Versatile Approach for Reducing Propagation Loss in Wet-Electrospun Polymer Fiber Waveguides

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ABSTRACT: Wet-electrospun (WES) polymer micron and submicron fibers are promising building blocks for small, flexible optical fiber devices, such as waveguides, sensors, and lasers. WES polymer fibers have an inherent cylindrical geometry similar to that of optical fibers and a relatively large aspect ratio. Furthermore, WES fibers can be produced using low-cost and low-energy manufacturing techniques with large-area fabrication and a large variety of materials. However, the high propagation loss in the fibers, which is normally on the order of tens or thousands of decibels per centimeter in the visible light region, has impeded the use of these fibers in optical fiber devices. Here, the origin of propagation losses is examined to develop a comprehensive and versatile approach to reduce these losses. The excess light scattering that occurs in fibers due to their inhomogeneous density is one of the primary factors in the propagation loss. To reduce this loss, the light transmission characteristics were investigated for single WES polymer fibers heated at different temperatures. The propagation loss was significantly reduced from 17.0 to 8.1 dB cm⁻¹ at 533 nm wavelength, by heating the fibers above their glass transition temperature, 49.8 °C. In addition, systematic verification of the possible loss factors in the fibers confirmed that the propagation loss reduction could be attributed to the reduction of extrinsic excess scattering loss. Heating WES polymer fibers above their glass transition temperature is a versatile approach for reducing the propagation loss and should be applicable to a variety of WES fibers. This finding paves the way for low-loss WES fiber waveguides and their subsequent application in small, flexible optical fiber devices, including waveguides, sensors, and lasers.

INTRODUCTION

Wet electrospinning is a simple, versatile, and widely used technique for producing submicron and micron polymer fibers. This technique has considerable potential for low-cost and low-energy manufacturing with large fabrication area, providing high material utilization ratios and high positional accuracy.1,2 The electrospinning technique can instantaneously and continuously produce fibers with lengths of more than tens of centimeters that have an inherent cylindrical geometry similar to that of optical fibers.3 Furthermore, wet-electrospun (WES) fibers can be produced from a wide variety of spinnable polymers and composites, including highly transparent polymers and optically active composites.4–6 Thus, WES fibers are promising building blocks for small, flexible optical fiber devices, such as waveguides, sensors, and lasers.5–11 However, high propagation loss in WES fibers, normally on the order of tens or thousands of decibels per centimeter in the visible light region,6,7,9–18 has impeded their widespread use.

Fasano et al. reduced the propagation loss caused by the surface morphology of WES conjugated polymer fibers by producing the fibers in a precisely controlled nitrogen atmosphere,14 but this approach could only be applied to specific materials. We previously reported that the high propagation loss in WES fibers could be attributed to (i) excess light scattering in the fibers resulting from their inhomogeneous density and (ii) loss at the interface between the fiber core and cladding, originating from nonuniformity of the fiber diameters.

In this study, we reduced the propagation loss in WES polymer fibers by reducing excess light scattering in the fibers by a versatile heat treatment approach. The light transmission characteristics of single WES polymer fibers treated at different post-electrospinning temperatures revealed that the propagation loss was reduced significantly by 5.9 dB cm⁻¹ at 532 nm wavelength when the fibers were heated above their glass transition temperature (T_g).

EXPERIMENTAL DETAILS

Fiber Fabrication and Morphological Characterization. Amorphous poly(lactic acid) composed of a racemic mixture of D- and L-lactic acid units (PDLLA) was used as the fiber material because it exhibits high transparency in the
visible ranges\textsuperscript{16} and has a lower $T_g$ than other well-known amorphous transparent polymers such as poly(methyl methacrylate) (PMMA) and polystyrene (PS).\textsuperscript{15} The lower $T_g$ value enables easier investigation of the thermal properties of samples in this initial study. The as-received PDLLA pellets ($M_w = 300\,000–600\,000$, Polysciences, Inc.) were dissolved in chlorobenzene (99.0%, Wako Pure Chemicals Industries, Ltd.) with a concentration of 16 wt.%. The solution was then loaded into a glass syringe equipped with a 0.18 mm-diameter stainless-steel needle and was supplied continuously at a rate of 0.02 mL h$^{-1}$ using a syringe pump (KDS-100, KD Scientific, Inc.). A high-voltage power supply (HVU-30P100, MECC Inc.) was connected to the needle at 4.8 kV. The alternating biased-collector electrospinning method\textsuperscript{18} was used to fabricate single-aligned PDLLA fibers. Two stainless-steel collectors with 3 cm separation were placed 8 cm below the tip of the needle, one of which was biased with a negative voltage ($\pm 800$ V) using a high-voltage power source (HJPM-1N3, Matsusada Precision Inc.). The electrospinning experiments were performed in air at temperatures of 24$\,$°C with a relative humidity of 53–63%. The single-aligned electrosprun PDLLA fibers were collected in two lengths. One length was placed on a silicon substrate to characterize the shape of each fiber before heating. The other length was attached to two tapered optical silica fibers (Fine Glass Technologies Co., Ltd.) to conduct waveguiding measurements (see Figure 1, STEP 1).

