The linear and nonlinear refractive index of amorphous Al$_2$O$_3$ deduced from aluminosilicate optical fibers

Peter Dragic$^1$ | Maxime Cavillon$^{2,3}$ | John Ballato$^{2,3}$

$^1$Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois
$^2$Center for Optical Materials Science and Engineering Technologies, Clemson, South Carolina
$^3$Department of Materials Science and Engineering, Clemson University, Clemson, South Carolina

Correspondence
Peter Dragic
Email: p-dragic@illinois.edu

Funding information
Department of Defense Joint Technology Office, Grant/Award Number: FA9451-15-D-0009/0001, FA9451-15-D-0009/0002, N00014-17-1-2546

Abstract
The Sellmeier coefficients for the linear refractive index of amorphous alumina (α-Al$_2$O$_3$) are deduced from measurements on binary aluminosilicate glass optical fibers. This data is then used to approximate the nonlinear refractive index, $n_2$, for α-Al$_2$O$_3$, which was found to be 1.89 × 10$^{-13}$ esu (4.77 × 10$^{-20}$ m$^2$/W at a wavelength of 958 nm) and found to increase slightly sublinearly with increasing alumina concentration in silica glass. Several commonalities with some amorphous alumina thin films are suggested. In addition, a proposal for the extension of a simple additive materials model for the calculation of $n_2$ as a function of composition is presented. Alumina is an important dopant into silica for high energy optical fiber-based lasers and so the determination and modeling of its optical properties is of significant technological value.

KEYWORDS
aluminosilicate glass, glass products, modeling, nonlinear refractive index, optical fibers, optical properties, properties, refractive index

1 | INTRODUCTION

Aluminum oxide (Al$_2$O$_3$) is a ubiquitous laser material utilized both in its crystalline form$^1$ and as a component in glass laser systems.$^2$-$^8$ In the latter case, early interest stemmed from the apparent ability of alumina to “dissolve” clusters of otherwise insoluble rare earth dopants into the silica (SiO$_2$) network.$^2$ This solubilizing quality of alumina in silica increased the active dopant concentration prior to the on-set of deleterious concentration quenching. While alumina is an index-raising dopant, when added to silica, such that optical waveguiding is enabled,$^9$ it has other important properties, such as reducing the strength of Brillouin$^{10,11}$ and Raman$^{12}$ scattering, making it particularly attractive for high-power glass fiber laser applications.$^7$,$^{13,14}$

Unfortunately, little data in the literature exists to help guide in the prediction, or even the design, of the linear or nonlinear refractive index ($n$ and $n_2$, respectively) values in alumina-containing glasses. Importantly, knowledge of the Sellmeier refractive index coefficients of Al$_2$O$_3$ enables the calculation of the total dispersion curves for arbitrary aluminosilicate-based optical fibers. In addition, $n_2$ can be of particular importance for high-peak power and mode-locked fiber lasers.$^{15}$ However, alumina is not a bulk glass former,$^{16}$ although amorphous alumina has been realized in thin-film form.$^{17}$ It is for this reason that the characterization of its physical properties is particularly challenging, resulting in the stated lack of relevant literature data.

The approach taken here employs simple additivity models, coupled with optical fiber measurements, for the characterization of key properties of individual constituents within multicomponent glass systems.$^{18}$ More specifically, in the present case, this additive modeling approach is
taken to determining the Sellmeier coefficients for the refractive index of amorphous alumina based on pure binary aluminosilicate glass optical fibers. These values then are utilized to gain insight into $n_2$ of amorphous Al$_2$O$_3$, which presumably differs from that of its crystalline analog, sapphire.$^{19}$ The nonlinear refractive index is found to increase with alumina content when added to silica, an important finding for high-energy fiber lasers. This is not surprising, as generally one can correlate a larger value of $n_2$ with larger values of the linear refractive index.$^{20}$ Due to the highly multimoded nature of the fiber,$^{10}$ direct measurements of $n_2$ utilizing methods such as self-phase modulation (SPM)$^{21}$ could not be made.

