Advances in Disordered Transverse Anderson Localizing Optical Fibers

Arash Mafi\textsuperscript{1,*}, Matthew Tuggle\textsuperscript{2}, Cody Bassett\textsuperscript{1}, Esmaeil Mobini\textsuperscript{1}, and John Ballato\textsuperscript{1}

\textsuperscript{1}Center for High Technology Materials (CHTM) and the Department of Physics \& Astronomy, University of New Mexico, Albuquerque, NM 87131, USA

\textsuperscript{2}Center for Optical Materials Science and Engineering Technologies (COMSET) and the Department of Materials Science and Engineering, Clemson University, Clemson, SC 29625, USA

Disordered transverse Anderson localizing optical fibers have shown great promise in various applications from image transport to random lasing. Their success is due to their novel waveguiding behavior, which is enabled by the transverse Anderson localization of light. The strong transverse scattering from the transversely disordered refractive index structure results in transversely confined modes that can freely propagate in the longitudinal direction. Therefore, these fibers behave like large-core highly multimode optical fibers, with the peculiar property that most modes are highly localized. This property makes them ideal for such applications as image transport and spatial beam multiplexing. In this review paper, we will explore some of the recent advances in these fibers, especially those related to the material structure and fabrication methods.

I. INTRODUCTION

Transverse Anderson localizing optical fibers (TALOF)\textsuperscript{1} are a novel class of optical fibers that guide light, not in a conventional core-cladding setting, but using the Transverse Anderson localization (TAL), where any location across the transverse profile of the fiber can be used to guide light. Anderson localization (AL) is the absence of diffusive wave transport in highly disordered scattering media\textsuperscript{2–4} and is broadly applicable to quantum and classical waves\textsuperscript{5–18}. Transverse Anderson localization (TAL), which is essentially AL in a transversely disordered and longitudinally invariant optical system, was first proposed in a pair of visionary theoretical papers by Abdullaev et al.\textsuperscript{19} in 1980 and De Raedt et al.\textsuperscript{20} in 1989. In TAL structures, the dielectric constant is uniform along the direction of the propagation of light, similar to a conventional optical waveguide, and the disorder in the dielectric constant resides in the (one or two) transverse dimension(s). An optical field that is launched in a TAL structure undergoes a brief expansion in the transverse dimension(s) as it propagates freely in the longitudinal direction; however, the strong transverse scattering eventually halts the expansion, and the transversely localized field propagates along the structures just like a conventional optical waveguide\textsuperscript{18}.

TAL is ubiquitous in unbounded transversely disordered optical structures; however, to observe TAL for finite transverse size (similar to conventional optical fibers), the scattering due to the disorder must be sufficiently strong such that the transverse physical dimensions of the waveguide are larger than the transverse localization length. Of course, it is assumed that the waveguide is uniform in the longitudinal direction. Over the years, several experiments have successfully observed TAL, the earliest of which are by Schwartz et al.\textsuperscript{21} in a photorefractive crystal, and by Lahini et al.\textsuperscript{22} in a one-dimensional (1D) lattice of coupled optical waveguides patterned on an AlGaAs substrate. In this paper, we will briefly review the development of TALOFs and outline the best practices regarding the choice of materials and microstructures that can facilitate specific applications. Discussions on the applications of TALOFs, especially for imaging and random lasing can be found in Refs.\textsuperscript{18, 23–25} and will also be discussed briefly here.

The TALOF designs are mainly based on the structure proposed by De Raedt et al.\textsuperscript{20}, which is sketched in Fig.\textsuperscript{1}. The optical medium in Fig.\textsuperscript{1} consists of an optical fiber-like structure, whose refractive index profile is invariant in the longitudinal direction. In the transverse plane, the refractive index is pixelated into tiny squares, where the refractive index of each pixel is randomly selected to be $n_1$ or $n_2$ with equal probabilities. The edge length of each square is on the order of the wavelength of the light. De Raedt et al. showed that an optical field that is launched in the longitudinal direction remains localized in the transverse plane due to the transverse scattering, as it propagates freely in the longitudinal direction. The localization radius can be generally reduced by increasing the transverse scattering strengths, which is an increasing function of the refractive index contrast $\Delta n = |n_2 - n_1|$\textsuperscript{18–20, 26}.