The morphology of the single-aligned fibers was investigated using field-emission scanning electron microscopy (FESEM, SU8000, Hitachi) operating at 5.0 kV after a 4 nm-thick Os coating was applied. The mean diameter of each fiber was determined by averaging diameters taken from FESEM images at more than 12,800 positions along the 250 $\mu$m-long fibers using image analysis. A number of aligned WES PDLLA fibers were prepared by collecting the fibers for 30 min using a 15 cm-diameter gear-shaped rotating collector to conduct thermal, X-ray, and spectroscopic characterizations. The rotating speed of the collector was maintained at 100 rpm to prevent the as-spun fibers from being stretched by the collector.

**Waveguiding Measurements.** First, a collimated 532 nm laser (LCM-T-111, Laser-Export Co. Ltd.) beam with a 440 $\mu$m radius was irradiated to each fiber at different positions [Figure 1, STEP 1] to investigate the propagation loss in single WES PDLLA fibers. The laser beam was applied at a 43° angle to the fiber axis, and the polarization direction of the beam was perpendicular to the fiber axis. A portion of the laser beam was coupled to a guiding mode in the PDLLA fiber and collected via a right-tapered optical fiber after being guided through the PDLLA fiber. The intensity of the collected light was measured with a spectrometer (USB4000, Ocean Optics, Inc.). Then a 632.8 nm He–Ne laser (GLG5370, NEC Corp.) beam was introduced to the PDLLA fiber from the left tapered optical silica fiber, and the intensity of the guided light collected via the right tapered optical fiber was monitored while using different heating temperatures (see Figure 1, STEP 2). After cooling of the heated PDLLA fibers by stopping the heating, the measurement performed in STEP 1 was repeated in STEP 3 (see Figure 1, STEP 3). After the measurement, each fiber was placed on a silicon substrate to characterize the fiber shape. The propagation loss was also investigated at the following wavelengths using collimated laser diode modules in the same manner as that in STEP 1 and STEP 3: 450 nm (CPS450, Thorlabs Inc.), 521 nm (CPS520, Thorlabs Inc.), 639 nm (CPS635, Thorlabs Inc.), and 849 nm (CPS850, Thorlabs Inc.). Each collimated laser beam was irradiated to the single PDLLA fiber though a 1.0 mm-diameter pinhole.

**Thermal, X-ray, and Spectroscopic Characterization.** The thermal properties of the WES PDLLA fibers and PDLLA pellets were investigated with a differential scanning calorimeter (DSC-60, Shimadzu Corp.) under a nitrogen gas flow at a rate of 50 mL min$^{-1}$. Each sample of the WES PDLLA fibers (1.6 mg) or PDLLA pellets (3.0 mg) was heated from ambient temperature to 200 $^\circ$C.

The molecular structure of the PDLLA in the WES fibers was investigated using an X-ray diffractometer (RINT-2500, Rigaku Corp.) with a Cu K$\alpha$ source (wavelength of 1.5418 Å), which was operated at 40 kV and 200 mA.

The specific optical rotation of the PDLLA was measured in chloroform at a concentration of 10 g L$^{-1}$ at 25 $^\circ$C using a polarimeter (P-2100, JASCO) with a wavelength of 0.589 $\mu$m.

The ultraviolet (UV)–visible (Vis)–near infrared (NIR) attenuation spectra were measured using a UV–Vis–NIR spectrophotometer (U-4100, Hitachi). A fused glass cell with a 1.0 cm path length was used to measure the transmittance spectra of pure PDLLA, chlorobenzene, and 16 wt % PDLLA solution in chlorobenzene. The pure PDLLA sample was prepared by filling the PDLLA pellets into the cell and melting them at 120 $^\circ$C for 12 h.