2 | EXPERIMENTAL PROCEDURE

The optical fiber used in this study was originally reported in Ref. 10 In order to extract the refractive index values of alumina from data on the aluminosilicate fiber, one needs both the alumina concentration and refractive index values as a function of wavelength. Optical fibers with high alumina content were preferred for this study since a larger index difference (relative to silica) and larger fiber diameter would yield less measurement uncertainty as a function of wavelength. Therefore, the molten core method$^{10,18,22}$ was employed in fabricating the fiber since it generally affords higher doping levels into silica than conventional chemical vapor deposition (CVD) methods. Readers are referred to Ref. 10 for details on the fiber fabrication and properties of these high Al$_2$O$_3$ content aluminosilicate glass optical fibers. In short, the amorphous nature of the fiber is presumed for the following reasons: (1) a draw temperature well above the liquidus for the compositions was used, and was coupled with rapid quench rates (>2000 K/s); (2) losses are on the order of 100 dB/km, much lower than would be expected via devitrified glass and resulting grain boundaries; and (3) the Raman spectra exhibit fully amorphous behavior.$^{14}$ Elemental analysis was conducted under high vacuum, using energy dispersive x-ray (EDX) spectroscopy in secondary electron (SE) mode on a Hitachi SU-6600 analytical variable pressure field emission scanning electron microscope.

Two-dimensional fiber refractive index profiles (RIPs) were measured transversely through the side of the fiber using a spatially resolved Fourier transform interferometer$^{23}$ at selected wavelengths (488 nm, 590 nm, 660 nm, 730 nm, 850 nm, and 958 nm). These refractive index data sets then were averaged in the azimuthal direction. Index differences are provided for the core relative to the pure silica (SiO$_2$) cladding. These multi-wavelength measurements of the RIP ultimately provide a means to deduce a Sellmeier model for the amorphous alumina given the precisely known values for pure silica coupled with the additivity model,$^{18,24}$ discussed in more detail below. It is important to point out that while the RIP (Interfiber Analysis LLC, Sharon, MA, USA) and EDX (Clemson University, Clemson, SC, USA) measurements were performed on different samples of fiber, they came from positions on the spool that were separated by less than 1 meter. As such, there is much confidence in the assumption that both segments were essentially identical within the context of the present work.

3 | RESULTS AND DISCUSSION

The compositional profile is provided in Figure 1. At core center, the fiber under study has an alumina content of just over 40 mole percent. It is worth noting that conventional CVD methods used for manufacturing optical fibers are limited to only about 8 mole percent alumina. The core diameter, defined here to be the full-width at
half-maximum of the Al₂O₃ compositional profile, is approximately 20 μm. Figure 2 provides a radial RIP, from core center to the silica cladding (zero index difference), along with an expanded view of the region utilized in this study. Since the azimuthally averaged profiles are radially symmetric, only one radial RIP is needed for the analysis. In order to show the agreement between the compositional profiles and RIPS, the compositional data has been scaled linearly to overlap with the (arbitrarily selected) 488 nm RIP. Scaling to the 488 nm, or topmost RIP for this comparison simply offered the clearest visual in Figure 2.

3.1 | Materials modeling and analysis

The analysis was limited to the range from 0 to 10 μm in the fiber radial direction in order to avoid significant uncertainty introduced by the positions of the RIPS where the slope is most steep. Within this range, three compositions were measured, at radial positions of 1.7 μm, 5.2 μm, and 8.6 μm. The Sellmeier model for fused silica found in Ref. 24 was first used to calculate the refractive index of pure silica at these three positions at the six previously identified wavelengths. Then, the local refractive index for the binary glass is determined by adding the refractive index difference measured at those positions to the pure silica value. These values are listed in Table 1 at the positions identified above (rows “Binary Glass”).