II. TRANSVERSE ANDERSON LOCALIZING OPTICAL FIBERS: EXISTING DESIGNS

The first demonstration of TAL in an optical fiber was reported in 2012 by Karbasi et al.\textsuperscript{1}. The TALOF is shown in Fig.\textsuperscript{2}a)—it was fabricated by the stack-and-draw method from a low-index component, polymethyl methacrylate (PMMA) with a refractive index of 1.49, and a high-index component, polystyrene (PS) with a refractive index of 1.59 ($\Delta n = 0.1$). 40,000 pieces of PMMA and 40,000 pieces of PS fibers were randomly mixed\textsuperscript{27}, fused together, and redrawn to a fiber with a nearly square profile and approximate side-width of...
FIG. 1. A conceptual sketch of the longitudinally invariant and transversely random dielectric waveguide is shown. This structure which was proposed by De Raedt et al. [20] is the basis of TALOFs discussed in this paper. In the transverse plane, the refractive index is pixelated into tiny squares, and the refractive index of each pixel is randomly selected to be $n_1$ or $n_2$ with equal probabilities.

250 $\mu$m. Figure 2(b) shows the zoomed-in scanning electron microscope (SEM) image of an approximately 24$\mu$m-wide region on the tip of the fiber after exposing the tip to an ethanol solvent to dissolve the PMMA. The typical random feature size in the structure shown in Fig. 2(b) is around 0.9 $\mu$m. The TALOF was subsequently used for detailed studies of TAL [26], spatial beam multiplexing [28], and image transport [24].

The first successful fabrication of a silica TALOF was reported by Karbasi et al. [29] in 2012. The glass-air disordered fiber was drawn at Clemson University from “satin quartz” (Heraeus Quartz) which is a porous artisan glass. The starting rod had dimensions of 8 mm in diameter and 850 mm in length and was drawn at a temperature of 1890°C to a fiber with the diameter of 250 $\mu$m. The cross-sectional SEM image of this fiber is shown in Fig. 2(c), and a zoomed-in SEM image is shown in Fig. 2(d). The light-gray background matrix is glass, and the random black dots represent the airholes, where the diameters of the airholes vary between 0.2 $\mu$m and 5.5 $\mu$m. Although the air-glass design with $n_1 = 1.0$ and $n_2 = 1.46$ ($\Delta n = 0.46$) led to a sharp index contrast and consequently a strong transverse scattering, the fill-fraction of the airholes in this fiber ranged from nearly 2% in the center of the fiber to approximately 7% near the edges; therefore, TAL was only observed near the periphery of the fiber. This fiber was subsequently used for the first observation of random lasing in a TALOF [25].

In 2014, there was another successful attempt in observing TAL in an air-glass optical fiber by Chen and Li [30] at Corning Incorporated. They fabricated random air-line fibers using the outside vapor deposition process by first creating a pure silica soot blank by soot deposition in laydown process. After laydown, the silica soot blank was chlorine dried first at 1125°C for one hour in a consolidation furnace. Then the blank was consolidated at 1490°C in the presence of 100% $N_2$. During the sintering process, $N_2$ was trapped in the blank to form glass with randomly distributed air bubbles. The random air bubbles were subsequently drawn into random airlines when the preform was drawn to three fiber samples with approximately 150, 250 and 350 $\mu$m diameters. The airline diameters ranged from 0.18 $\mu$m to 0.39 $\mu$m depending on the fiber diameter, and the air-fill fraction was measured to be around 1%, which is a significantly lower air fill-fraction than those reported in Ref. [29]. However, the authors reported the successful observation of TAL. This can be attributed to the far-subwavelength size of the transverse scattering centers and the higher scatterer density (air-line density) compared to Ref. [29].

Recently in 2018, Zhao et al. [31, 32] at CREOL, University of Central Florida, reported a glass-air TALOF that was fabricated using the stack-and-draw technique. They randomly mixed thousands of silica capillaries with different diameters and airhole diameters and assembled them in a jacket tube to make the preforms. Subsequently, fibers were drawn to desired diameters. For example, they reported drawing a fiber with the inner diameter of the randomly disordered region at 278 $\mu$m, and the outer diameter of 414 $\mu$m. The air-filling fraction was about 28.5% and the air-hole areas ranged from...
0.64 \mu m^2 to over 100 \mu m^2, with 2.5 \mu m^2 being the peak of the statistical distribution. The fiber was used for the first successful report of high-quality optical image transfer through a 90 cm-long TALOF. In a more recent attempt, Zhao et al. [33] applied deep learning techniques to improve the quality of the image transport in these fibers.