The polymer chain orientation in the WES PDLLA fibers was evaluated using a Fourier transform infrared (FT-IR) spectrometer (Thermo Nicolet 6700, Thermo Fisher Scientific Inc.) equipped with a wire grid polarizer (KRS-5 Wire Grid Polarizer, S. T. Japan). The FT-IR spectrometer resolution was 4 cm$^{-1}$, and 128 scans were collected and averaged. In parallel polarization, the direction of the oscillating electric field of the incident IR beam is parallel to the aligned fiber axis; in perpendicular polarization, it is perpendicular to the fiber axis.

**RESULTS AND DISCUSSION**

The specific optical rotation of the used PDLLA was measured to be approximately zero, while the optical rotations of poly(lactic acid) composed of pure optical isomers, namely

![Figure 1. Schematic of the experimental setup for measuring the propagation loss and transmitted light intensity in a single PDLLA fiber.](image-url)
poly(L-lactic acid) (PLLA) or poly(D-lactic acid), are reported to be $-156$ and $156\,\text{dm}^{-1}\text{g}^{-1}\text{cm}^{3}$, respectively.\textsuperscript{19} This result confirmed that the PDLLA used in this study was comprised of equivalent amounts of L- and D-lactic acid\textsuperscript{20} to form an amorphous polymer. The X-ray diffraction patterns of the WES PDLLA fibers were also measured, but no obvious diffraction peaks were found at 20 between 15° and 20°, even though crystallized PLLA exhibits diffraction peaks within this angle range.\textsuperscript{21} This result confirmed that the WES PDLLA fibers were amorphous.

Five single-aligned WES PDLLA fibers, which were approximately 3 cm long, (Fibers A–E) were fabricated. One part of each fiber was placed on a silicon substrate to investigate the fiber morphology. Figure 2a shows an FESEM image of a single-aligned PDLLA fiber (Fiber A). The fiber was obtained with a smooth surface. The mean and standard deviation of the fiber diameters of each fiber are summarized in Table 1. The mean diameter ranges from 1.60 to 1.76 μm.

Then, a part of each fiber was attached to two tapered optical fibers, where a 632.8 nm laser beam is introduced from the left tapered fiber to the PDLLA fiber.

Table 1. Mean and Standard Deviation of the Fiber Diameters before and after Heating

| Fiber | A (μm) | B (μm) | C (μm) | D (μm) | E (μm) |
|-------|--------|--------|--------|--------|--------|
| before heating mean diameter | 1.68 | 1.69 | 1.67 | 1.60 | 1.76 |
| standard deviation (μm) | 0.29 | 0.14 | 0.32 | 0.15 | 0.18 |
| after heating mean diameter | 1.71 | 1.49 | 1.51 | 1.57 | 1.60 |
| standard deviation (μm) | 0.14 | 0.13 | 0.22 | 0.23 | 0.20 |

electrospun PDLLA fibers and tapered fibers. As shown in the bright- [Figure 2b] and dark-field [Figure 2c] microscopy images, a red laser beam with 632.8 nm wavelength was coupled to the PDLLA fiber from the left tapered fiber, although part of the laser beam was radiated at the tip of the left tapered fiber. The thin red line observed in Figure 2b,c along the PDLLA fiber position demonstrates that the light was guided in the fiber. Relatively bright dots observed along the PDLLA fiber in Figure 2c could be attributed to scattering of the guided light at the points with locally inhomogeneous morphology.

Figure 3 shows dependence of the transmitted light intensity, normalized by the peak intensity, on the fiber temperature, using the same setup as that illustrated in Figure 1 STEP 2. The fiber temperature was increased from room temperature by 1.1–1.4 °C min$^{-1}$ until the PDLLA fiber was broken. Even at room temperature (25–28 °C), the transmitted light intensity was more than 160 times higher than that after the PDLLA fiber was broken, which confirmed that direct light coupling from the left-tapered silica fiber to the right-tapered silica fiber, which was primarily caused by the radiated light at the tip of the left fiber, was negligible. Consequently, the introduced laser beam was mainly guided in the PDLLA fiber and was collected via the right-tapered optical fiber. The transmitted light intensity increased with increasing temperature, showing significant increases at around 45–55 °C. Moreover, the intensity showed peaks at around 55–60 °C. Over this temperature range, the intensity showed a saturated and/or unstable value until the intensity drop occurred because of the break of the PDLLA fiber. The transmitted light intensity was 3.5 times higher after heating than that before heating. These results indicated that the propagation loss in the PDLLA fibers was reduced by heating, but reduction of the connection loss between the PDLLA fiber and the tapered silica fibers remained a possible reason for the increased transmitted light intensity because the connection area was also heated in the present setup, as shown in Figure 1 STEP 2.