Next, the model found in Ref. 25 for the additivity of the refractive index is invoked with the assumption that the refractive index, \( n_A \) needed to achieve the binary index (\( n_B \)) listed in the Table 1 then is found using Equation 1, with the silica refractive index (\( n_S \)) still taken from Ref. 24. The results of this calculation are also provided in Table 1 in the rows labeled “Al₂O₃ Component.”

Next, the three “pure” alumina refractive index values at the three distinct points on the fiber radial axis are averaged at each wavelength. As in Ref. 24, a three-oscillator Sellmeier model, given by,

\[
n^2 = 1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2},
\]

then is fit to this averaged data. These results are shown graphically in Figure 3 and are tabulated in Table 2 where the best-fit coefficients are provided. To roughly one part in a billion, the \( A_1 \) term can be neglected and a two-oscillator model is found to be an excellent fit to the data.

3.2 | Nonlinear refractive index

A simple model (BGO model) to estimate the nonlinear refractive index, \( n_2 \), is provided in Ref. 26 and reproduced here as follows:

\[
n_2(10^{-13} \text{ esu}) = 391 \left( \frac{n_d - 1}{n_d} \right)^{5/4}.
\]

While several empirical relations can be found in Ref. 26 for the nonlinear refractive index, the version embodied

| Wavelength (nm) | 488 | 590 | 660 | 730 | 850 | 958 |
|----------------|-----|-----|-----|-----|-----|-----|
| Position from center: 1.7 μm; Al₂O₃ concentration = 41.2 mole percent | 1.55917 | 1.55248 | 1.54958 | 1.54754 | 1.54476 | 1.54316 |
| Binary Glass | 1.55917 | 1.55248 | 1.54958 | 1.54754 | 1.54476 | 1.54316 |
| Al₂O₃ Component | 1.6823 | 1.6730 | 1.6691 | 1.6665 | 1.6629 | 1.6612 |
| Position from center: 5.2 μm; Al₂O₃ concentration = 38.9 mole percent | 1.55391 | 1.54757 | 1.54467 | 1.54243 | 1.53996 | 1.53824 |
| Binary Glass | 1.55391 | 1.54757 | 1.54467 | 1.54243 | 1.53996 | 1.53824 |
| Al₂O₃ Component | 1.6820 | 1.6733 | 1.6692 | 1.6662 | 1.6632 | 1.6612 |
| Position from center: 8.6 μm; Al₂O₃ concentration = 34 mole percent | 1.54176 | 1.53587 | 1.53312 | 1.53078 | 1.52846 | 1.52662 |
| Binary Glass | 1.54176 | 1.53587 | 1.53312 | 1.53078 | 1.52846 | 1.52662 |
| Al₂O₃ Component | 1.6789 | 1.6709 | 1.6670 | 1.6634 | 1.6608 | 1.6584 |
by Equation 4 (Equation 39 in Ref. 26) seems to offer the best fit to a wide set of \( n^2 \) data across a broad compositional range, and has gained broad acceptance.\(^2\) An alternate expression, based on a derivation from physical properties (Equation 38 in Ref. 26) is also often found used in the literature,\(^2,29\) but frequently with modified coefficients for improved fittings to data.\(^3\) This alternate formula is given to be,\(^26\)

\[
n^2(10^{-13} \text{ESU}) = \frac{68(n_d - 1)(n_d^2 + 2)^2}{v_d \left[ 1.517 + \frac{(n_d^2 + 2)(n_d + 1)}{6n_d} v_d \right]^{1/2}}. \tag{5}\]

The terms in Equations 4 and 5 are the refractive indices \((n_F, n_a, n_C)\) and Abbé number, \(v_d = (n_d - 1)/(n_F - n_C)\), at the historically based wavelengths of the hydrogen F line \((\lambda_F = 486.13 \text{ nm})\), the helium d line \((\lambda_d = 587.56 \text{ nm})\), and the hydrogen C line \((\lambda_C = 656.27 \text{ nm})\). Since according to Ref. 26 Equation 4 provides a better fit to materials that possess \( n^2 \) values above about \( 2 \times 10^{-13} \text{ ESU} \), Equation 4 shall be used for the remaining analysis. It should be pointed out, however that neither equation provides any direct dependence of \( n^2 \) (in ESU units) on optical wavelength.

