Cleaving of Extremely Porous Polymer Fibers

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Abstract: Different cleaving techniques, based on the use of a semiconductor dicing saw, focused-ion-beam milling, and a 193-nm ultraviolet laser, have been exploited to cleave highly porous polymer fibers developed for guiding terahertz radiation. Porous fibers made up of two different polymer materials have been cleaved with the proposed methods and compared with those achieved from the conventional cleaving method. Regardless of the polymer material used for fabricating terahertz porous fibers, using an ultraviolet laser for cleaving and rotating the fiber during the process rapidly provides smooth and reproducible cleaves across the entire fiber cross section.

Index Terms: Waveguides, subwavelength structures, terahertz, excimer laser.

1. Introduction

In recent years, there has been increased interest in low-loss and low-dispersion terahertz waveguides as potential substitutes for free-space optics in terahertz spectroscopy and imaging systems. A number of waveguide solutions based on technologies from both microwave and optics, as reviewed in [1], have been studied. The metal- and dielectric-based waveguide solutions suffer from high losses due to the finite conductivity of the metals and high absorption coefficient of dielectrics, respectively. Polymers are the common material being used for fabrication of the terahertz fibers due to their low-material loss and -dispersion characteristics in the terahertz regime [2]. Recently, porous fibers have been identified as a means of achieving low losses, low dispersion and high birefringence among terahertz polymer fibers. Porous fibers are air-clad fibers with subwavelength features in the core [1], [3]. Compared with solid-core air-clad fibers, referred to as microwires [2], porous fibers offer better confinement and lower dispersion and can be designed to maintain the polarization of the field by using asymmetrical subwavelength air holes [4]. Two types of porous fibers, i.e., symmetrical and asymmetrical porous fibers, have been fabricated [4]. The low-dispersion characteristics of these porous fibers compared with their microwire counterparts and the birefringence characteristics have experimentally been confirmed [5]. It was identified that the quality and repeatability of the cleaved end-face of the porous fibers introduces uncertainty in the loss measurements [5]. Thus, for loss measurements, either a rapid, reproducible, and *in situ* cleaving method is required to conduct a cut-back-based loss measurement, or methods such as the directional coupler [6], where no cleaving of the fiber is necessary, will be required.

The polymer porous fibers are mechanically soft thus they are easily squashed and deformed by using conventional cleaving blades as discussed in [5]. This can be avoided if there are glass materials available for the terahertz region with low absorption coefficient characteristics; however, there are no known suitable glasses presently available.

To improve the cleaved end-face results of polymer optical fibers, the impact of different parameters such as magnitude of the stress due to the force [7] and crack depth [8] have been studied. The process of cleaving becomes more delicate when the polymer optical fiber has structures especially with high air-filling factor.

For microstructured polymer optical fibers with relatively low air fraction, it has been shown by Law *et al.* [9], [10] that heating up the cleaving blade and the fiber to 70 °C–80 °C improves the cleaved end-face of the optical fibers. However, we find that this approach does not improve the cleave quality for high-air-fraction terahertz porous fibers. We have observed that the structure becomes deformed, especially the outer ring, because of high porosity and missing the outer solid region as in optical microstructured fibers [5]. Furthermore, the quality of the cleaved end-face of the porous fibers varies from cleave to cleave by using a conventional blade for cleaving, which introduces significant variations in the coupling into these fibers as well as a large error in the loss measurements for such fibers. Hence, it is important to develop a method for repeatable, high quality, and rapid cleaving of these porous fibers.

In this paper, different cleaving methods, including a semiconductor dicing (SD) saw, focused-ion-beam (FIB) milling, and a 193-nm ultraviolet (UV) laser, have been studied for terahertz porous fibers. For each method, different parameters have been considered to find the optimum cleaving conditions (cleaving quality and time). The optimized cleaving parameters for each method are explained in corresponding sections. It should be noted that the UV laser cleaving has been used by Canning *et al.* for comparatively low-air-fraction microstructured polymer optical fibers with an outer solid region [11]. This is the first time that this method is being used for the cleaving of extremely porous polymer fibers, i.e., fibers that have no outer solid region.

2. Porous Fiber Cleaving

The cleaving of two types of terahertz porous fibers are investigated in this paper: spider-web and rectangular porous fibers. The scanning electron microscope (SEM) images of the cross section of these fibers, for which we have used SD sawing described in the following section, is shown in Fig. 1(a) and (b). The polymer materials used for the fabrication of porous fibers are polymethyl methacrylate (PMMA) and cyclic olefin copolymer (TOPAS) [12]. Three different techniques employing an SD saw, FIB milling, and a UV laser have been investigated to cleave these porous fibers.