The thermal properties of the WES PDLLA fibers and the as-received PDLLA pellets were investigated using DSC, as shown in Figure 4. The $T_g$ value was determined to be 49.8 °C for the fibers (first heating), 53.1 °C for the fibers (second heating), and 53.5 °C for the pellets (second heating). Both samples from the second heating showed approximately equivalent $T_g$ values because their erased thermal history.
allowed the thermal properties of the PDLLA material to dominate; however, the $T_g$ value for the first heating fibers showed a slight decrease. Similar $T_g$ decreases were previously reported for WES PDLLA fibers and thin polymer films. The evaluated $T_g$ of the WES fibers corresponded to the temperature range of 45–55 °C, where the transmitted light intensity significantly increased. Excess light scattering loss in PMMA bulks has been reduced by polymerization or by heating the material above $T_g$; thus, the increase in the transmitted light intensity near and above the $T_g$ value could be partially attributed to the reduction of excess light scattering loss in the PDLLA fibers.

To understand the change in propagation loss in each WES fiber due to heating and avoiding the effects of the connection loss, we measured the propagation loss before and after heating using the procedure shown in Figure 1. Here, the maximum heating temperature was determined to be around 55 °C because this temperature was above $T_g$ of the PDLLA fibers and where the transmitted light intensity showed the maximum intensity (Figure 3).

The propagation loss was determined by measuring the guided light intensity with different propagation lengths ($l$) using the procedure explained above. Here, $l$ was determined as the length from the center of the spot at which the collimated laser was irradiated to the tip of the right tapered silica fiber. Figure 5a shows the normalized guided light intensity with different $l$, measured for a single WES PDLLA fiber (Fiber A) before and after heating. The wavelength of the irradiated light was 532 nm. The intensity decreased with increasing $l$, and the plots adequately fit the function $e^{-al}$ [solid lines in Figure 5a], where $a$ is the loss coefficient. The propagation loss was evaluated using the following formula: 

$$-10 \log(e^{-al_{1.0cm}}/e^{-al_{0cm}}) = 10a \log(e) \ [\text{dB cm}^{-1}]$$

Figure 5b summarizes the evaluated propagation loss of each PDLLA fiber before and after heating. The propagation loss was significantly reduced after heating for all five PDLLA fibers. For example, the propagation loss of Fiber A was reduced from 17 to 8.1 dB cm$^{-1}$, which corresponded to an 8.2-fold increase in the transmitted light intensity when the light is guided through 1.0 cm of the fiber. These results demonstrated that heating of the WES PDLLA fibers above $T_g$ significantly reduced the propagation loss in the fibers. The propagation loss of Fiber E was reduced to 5.9 dB cm$^{-1}$, which was the lowest propagation loss reported for WES polymer fibers. Increase in fiber diameters normally decreases the propagation loss in the fibers, but significant increase in the mean diameter was not observed after heating, as shown in Table 1, although the propagation loss was significantly reduced for all five fibers. This result shows that some other loss factors were reduced after heating.

The possible loss factors for WES fibers (from refs60–32) are summarized in Figure 6, separated into intrinsic and extrinsic factors.