Applying the Sellmeier model parameters deduced above for amorphous \( \text{Al}_2\text{O}_3 \) to compute the appropriate refractive indices \((n_F, n_a, n_C)\), \( n^2 \) is determined to be \( 1.89 \times 10^{-13} \text{ ESU} \) \((4.77 \times 10^{-20} \text{ m}^2/\text{W}) \) at 958 nm using \( n_a(m^2/\text{W}) = 40\pi n_2(\text{ESU})/cn_d \). Using the data in Ref. 24 the value for silica is found to be \( 0.92 \times 10^{-13} \text{ ESU} \) \((2.66 \times 10^{-20} \text{ m}^2/\text{W}) \) at 958 nm), which is similar to values typically accepted for silica \( (0.97 \times 10^{-13} \text{ ESU}) \).\(^31\) Hence, based on the Sellmeier data and the approximation given by Equation 4, adding alumina into silica is expected to increase the nonlinear refractive index of the binary glass. A corollary finding is found in Ref. 32 where increasing the concentration of \( \text{La}_2\text{O}_3 \) in a bulk lanthanum aluminosilicate glass was shown to increase \( n^2 \). While the results obtained here are consistent with those found in Ref. 28 for an aluminosilicate core glass fiber, that fiber also possessed Yb and Tm as co-dopants, which may have had some influence on \( n^2 \). In contrast, the results obtained here are not fully consistent with those found in Ref. 33 for an aluminosilicate glass core fiber. With approximately 14 weight \% \((8.8 \text{ mol } \%)\) of \( \text{Al}_2\text{O}_3 \), Ref. 34 \( n^2 \) was found to be \( 2.5 \times 10^{-20} \text{ m}^2/\text{W} \) at 1550 nm (and slightly higher with less alumina), suggesting that alumina decreases \( n^2 \) when added to silica. It is important to point out, however, that the fibers in Ref. 34 possessed an F-doped trench. Indeed, the measurement of \( n^2 \) gives that of the optical mode. As such, any overlap between the optical mode and the depressed cladding may have reduced the modal \( n^2 \) relative to that of bulk aluminosilicate glass since F is known to decrease \( n^2 \) when added to silica.\(^35\)

Direct measurements of the nonlinear refractive index or \( \chi^{(3)} \) susceptibility of thin alumina films vary considerably in the literature.\(^36-38\) Therefore, by way of comparison, the Sellmeier fit from Ref. 39 for thin-film \( \text{Al}_2\text{O}_3 \) grown on a soda lime glass substrate is provided in Figure 3 (dashed curve). It is found that the dispersion (refractive index as a function of wavelength) curve very closely resembles that found in these low-density thin alumina films.\(^39,40\) As a side note, “low-density” refers here to a density value relative to bulk sapphire; alumina increases glass density when added to silica.

First, the chromatic dispersion curves do indeed appear to be quite similar. Applying Equation 4 to the thin-film data from Ref. 39 leads to a nonlinear refractive index of \( 1.84 \times 10^{-13} \text{ ESU} \) \((4.64 \times 10^{-20} \text{ m}^2/\text{W}) \) at 958 nm); within roughly 3\% of the value obtained from the fiber measurements. This very reasonable agreement further suggests that many of the observed properties of alumina are driven mainly by its in situ apparent mass density.\(^41\) The slightly higher refractive index from the Ref. 39 data suggests the density of the thin film is slightly higher than that encountered in the aluminosilicate glass found in the optical fiber, but density can vary somewhat in both cases\(^39,41\) for a number of reasons.

