursor LuAG crystal suggest that both the mass density and acoustic velocity decrease in the crystal → glass phase transition, in common with the other rare earth aluminosilicates. However, the magnitude of the reduction in the acoustic velocity seems to be more significant in the LuAG-derived fibers. Indeed it rendered what should have been an acoustic anti-waveguide an acoustic waveguide. Advantages of the LuAG-derived fiber for the sensing application are stronger strain response and larger Brillouin gain with narrower Brillouin spectral width.

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New J. Phys. 18 (2016) 015004
PD Dragic et al

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