2.1. SD Saw

In this approach, a silicon blade, with the width of 40–50 μm and exposure of 1.02–1.15 mm, was used to cleave the PMMA and TOPAS porous fibers. The dicing process is carried out in water and spindle rotation speed is 30 000 rev/min. The fibers need to be fixed firmly on a surface to prevent any damage and tearing during the dicing process. Typically, the fibers can be fixed firmly to a wafer frame with a dicing tape. However, there is a high possibility of damaging the fiber during the fixing and/or releasing process. Hence, we laid the fibers on a clear UV tape with 120-μm thickness. The tape has strong adhesive characteristics, and there is no need to sandwich the fiber between the tape and substrate. To release the adhesive, the tape needs to be exposed to UV radiation for at least 5 minutes. The SEM images of the resulting cross section of the diced PMMA and TOPAS spider-web and rectangular porous fibers are shown in Fig. 1(a)–(d), respectively. As can be seen, for the PMMA porous fibers, the cross section is well maintained. Moreover, one can observe that the end-face is chipped along the direction of the cleave, which is more pronounced for the spider-web

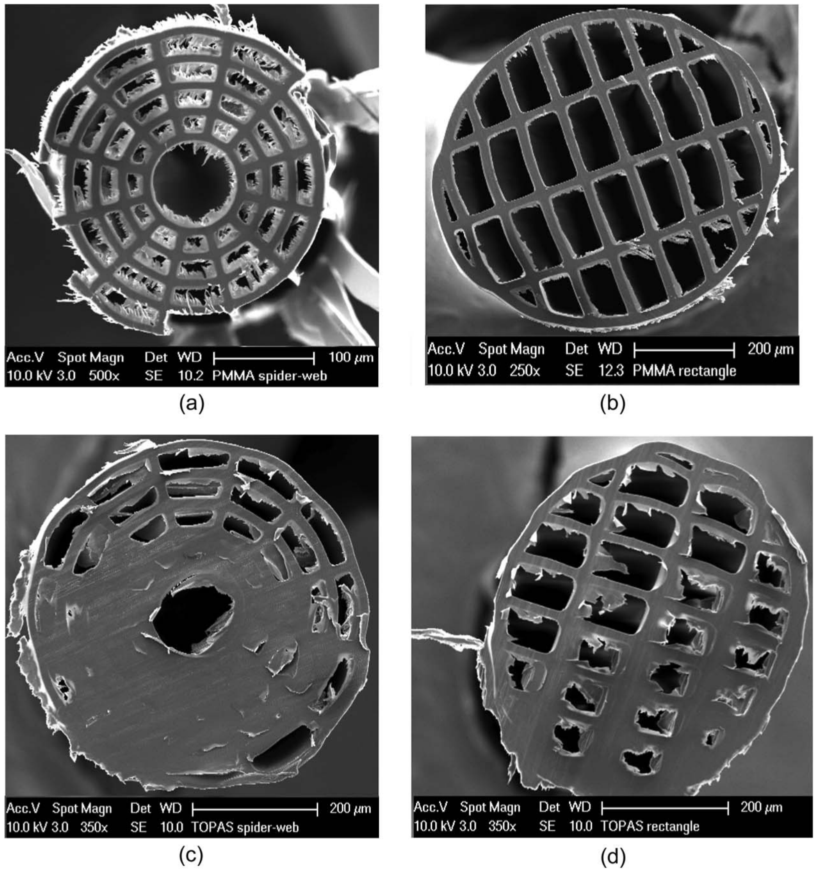

Fig. 1. SEM images of cleaved end-face of fibers cleaved using a SD saw. (a) PMMA spider-web, (b) PMMA rectangular, (c) TOPAS spider-web, and (d) TOPAS rectangular air-hole porous fibers.

porous fiber. Furthermore, the missing outer ring of spider-web porous fiber [see Fig. 1(a)] is where the blade touches the fiber and is due to the blade tearing the material. It is worth highlighting that among all the cleaving trials there was no tearing of outer ring for rectangular porous fibers. This shows that the mechanical stability of the rectangular porous fiber is better, compared with that of the spider-web porous fiber.

For the TOPAS porous fibers as seen in Fig. 1(c) and (d), the material has been smeared on the cleaved end-face due to the grinding action of the blade. TOPAS has a glass transition temperature 78 °C, which is 20 °C–25 °C less than PMMA. Reducing the spindle rotation speed will lessen smearing of the structure. However, for such soft polymer the friction between the material clogged in the blade's grit and the fiber will result in smearing the cross section regardless of the speed. Therefore, using the SD saw is not a suitable cleaving option for TOPAS porous fibers.