Next, the additivity of the nonlinear refractive index is considered. In the presence of a strong optical field, Equation 1 may be recast by definition where \( n = n_0 + n^2 I \), as

| Table 2 | Sellmeier coefficients for amorphous \( \text{Al}_2\text{O}_3 \) as deduced from an aluminosilicate optical fiber |
|---------|-----------------------------------------------|
| \( A_1 \) | \( A_2 \) | \( A_3 \) | \( A_4 \) |
| 2.4989 \times 10^{-9} | 52575.7 | 0.14498 | 17018.5 | 1.58869 | 11645.0 |

 FIGURE 3 Refractive index as a function of wavelength for amorphous \( \text{Al}_2\text{O}_3 \) deduced from an aluminosilicate optical fiber. The data points (*) are an average of the index values from the three compositional positions at each of the six measurement wavelengths. The solid black line is the Sellmeier fitting (Table 2). The dashed curve is the Sellmeier fitting from Ref. 39 for a thin amorphous \( \text{Al}_2\text{O}_3 \) film on a glass substrate (Color figure can be viewed at wileyonlinelibrary.com)
\[ n = m(n_A + n_{2A}I) + (1 - m)(n_s + n_{2S}I) = mn_A + (1 - m)n_s + (mn_{2A} + (1 - m)n_{2S})I. \] (6)

Here, \( I \) is the intensity of an optical wave (W/m^2) and the nonlinear indices for the silica (S) and alumina (A) components, \( n_{2A,S} \), are in units of m^2/W. This equation can be rewritten to possess linear (corresponding to Equation 1) and nonlinear (corresponding to \( n_2 \)) components that can be added separately as shown. Therefore, Equation 6 suggests simple linear additive modeling of the nonlinear index \( n_2 \). \( n_2 \) in Equation 6 is rewritten to convert from \( \text{esu} \) to m^2/W units using,

\[ n_2 \left( \frac{m^2}{W} \right) = \frac{40\pi}{c_0} \left( m \frac{n_2A(\text{esu})}{n_A} + (1 - m)\frac{n_{2S}(\text{esu})}{n_S} \right). \] (7)

where \( c_0 \) is the vacuum speed of light and \( n_2 \) (units of \( \text{esu} \)) is obtained from Equation 4. Finally, Equation 7 gives the nonlinear index of the binary glass as a function of composition. This can be plotted as a function of Al2O3 concentration, with the results provided in Figure 4 for an optical wavelength of 958 nm, selected as being the wavelength (from measurement data) closest to that of interest for Yb-based lasers. Again, since Equation 4 is not a function of wavelength, the wavelength is only relevant for the linear index, ultimately affecting \( n_2 \) (m^2/W) in a minor way. Considering the relatively low concentrations of Al2O3 in most rare-earth-doped active fiber types (much lower than those considered here), as a general rule, \( n_2 \) can be presumed to increase by about 1% for each 1 mole percent of alumina added to silica at low Al2O3 contents.

In order to complete the analysis, and as a check for self-consistency, the Sellmeier model (Equation 3) was fit to each of the “Binary Glass” refractive index values at each position given in Table 1, giving rise to three sets of binary glass Sellmeier coefficients. From this model, Equation 4 was then used to calculate \( n_2 \) at each of these positions. These values are plotted in Figure 5 (three data points) with the original modeling result shown in Figure 4 (solid black curve). As explained below, the fitted curve (dashed orange line) requires that \( n_2 \) be increased by 12% in order to match the values determined from the data points. This value is therefore taken to be the uncertainty in the measurement and the assignment of 1.89 × 10^{-13} ± 12% \( \text{esu} \) to the \( n_2 \) of Al2O3, including uncertainty, is made. Considering that the reliability of the BGO model is typically taken to be ±20%,\(^{26}\) the agreement between the additive model (\( n_2 \) vs Al2O3 concentration) and the calculations for the three positions (or compositions) are reasonable and well within expected uncertainty. Indeed, the modeling curve and calculated points are only about 6% apart. It is important to note that the calculation in Figure 4 presumes an \( n_2 \) value for SiO2 (deduced using data in Ref. 24), whereas the calculated points in Figure 5 are directly from the binary glass and therefore do not presume anything about the constituents. This likely represents the largest source of uncertainty in this comparison, and analysis generally.