To investigate the absorption loss in the WES PDLLA fibers, UV–Vis–NIR measurement was conducted. Figure 7 shows the UV–Vis–NIR attenuation spectra of pure PDLLA, chlorobenzene, 16 wt % PDLLA solution in chlorobenzene, and water in a 1.0 cm path-length fused glass cell. Each attenuation spectrum was converted from the transmittance spectrum of the respective sample; thus, the measured attenuation included attenuation due to light reflection and scattering at each interface including that between air and the fused glass cell. Unique attenuation peaks due to the electronic transition absorption or molecular vibration absorption of materials were observed at wavelengths shorter than 450 nm and longer than 700 nm for pure PDLLA, chlorobenzene, and PDLLA solution. On the other hand, in the wavelength range from 450 to 680 nm, the attenuation spectra decreased with...
increasing wavelength as a result of the light reflection and scattering at each interface and the light scattering inside each filled material. Consequently, the intrinsic absorption loss in the wavelength range of 450–680 nm was estimated to be less than 0.02 dB cm\(^{-1}\) from the attenuation spectrum of pure PDLLA, by subtracting the gradually decreasing attenuation and considering the 1 cm pass length. The extrinsic absorption loss caused by transition metals and organic contaminants was estimated to be less than 0.02 dB cm\(^{-1}\) from the attenuation spectrum of the pure PDLLA, chlorobenzene, and PDLLA solution because no peaks exceeding 0.02 dB were observed at this wavelength range. Although the attenuation spectrum of water indicated that its absorption loss was less than 0.5 dB cm\(^{-1}\) in the wavelength range of 450–680 nm, as shown in Figure 7, the absorption loss of WES PDLLA fibers could decrease to less than 0.05 dB cm\(^{-1}\) if the fibers contained 10% water relative to the fiber volume. These results confirmed that the intrinsic and extrinsic absorption losses were much lower than the propagation loss in the WES PDLLA fibers.

The intrinsic scattering loss originating from the intrinsic density inhomogeneity of the materials was the lower limit of scattering loss inherent to each material that remained even after the extrinsic scattering loss, namely the excess light scattering loss.\(^{33}\) Thus, the intrinsic scattering loss was not significantly reduced by the heat treatment. By roughly estimating the intrinsic loss from the measured attenuation spectrum of pure PDLLA [Figure 7], the intrinsic scattering loss was estimated to be less than 0.8 dB cm\(^{-1}\). However, this value of the intrinsic scattering loss should be an overestimation because both the light reflection loss and extrinsic light scattering loss were included in the measured attenuation spectrum. Moreover, the intrinsic scattering loss for other amorphous polymers, namely PMMA and PS, has been estimated to be less than 1 \times 10^{-3} dB cm\(^{-1}\) at wavelengths of around 533 nm.\(^{32,34}\)

Extrinsic scattering due to dust in the environment may occur during the measurements for transmitting light intensity and propagation loss; however, no large dust particles were observed in the bright-field microscope image of the PDLLA fiber [Figure 2b]. The dark-field microscope image of the fiber [Figure 2c] indicated relatively bright scattering points because of small dust particles or other factors not visible in the bright-field image, and the plots of the guided light intensity showed some variation [Figure 5a]. However, the variation was smoothed by fitting the plots with a single exponential function before the propagation loss was determined. Therefore, the local scattering loss due to dust should be negligible for the measured propagation loss. Moreover, the heat treatment could not reduce the scattering loss due to dust; thus, other factors caused the propagation loss reduction after heating. Additionally, the extrinsic radiation loss due to bends in the PDLLA fibers was negligible because the PDLLA fibers were kept straight during the optical measurements [Figure 2b].

The extrinsic scattering loss and radiation loss due to fluctuations in the fiber diameter are possible factors influencing the propagation loss in the WES PDLLA fibers, as previously indicated for WES PMMA fibers.\(^{7}\) Higher fluctuations in the fiber diameter cause higher propagation loss.\(^{26}\) To discuss the fluctuations before and after heating, the root-mean-square roughness (\(R_{\text{RMS}}\)) for each fiber was calculated using the FESEM images of each 250 \(\mu m\) long PDLLA fiber; more than 12,800 readings for each fiber were recorded using image analysis. The \(R_{\text{RMS}}\) was calculated using the following formula

\[
R_{\text{RMS}} = \sqrt{\frac{1}{250} \int_{0}^{250} \left( \frac{D_{i} - D_{\text{avg}}}{2} \right)^{2} \, dl}
\]

where \(D_{i}\) and \(D_{\text{avg}}\) are the measured diameter of the fibers, the mean diameter of each fiber, and the position where the diameter was measured, respectively. Figure 8 summarizes

\(R_{\text{RMS}}\) of each fiber before and after heating. No clear reduction of the \(R_{\text{RMS}}\) was observed after heating even though all five WES PDLLA fibers demonstrated reduced propagation loss [Figure 5b]. This result confirmed that extrinsic scattering loss and radiation loss due to the fluctuations in the fiber diameter must be excluded from the factors for propagation loss reduction due to heat treatment.