It takes on average 30s to cleave a porous fiber with 400-μm diameter and further 10-minute exposure to UV radiation to remove the fiber from the tape without damaging the outer ring of the fiber. The UV radiation source used here, is an in-house-built UV light box. As mentioned earlier, the dicing process is carried out in water—this requires later annealing to remove water in the structure. While, in principle, the fiber end-tip can be polished to improve the facet quality, polishing is undesirable because it would contaminate the subwavelength air holes within these porous fibers, which would lead to scattering loss. Moreover, these fibers are relatively fragile, and the extra handling of the fiber during the polishing process is undesirable. Bearing in mind that a rapid and quick cleaving approach is essential not only for loss measurements, but for any other practical applications of the fibers as well, using an SD saw is not the best cleaving option.

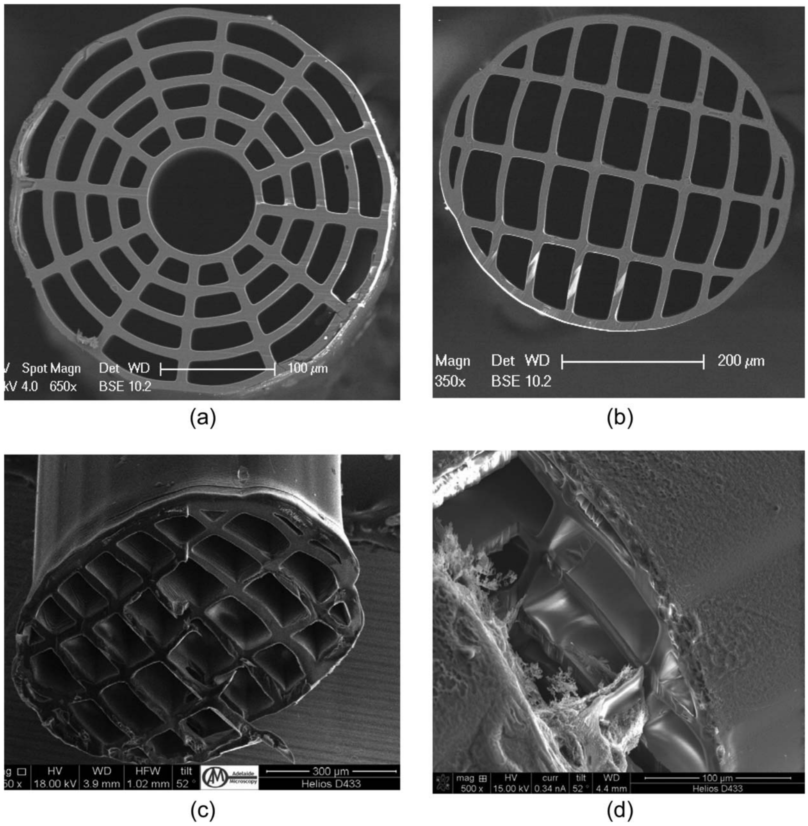

Fig. 2. SEM images of cleaved end-face of fibers using FIB milling. PMMA (a) Spider-web and (b) rectangular air-hole porous fibers, after [5]. Trial cleaves of TOPAS rectangular air-hole porous fiber with an ion beam current of (c) 21 nA and (d) 0.34 nA.

2.2. FIB Milling

In this method, gallium (Ga) ions are accelerated to an energy of 30 keV and then focused onto a sample. The SEM images of the resulting cross section of the FIB cleaved PMMA spider-web and rectangular porous fibers are shown in Fig. 2(a) and (b), respectively [5]. Although this method provides fibers with undistorted end-face results, the cleaving time of a porous fiber with 400-μm diameter is about 17.5 hours with an ion beam current of 21 nA. Using FIB milling to cleave TOPAS porous fibers failed for the following reasons. First, due to the lower glass transition temperature of TOPAS, applying the same conditions bulge and deform the cross section of the fiber as shown in Fig. 2(c). Second, decreasing the ion beam current to lower values such as 9.5 nA and 0.34 nA, takes 24 h to cleave a quarter of the structure as shown in Fig. 2(d). With the FIB milling technique, there is a deposition of ions on the fiber tips. Further investigations are required to study the effects of deposited ions on the performance of the fibers. Moreover, there is a limitation in the length of the fiber. The fiber should be wound around a spool that fits in the machine if longer lengths of fiber are required.