Next, using the additive model (Equation 7) instead as a fit to the points in Figure 5 (with \( n_{2A} \) being the fit parameter, rather than being calculated from Equation 4), it is found that \( n_{2A} \) must be increased from that listed above by ~12% for good matching (2.12 × 10^{-13} \( \text{esu} \), 5.34 × 10^{-20} m^2/W). The fitted model is shown in Figure 5 as the dashed curve. Accordingly, within the expected accuracy of the BGO model, a reasonable approximate range of values for the nonlinear refractive index of amorphous alumina has been identified.

Finally, it is worthwhile to compare aluminosilicate glass with the more common germanosilicate glasses typically found in optical fibers for telecommunication applications. Data for the germanosilicate glass found in Ref. 35 were used for this analysis, with the results shown in
Figure 6. It can be seen that the use of alumina results in a lower $n_2$ than for GeO$_2$ ($2.59 \times 10^{-13}$ esu). This suggests that highly nonlinear (high numerical aperture, small mode effective area) fibers fabricated from alumina will have reduced $n_2$ relative to their GeO$_2$-doped counterparts, but may prove to have significant advantages in narrow linewidth operation with the ability to suppress Brillouin scattering.\textsuperscript{42}

4 | CONCLUSION

A set of Sellmeier coefficients has been determined for the amorphous alumina component in an aluminosilicate glass optical fiber, deduced from refractive index measurements as a function of wavelength. A simple approximation to the nonlinear refractive index was then used to estimate $n_2$ of amorphous alumina, which was found to be about 80% larger than that of fused silica. Comparison of these results with those from the literature suggests that some thin alumina films share considerable similarities with the form of alumina found in optical fiber. This can likely be traced to similarity in mass density among the various forms of Al$_2$O$_3$. Finally, the simple additive model found in Ref. 25 was expanded slightly to calculate the nonlinear refractive index of binary aluminosilicate glass as a function of Al$_2$O$_3$ concentration. This expanded model is useful for the development of future high energy fiber-based lasers where $n_2$-related wave mixing effects contribute to optical power scaling limitations in present systems.

ACKNOWLEDGMENTS

The Authors thankfully acknowledge financial support from the US Department of Defense Joint Technology Office through contracts FA9451-15-D-0009/0001, FA9451-15-D-0009/0002, and N00014-17-1-2546. The J. E. Sirrine Foundation also is gratefully acknowledged for supporting the efforts of the Authors (JB and MC). Authors are grateful to R. Stolen (Clemson University) for thoughtful discussions and to A. Yablon (Interfiber Analysis) for the refractive index measurements.

ORCID

Peter Dragic\textsuperscript{16} \url{http://orcid.org/0000-0002-4413-9130}  
John Ballato\textsuperscript{17} \url{http://orcid.org/0000-0001-5910-3504}