Extrinsic scattering loss due to the extrinsic density inhomogeneity resulting from microvoids, microscopic density variation, and birefringence is the only possible remaining loss factor for the propagation loss reduction because of post-fabrication heat treatment. Consequently, extrinsic scattering loss must be the primarily reduced loss factor to account for the observed propagation loss reduction. Extrinsic density inhomogeneity causes excess light scattering, including Rayleigh, Mie, or geometric scattering, so that excess light scattering results in extrinsic scattering loss. Moreover, excess light scattering was recently reported to be one of the main factors for propagation loss in WES PMMA fibers,\(^{7}\) and the excess light scattering in PMMA bulks was reported to be reduced by heating them above \(T_{\text{g}}\). These reports support the present reduction of propagation loss in WES PDLLA fibers because of heat treatment. Figure 9 shows the measured
The propagation loss in an WES PDLLA fiber with different wavelengths before and after heating. The propagation loss significantly decreased with the increasing wavelength, which was also observed in the as-WES PMMA fibers. This result confirmed that the propagation loss in the PDLLA fiber included extrinsic scattering loss. The propagation loss was significantly reduced after heating, especially at shorter wavelengths, which indicated that the enhanced excess light scattering at shorter wavelengths, for example, enhanced Rayleigh scattering proportional to \((\text{wavelength})^{-4}\), was significantly reduced after heating.

To investigate birefringence in the WES PDLLA fibers, polarized FT-IR spectra of aligned PDLLA fibers were measured, as shown in Figure 10a. The peak at 1755 cm\(^{-1}\) was assigned to C\(\equiv\)O stretching, and the peaks at 1186 and 1090 cm\(^{-1}\) were assigned to C\(\equiv\)O\(\equiv\)C stretching.\(^{36,37}\) These stretchings are parallel to the polymer backbone. The main chains of PDLLA in the as-electrospun PDLLA fibers were modestly aligned along the fiber axis because the absorbance was higher with parallel polarization at around 1090, 1186, and 1755 cm\(^{-1}\) than that with perpendicular polarization. The dichroic ratio was calculated to be 2.14 by integrating the polarized absorbance in the range from 1650 to 1850 cm\(^{-1}\).

The alignment of the PDLLA chains was relaxed after heating because the dichroic ratio after heating decreased to 1.35, as shown in Figure 10b. This alignment relaxation should reduce the birefringence in the PDLLA fibers and partially decrease the extrinsic scattering loss. The effects of microvoids and microscopic density variation are still unclear, but wet-electrospinning produces fibers with rapidly evaporating solvents so that microvoids and microscopic density variation are generated. Several papers reported inhomogeneous inner structures in WES fibers,\(^{5,58}\) and the WES PDLLA fibers in the present study showed higher propagation loss at shorter wavelength, reflecting the extrinsic density inhomogeneity. A previous work reported that PMMA bulks without heat treatment above \(T_g\) included inhomogeneous structures with a dimension of about 100 nm, which caused excess light scattering and increased scattering loss.\(^{25,26}\) Additionally, the inhomogeneous structures disappeared after heat treatment above \(T_g\) and the scattering loss was reduced. On the basis of these results, inhomogeneous structures in the WES PDLLA fibers, microvoids, and microscopic density variation, should be reduced after heat treatment above \(T_g\).

We demonstrated that heating amorphous WES fibers above \(T_g\) is a versatile approach for reducing their propagation loss. This technique should be applicable to a variety of WES fibers composed of amorphous polymers. Moreover, optimizing the heating conditions should reduce the propagation loss below the loss observed in this study (lower than 5 dB cm\(^{-1}\) at 533 nm wavelength).

**CONCLUSIONS**

We demonstrated a comprehensive and versatile approach for reducing propagation loss in WES polymer fibers by heating the fibers above the glass transition temperature of PDLLA. This heat treatment significantly reduced the propagation loss in amorphous WES PDLLA fibers from 17.0 to 8.1 dB cm\(^{-1}\) at a wavelength of 533 nm. The propagation loss reduction could be attributed to the reduction of extrinsic excess scattering losses due to the extrinsic density inhomogeneity in the fibers. These findings pave the way for low-loss WES fiber waveguides and their application in small, flexible optical fiber devices such as waveguides, sensors, and lasers.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

**Notes**

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