Image Transport Through Meter-Long Silica-Air Disordered Optical Fiber

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Abstract: Robust optical image transport through 90cm-long low-loss silica-air disordered fiber is reported for the first time. Transverse Anderson localization is confirmed by propagating a 405nm laser beam through the disordered optical fiber.

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1. Introduction

Transverse Anderson localization (TAL) of light was observed experimentally by Schwartz *et al*. in 2007 [1]. Since then considerable attention has been paid to develop device applications that benefit from TAL in waveguide structures. In 2012, TAL was confirmed in polymer random fiber [2], and this type of polymer random fiber was demonstrated to transport image successfully in 2014 [3]. The quality of the transported images was found to be comparable to or even better than some of the best commercial multicore imaging fibers [3] indicating great potential for applications such as endoscopy. However, the small refractive index contrast (~0.1) between the two materials inside the random polymer fiber is a barrier to reducing beam localization radius, which limits the image resolution [3]. There was also a rather large signal attenuation in the polymer fiber limiting the image transmission distance to a few centimeters. This is an important aspect, since for most applications longer image transmission distances are desired, and, therefore, materials with low signal attenuation are required. Due to the high refractive index contrast and low loss, glass-air random fibers with about 50% air-hole-fill-fraction were proposed as potential solution [3]. Although previous attempts in glass-air random fiber were reported [4,5], it still remains a challenge to demonstrate small beam localization radii and any image transport most likely due to low air-hole-fill-fraction (<8%) in this first generation glass-air random fibers.

In this work, we fabricated a glass-air random fiber (GARF) with high air-hole-fill-fraction (~28.5%) in the core with 278 μm diameter and low attenuation below 1 dB per meter. TAL is observed by sending a small diameter Gaussian probe beam into the GARF. Robust image transport through a 90cm-long GARF is demonstrated, and the spatial resolution of the GARF image transmission is quantified.

2. Experiment and Results

The GARF was fabricated at CREOL using fused-silica rods and tubes and the well-known stack-and-draw method. A SEM image of the GARF cross-section is shown in Fig. 1(a). The outer diameter of fused silica fiber cladding is 414 μm and the diameter of the random core is 278 μm. The air-hole-fill-fraction in the random core is 28.5%. The air hole feature sizes range from 0.8μm to over 10 μm with a maximum in the air hole size distribution around 1.6μm.

To observe TAL, a laser beam from a 405nm laser diode delivered by single mode fiber S405-XP (Thorlabs) is butt-coupled to a 4.5cm-long GARF. The output beam profile is imaged onto a CCD camera by a 20x microscope objective. By launching beams into different positions of the GARF core, strong transverse Anderson localization is demonstrated at both near center and off-center positions of the random core by output intensity spots with widths well below 10 μm FWHM. Near-field intensity distributions and the corresponding intensity profiles are shown in Fig. 1 (b) to (e).

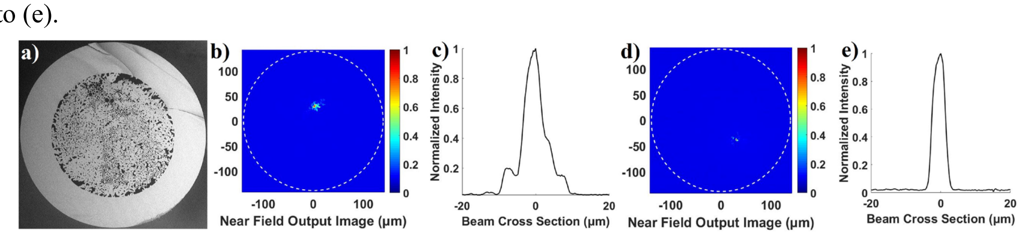

Fig. 1. a) SEM cross-section image of CREOL's GARF with a random core diameter of 278μm and 414μm outer diameter. b) and d) Near-field intensity measurement at the output facet of the GARF for two different launch positions. c) and e) The corresponding intensity profile cross sections of the respective localized beam.