REFERENCES

1. Moulton P. Spectroscopic and laser characteristics of Ti:Al$_2$O$_3$. J Opt Soc Am B. 1986;3:125-133.
2. Arai K, Namikawa H, Kumata K, et al. Aluminum or phosphorus co-doping effects on the fluorescence and structural properties of neodymium-doped silica glass. J Appl Phys. 1986;59:3430-3436.
3. Kim J, Soh D, Nilsson J, et al. Fiber design for high-power low-cost Yb:Al-doped fiber laser operating at 980 nm. IEEE J Sel Topics Quantum Electron. 2007;13:588-597.
4. Deschamps T, Ollier N, Vezin H, et al. Clusters dissolution of Yb$^{3+}$ in codoped SiO$_2$-Al$_2$O$_3$-P$_2$O$_5$ glass fiber and its relevance to photodarkening. J Chem Phys. 2012;136:014503.
5. Wang Z, Zhan H, Ni L, et al. Research progress of chelate precursor doping method to fabricate Yb-doped large-mode-area silica fibers for kW-level laser. Laser Phys. 2015;25:111503.
6. Moulton P, Rines G, Sloboditchik E, et al. Tm-doped fiber lasers: fundamentals and power scaling. IEEE J Sel Topics Quantum Electron. 2009;15:85-92.
7. Herrmann A, Rüssel C. New aluminosilicate glasses as high-power laser materials. Int J Appl Glass Sci. 2015;6:210-219.
8. Ballato J, Dragic P. On the clustering of rare earth dopants in fiber lasers. J Directed Energy. 2017;6:175-181.
9. Kobayashi S, Nakagome H, Shimizu N, et al. Low-loss optical glass fibre with Al$_2$O$_3$-SiO$_2$ core. Electron Lett. 1974;10:410-411.
10. Dragic P, Hawkins T, Morris S, et al. Sapphire-derived all-glass optical fibers. Nature Photon. 2012;6:629-635.
11. Dragic P, Ballato J, Morris S, et al. Pockels’ coefficients of alumina in aluminosilicate optical fiber. J Opt Soc Am B. 2013;30:244-250.
12. Dragic PD, Ballato J. Characterisation of Raman gain spectra in Yb:YAG-derived optical fibres. Electron Lett. 2013;49:895-897.
13. Richardson D, Nilsson J, Clarkson W. High power fiber lasers: current status and future perspectives. J Opt Soc Am B. 2010;27:B63-B92.
14. Ballato J, Dragic P. Materials development for next generation optical fiber. Materials. 2014;7:4411-4430.
15. Kutz JN. Mode-Locked Soliton Lasers. SIAM Rev. 2006;48:629-678.
16. Ballato A, Dragic PD, Martin SW, et al. On the anomalously strong dependence of the acoustic velocity of alumina on temperature in aluminosilicate glass optical fibers—Part II: acoustic properties of alumina and silica polymorphs, and approximations of the glassy state. Int J Appl Glass Sci. 2016;7:11-26.
17. Nayar P, Khanna A, Kabiraj D, et al. Structural, optical and mechanical properties of amorphous and crystalline alumina thin films. Thin Solid Films. 2014;568:19-24.
18. Ballato J, Dragic P. Rethinking optical fiber: new demands, old glasses. *J Am Ceram Soc.* 2013;96:2675-2692.
19. Major A, Yoshino F, Nikolakakos I, et al. Dispersion of the nonlinear refractive index in sapphire. *Opt Letters.* 2004;29:602-604.
20. Adair R, Chase L, Payne S. Nonlinear refractive index of optical crystals. *Phys Rev B.* 1989;39:3337-3350.
21. Kim S, Stolen R, Reed W, et al. Measurement of the nonlinear index of silica-core and dispersion-shifted fibers. *Opt Lett.* 1994;19:257-259.
22. Morris S, Ballato J. Molten-core fabrication of novel optical fibers. *Am Ceram Soc Bulletin.* 2013;92:24-29.
23. Yablon AD. Multi-wavelength fiber refractive index profiling by spatially resolved Fourier transform spectroscopy. *J Lightwave Technol.* 2010;28:360-364.