Another successful demonstration of TALOFs was reported in 2019 by Tuan et al. [34] from the Toyota Technological Institute in Japan. This effort is notable for two reasons: first, it is an all-solid structure, so two species of glass are used to create the random structure; and second, the fabrication is based on tellurite optical glasses for applications in near-infrared image transport. To avoid undesirable stresses and cracks during the drawing process, Tuan et al. developed two tellurite glasses with high compatibility in thermal and mechanical properties. The two tellurite glasses were made of TeO_2, Li_2O, WO_3, MoO_3, Nb_2O_5 (TLWMN) and TeO_2, ZnO, Na_2O, La_2O_3 (TZN) with the refractive index contrast of \Delta n = 0.095. TLWMN and TZN glass rods were drawn down at 440 \degree C to fibers whose diameters were 100 \mu m using a home-designed fiber drawing tower. In total, 5000 fiber segments of each TLWMN and TZN glasses were obtained. The 15 cm long segments were randomly stacked with a 50-50 ratio in a TZN cladding tube whose inner and outer diameters were 10 and 12 mm, respectively. The fiber was finally drawn to an all-solid TALOF with the outer diameter of 125 \mu m, where the random pixel size was approximately 1.0 \mu m. The all-solid tellurite-glass TALOF was successfully used to transport the optical image of three vertical slits, with the slit-width as small as 14 \mu m, over the wavelength range of 1.44-1.60 \mu m. The images transported over a 10 cm length with high contrast and high brightness.

Finally, we would like to highlight some of on-going as well as past work on phase-separated glasses. The work led by Thomas P Seward III of Corning Incorporated in the 1970s on phase-separated glasses resulted in random elongated needle-like structures after drawing [35, 36]. The fiber-like glass rods were successfully used for image transport and most likely operated based on the TAL principles. More recently, Ballato’s group at Clemson University has been studying optical fibers that exhibit phase separation during the draw process; i.e., the compounds comprising the core exhibit liquid-liquid immiscibility and undergo phase separation in-situ during fiber formation. More specifically, the molten core method [37] has been used whereby the initial core phase is selected such that it is molten at the temperature where the cladding glass softens and draws into fiber. As an example, the rare-earth oxide-silica (RE_2O_3-SiO_2) system is well known to exhibit liquid-liquid immiscibility at high SiO_2 contents. During the fiber draw, silica from the cladding is dissolved by the molten core and becomes incorporated into the core material, forming a silicate melt. Thereby the core composition shifts to higher silica concentrations, oftentimes within the liquid-liquid immiscibility dome, leading directly to a phase separated core that is quenched into a solid when the fiber cools.

### III. FUTURE DIRECTIONS AND CONCLUSIONS

Disordered TALOFs demonstrate many novel physical properties, mainly because they allow for localized beam transport at any location across the entire cross section of the optical fiber. In general, it is desirable for these fibers to be designed for the smallest average localized beam diameter. It has been noted that the statistical distribution of the localized beam diameters in TALOFs follows a nearly Poisson-like distribution [23, 29, 35, 39, 40]. Therefore, any attempt in reducing the average mode field diameter also reduces the mode-to-mode diameter variations and results in a more uniform behavior across the fiber cross section. A smaller mode field diameter requires a stronger transverse scattering, which is achieved by a higher index contrast, \Delta n, as well as a judicious choice of the random pixel size. The successful experiments using TALOFs have so far been based on \Delta n \geq 0.1, consistent with the analysis reported in Ref. [26]. Of course, strongest transverse scattering is achieved for a 50-50 ratio in the design proposed by De Raedt et al. [20]. There has been some unsettled questions and uncertainties regarding a judicious choice of the random pixel size [23, 39, 40]. Those designs that target the pixel size to be around half the free-space wavelength, at least for \Delta n \approx 0.1 – 0.5, seem to be successful. Of course, in structures that somewhat deviate from that of De Raedt et al. such as the air-glass optical fiber by Chen and Li [30], the rules of design are likely different and must be studied in detail using appropriate statistical methods [35, 39].