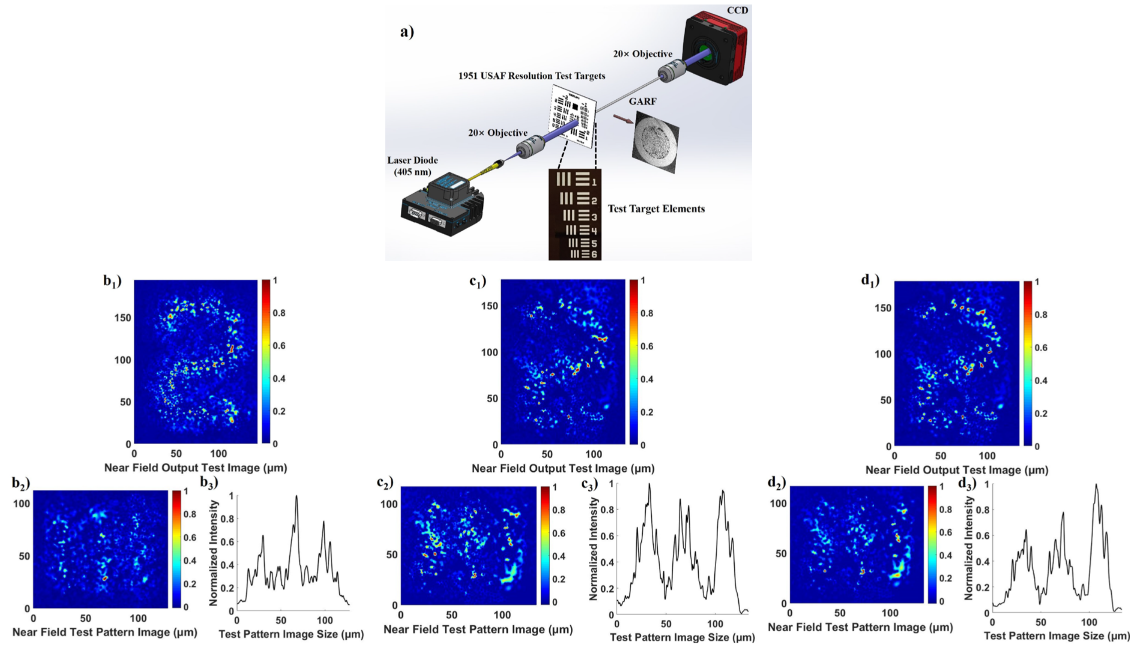

Fig. 2. a) Schematic of the image transport experimental setup. b1)-b3) show transmission through a 4.5 cm straight GARF sample; c1)-c3) show transmission through a 90cm straight GARF sample; d1)-d3) show transmission through the same 90cm sample that has been bent to a 20cm radius of curvature. b1), c1) and d1) are near field intensity profiles at the GARF output facet, when number 2 in group 3 is illuminated at the fiber input; b2), c2) and d2) demonstrate the maximum spatial resolution for each case. b2) is near field intensity profile of 3 lines with 17.54μm width and b3) is corresponding intensity cross section. c2) and d2) are near field intensity profiles of 3 lines with 19.69μm width, and c3) and d3) are corresponding intensity cross sections.

To demonstrate image transmission, a 1951 USAF resolution test target is placed directly in front of the cleaved input facet of the GARF as shown in Fig. 2a. Various elements of the resolution target are then illuminated by a collimated beam from a 405nm laser diode. The output facet of the GARF is imaged onto a CCD camera by a 20x microscope objective. In any case, the transmitted image has the same size as the illuminated original target element and can be clearly identified even after propagation through 90 cm of GARF (Fig. 2c1) and after bending the GARF with a 20 cm radius (Fig. 2d1). The maximum resolution studied by illuminating 3 bars of various widths, can reach ~17 μm for few-cm GARF segments but is only slightly lower (~20 μm) for an almost 1 m long GARF segments (see Fig. 2 (b2, b3) and (c2,c3)). This slight loss in resolution also results in a slight reduction in image quality, visible by comparing Figs. 2b1 with 2c1, and might be attributed to slight variation of fiber dimension and cross-section along the GARF. However, the transmitted number can still be clearly identified, and the maximum resolution remains high. Even when the 90cm long GARF is tightly bent to a 20 cm radius of curvature (see Fig. 2d), the transmitted image and maximum resolution remain unchanged, illustrating strong TAL in this GARF. This kind of bending-independent characteristics can be related to the single mode nature of the localized states in disordered fibers [6].

3. Conclusion

In conclusion, we have fabricated fiber with glass-air disordered core structure and high air-hole-fill-fractions. We demonstrated strong transverse Anderson localization. Bend-independent image transport has been demonstrated for the first time through meter-long disordered segments with a maximum resolution below 20 μm. Our results highlight the potential of random glass-air fibers for flexible endoscopic imaging system.

4. References

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