24. Fleming JW. Dispersion in GeO₂-SiO₂ glasses. *Appl Opt.* 1984;23:4486-4493.
25. Dragic PD. Simplified model for the effect of Ge doping on silica fibre acoustic properties. *Electron Lett.* 2009;45:256-257.
26. Boling NL, Glass AJ, Owyoung A. Empirical relationships for predicting nonlinear refractive index changes in optical solids. *IEEE J Quantum Electron.* 1978;14:601-608.
27. Tanaka K. Optical nonlinearity in photonic glasses. *J Mater Sci - Mater Electron.* 2005;16:633-643.
28. Watekar P, Ju S, Boo S, et al. Linear and non-linear optical properties of Yb³⁺/Tm³⁺ co-doped aluminosilicate glass prepared by sol-gel method. *J Non-Cryst Solids.* 2005;351:2446-2452.
29. Adair R, Chase LL, Payne SA. Nonlinear refractive-index measurements of glasses using three-wave frequency mixing. *J Opt Soc Am.* 1987;5:875-881.
30. Chase L, Van Styrand WE. Nonlinear optical properties. In: Weber MJ, ed. *CRC Handbook of Laser Science and Technology, Supplement 2: optical Materials.* Boca Raton, FL: CRC Press; 1995: Section 8.
31. https://www.rp-photonics.com/nonlinear_index.html
32. Karras C, Litzkendorf D, Grimm S, et al. Nonlinear refractive index study on SiO₂-Al₂O₃-L₂O₃ glasses. *Opt Mater Express.* 2014;4:2066-2077.
33. Grüner-Nielsen L, Herstrøm S, Dasgupta S, et al. Brillouin Suppressed Highly Nonlinear Fibers. Paper MD3.2. In: *Proceedings of IEEE Winter Topicals 2011.* Keystone, Colorado, USA, 2011:171-172.
34. Grüner-Nielsen L, Jakobsen D, Herstrøm S, et al. Brillouin Suppressed Highly Nonlinear Fibers. Paper We.1.F.1. In: *Proceedings of ECOC 2012,* Amsterdam, Netherlands, 2012;38:We.1.F.1.
35. Nakajima K, Ohashi M. Dopant dependence of effective nonlinear refractive index in GeO₂- and F-doped core single-mode fibers. *Photon Technol Lett.* 2001;14:492-494.
36. Rodríguez C, Rudolph W. Characterization and χ⁽³⁾ measurements of thin films by third-harmonic microscopy. *Opt Lett.* 2014;39:6042-6045.
37. Lin SS. The optical properties of hydrophilic Ti-doped Al₂O₃ films. *Opt Mater.* 2014;36:1488-1493.
38. Korcal A, Płosciennik P, Zawadzka A, et al. Optical Properties of Al₂O₃ Thin Film Deposited by sol-gel Technique. *Paper presented at International Conference on Transparent Optical Networks.* 2015; paper We.P.15.
39. Kumar P, Wiedmann MK, Winter CH, et al. Optical properties of Al₂O₃ thin films grown by atomic layer deposition. *Appl Opt.* 2009;48:5407-5412.
40. Gorham C, Gaskins J, Parsons G, et al. Density dependence of the room temperature thermal conductivity of atomic layer deposition-grown amorphous alumina (Al₂O₃). *Appl Phys Letters.* 2014;104:253107.
41. Dragic P, Ballato J, Ballato A, et al. Mass density and the Brillouin spectroscopy of aluminosilicate optical fibers. *Opt Mater Express.* 2012;2:1641-1654.
42. Nakanishi T, Tanaka M, Hasegawa T, et al. Al₂O₃-SiO₂ Core Highly Nonlinear Dispersion-Shifted Fiber With Brillouin Gain Suppression Improved by 6.1 dB. Paper TH.4.2.2. In: *Proceedings of ECOC 2006,* Cannes, France, 2006;6:17-18.

**How to cite this article:** Dragic P, Cavillon M, Ballato J. The linear and nonlinear refractive index of amorphous Al₂O₃ deduced from aluminosilicate optical fibers. *Int J Appl Glass Sci.* 2018;9:421-427. https://doi.org/10.1111/ijag.12337