As efforts are made to improve the understanding and design of the transverse microstructure of TALOFs, it is important to improve the longitudinal invariance in such fibers to reduce the attenuation. The attenuation for the initial polymer TALOFs by Karbasi et al. [1] were in the range of 0.1-1.0 dB/cm. This relatively large attenuation was caused primarily by the exposure of the preliminary fibers in the stack-and-draw procedure to room dust during the random mixing process over 3 weeks. Also, the longest piece in which TAL was observed was a 60 cm segment, because the fiber thickness varied substantially over the length-scale of one meter or less. Improved attenuation was reported in glass fibers; e.g., Ref. [30] reported 0.4 dB/m at 1550 nm wavelength, and Ref. [31] reported 1 dB/m at visible wavelengths. TALOFs have shown great potential in many applications including in beam multiplexing [28], image transport [23, 32, 34], wave-front shaping and sharp focusing [11], nonlocal nonlinear behavior [42, 43], single-photon data packing [44], and random lasers [25]. Future progress will improve TALOF specifications for these applications and will open new venues for TALOFs to be
utilized.

FUNDING

National Science Foundation (NSF) (1807857) and (1808232).

[1] S. Karbasi, C. R. Mirr, P. G. Yarandi, R. J. Frazier, K. W. Koch, and A. Mafi, “Observation of transverse Anderson localization in an optical fiber,” Opt. Lett. 37, 2304–2306 (2012).
[2] P. W. Anderson, “Absence of diffusion in certain random lattices,” Phys. Rev. 109, 1492–1505 (1958).
[3] A. Lagendijk, B. van Tiggelen, and D. S. Wiersma, “Fifty-years of Anderson localization,” Physics Today 62, 24–29 (2009).
[4] P. Sheng, Introduction to wave scattering, localization and mesoscopic phenomena (Springer-Verlag, Berlin, Germany, 2006), 2nd ed.
[5] C. M. Soukoulis and E. N. Economou, “Electronic localization in disordered systems,” Waves in Random Media 9, 255–269 (1999).
[6] J. Billy, V. Josse, Z. Zuo, A. Bernard, B. Hambrecht, P. Lugan, D. Clément, L. Sanchez-Palencia, P. Bouyer, and A. Aspect, “Direct observation of Anderson localization of matter waves in a controlled disorder,” Nature 453, 891–894 (2008).
[7] Y. Lahini, Y. Bromberg, D. N. Christodoulides, and Y. Silberberg, “Quantum correlations in two-particle Anderson localization,” Phys. Rev. Lett. 105, 163905 (2010).
[8] A. F. Abouraddy, G. Di Giuseppe, D. N. Christodoulides, and B. E. A. Saleh, “Anderson localization and colocalization of spatially entangled photons,” Phys. Rev. A 86, 040302 (2012).
[9] R. Weaver, “Anderson localization of ultrasound,” Wave Motion 12, 129–142 (1990).
[10] I. S. Graham, L. Piché, and M. Grant, “Experimental evidence for localization of acoustic waves in three dimensions,” Phys. Rev. Lett. 64, 3135–3138 (1990).
[11] H. Hu, A. Stryblevych, J. H. Page, S. E. Skipetrov, and B. A. van Tiggelen, “Localization of ultrasound in a three-dimensional elastic network,” Nat. Phys. 4, 945–948 (2008).
[12] S. John, “Electromagnetic absorption in a disordered medium near a photon mobility edge,” Phys. Rev. Lett. 53, 2169–2172 (1984).
[13] A. A. Chabanov, M. Stoytchev, A. Z. Genack, “Statistical signatures of photon localization,” Nature 404, 850–853 (2000).
[14] R. G. S. El-Dardiry, S. Faez, and A. Lagendijk, “Snapshots of Anderson localization beyond the ensemble average,” Phys. Rev. B 86, 125132 (2012).
[15] P. W. Anderson, “The question of classical localization a theory of white paint?” Philos. Mag. B 52, 505–509 (1985).
[16] S. John, “Localization of light,” Phys. Today 44, 32–40 (1991).
[17] Y. S. Mordechai Segev and D. N. Christodoulides, “Anderson localization of light,” Nat. Photonics 7, 197–204 (2013).
[18] A. Mafi, “Transverse Anderson localization of light: a tutorial,” Adv. Opt. Photon. 7, 459–515 (2015).
[19] S. S. Abdullaev and F. K. Abdullaev, “On propagation of light in fiber bundles with random parameters,” Radiofizika 23, 766–767 (1980).
[20] K. W. Koch, and A. Mafi, “Observation of transverse Anderson localization of light in disordered optical fibers,” Opt. Lett. 453, 2169–2172 (1984).
[21] S. Karbasi, T. Hawkins, J. Ballato, and A. Mafi, “Image transport through a disordered optical fibre mediated by transverse Anderson localization,” Nat Commun 5 (2014).
[22] B. Abaie, E. Mobini, S. Karbasi, T. Hawkins, J. Ballato, and A. Mafi, “Random lasing in an Anderson localizing optical fiber,” Light Sci. Appl. 6 (2017).
[23] S. Karbasi, C. R. Mirr, R. J. Frazier, P. G. Yarandi, K. W. Koch, and A. Mafi, “Detailed investigation of the impact of the fiber design parameters on the transverse Anderson localization of light in disordered optical fibers,” Opt. Express 20, 18692–18706 (2012).
[24] S. Karbasi, R. J. Frazier, C. R. Mirr, K. W. Koch, and A. Mafi, “Fabrication and characterization of disordered polymer fibers for transverse Anderson localization of light,” J. Vis. Exp. 77, e50679 (2013).
[25] S. Karbasi, K. W. Koch, and A. Mafi, “Multiple-beam propagation in an Anderson localized optical fiber,” Opt. Express 21, 305–313 (2013).
[26] S. Karbasi, T. Hawkins, J. Ballato, K. W. Koch, and A. Mafi, “Transverse Anderson localization in a disordered glass optical fiber,” Opt. Mater. Express 2, 1496–1503 (2012).
[27] M. Chen and M.-J. Li, “Observing transverse Anderson localization in random air line based fiber,” in Photonic and Phononic Properties of Engineered Nanostructures IV, vol. 8904 (International Society for Optics and Photonics, 2014), p. 89941S.
[28] J. Zhao, J. E. Antonio-Lopez, R. A. Correa, A. Mafi, M. Windeck, and A. Schülzgen, “Image transport
through silica-air random core optical fiber,” in Conference on Lasers and Electro-Optics, (Optical Society of America, 2017), p. JTu5A.91.

[32] J. Zhao, J. E. A. Lopez, Z. Zhu, D. Zheng, S. Pang, R. A. Correa, and A. Schülzgen, “Image transport through meter-long randomly disordered silica-air optical fiber,” Sci. Rep. 8, 3065 (2018).

[33] J. Zhao, Y. Sun, Z. Zhu, J. E. Antonio-Lopez, R. A. Correa, S. Pang, and A. Schulzgen, “Deep learning imaging through fully-flexible glass-air disordered fiber,” ACS Photonics 5, 3930–3935 (2018).

[34] H. T. Tong, S. Kuroyanagi, K. Nagasaka, T. Suzuki, and Y. Ohishi, “Characterization of an all-solid disordered tellurite glass optical fiber and its near-infrared optical image transport,” Jpn. J. Appl. Phys. (2018).

[35] T. P. Seward III, “Elongation and spheroidization of phase-separated particles in glass,” J. Non-Cryst. Solids 15, 487–504 (1974).

[36] T. Seward III, “Some unusual optical properties of elongated phases in glasses,” The Physics of Non-Crystalline Solids; Trans Tech Publications: Aedermannsdorf, Switzerland pp. 342–347 (1977).

[37] J. Ballato and P. Dragic, “Rethinking optical fiber: New demands, old glasses,” Journal of the American Ceramic Society 96, 2675–2692 (2013).

[38] B. Abaie and A. Mafi, “Scaling analysis of transverse Anderson localization in a disordered optical waveguide,” Phys. Rev. B 94, 064201 (2016).

[39] B. Abaie and A. Mafi, “Modal area statistics for transverse Anderson localization in disordered optical fibers,” Opt. Lett. 43, 3834–3837 (2018).

[40] W. Schirmacher, B. Abaie, A. Mafi, G. Ruocco, and M. Leonetti, “What is the right theory for Anderson localization of light? an experimental test,” Phys. Rev. Lett. 120, 067401 (2018).

[41] M. Leonetti, S. Karbasi, A. Mafi, and C. Conti, “Light focusing in the Anderson regime,” Nat. Commun. 5 (2014).

[42] M. Leonetti, S. Karbasi, A. Mafi, and C. Conti, “Observation of migrating transverse Anderson localizations of light in nonlocal media,” Phys. Rev. Lett. 112, 193902 (2014).

[43] Leonetti, Marco and Karbasi, Salman and Mafi, Arash and Conti, Claudio, “Experimental observation of disorder induced self-focusing in optical fibers,” Appl. Phys. Lett. 105, 171102 (2014).

[44] M. Leonetti, S. Karbasi, A. Mafi, E. DelRe, and C. Conti, “Secure information transport by transverse localization of light,” Sci. Rep. 6 (2016).