2.3. UV 193-nm Laser

In this method, we used a 193-nm UV laser to cleave the porous fibers. Earlier work by Lippert *et al.* [13] and Canning *et al.* [11] have shown that the ablation of polymers require wavelengths less than 308 nm and that a 193-nm UV laser is the standard and direct structuring tool for polymers. Thus, an Argon–Fluoride (ArF) exciplex laser with 0–200-Hz repetition rate, 0–100-mJ pulse energy, and a 20-ns pulse width is used. The laser central wavelength is 193 nm, and the beam size is approximately 10×10 mm^2. For the laser cleaving, a cylindrical lens with the focal length of 15 cm is

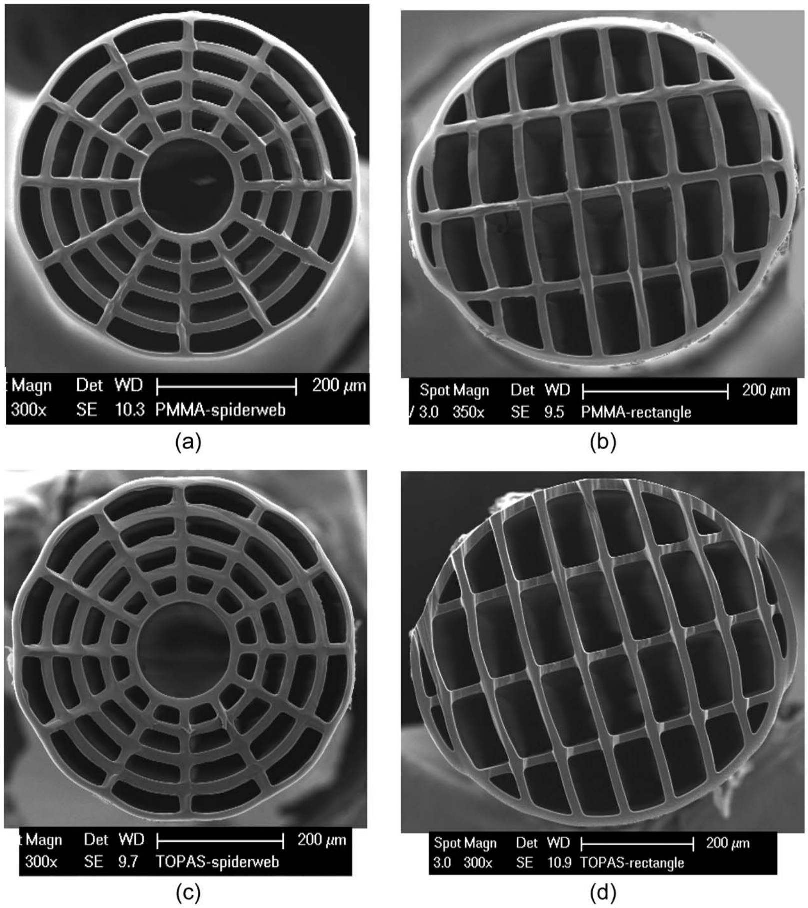

Fig. 3. SEM images of cleaved end-face of fibers using a UV laser. (a) PMMA spider-web, (b) PMMA rectangular, (c) TOPAS spider-web, and (d) TOPAS rectangular air-hole porous fibers.

used to create a line focus perpendicular to the fiber. The focal spot size of the beam after the lens is approximately a rectangle with dimensions 40 μm $\times$ 10 mm.

The cleaving process of the PMMA and TOPAS porous fibers are carried out at a 20-Hz and 40-Hz repetition rate, respectively. The energy densities of 312 mJ/cm^2 and 425 mJ/cm^2 are used for the PMMA and TOPAS porous fibers, respectively. The fiber is held by two clamps 20 mm apart. The fibers are clamped with minimal tension, in order to prevent damage to the fiber due to clamping. The fiber is rotated 3.6°/s during the cleaving process using two rotating, synchronized, and motorized fiber mounts. This reduces the time needed for cleaving to half compared to the case with no rotation. The amount of the time required for UV cleaving is determined by the laser intensity and repetition rate. With the above chosen parameters it takes about an average 270 s and 210 s to cleave a PMMA and TOPAS porous fiber with 400–500-μm outer diameters. The SEM images of the cross sections of the UV cleaved PMMA and TOPAS spider-web and rectangular porous fibers are shown in Fig. 3(a)–(d), respectively. These images show that, the UV laser cleaving leaves traces on the cleaved end-face in the direction of the beam due to ablation. Moreover, there is clear axial difference between orthogonal struts of the rectangular porous fiber, one orientation is sunken relative to the other. Also, it is noticeable that the nodes, where the struts cross in Fig. 3(b) and (d), seem to be more resistant to UV cleaving in case of rectangular porous fiber. This indicates that the energy dissipation at these points are high. This also indicates that the mechanical stability of the rectangular porous fiber is higher compared with that of spider-web porous fiber. The end-face results of the cleaves achieved by using a UV laser have very high reproducibility.

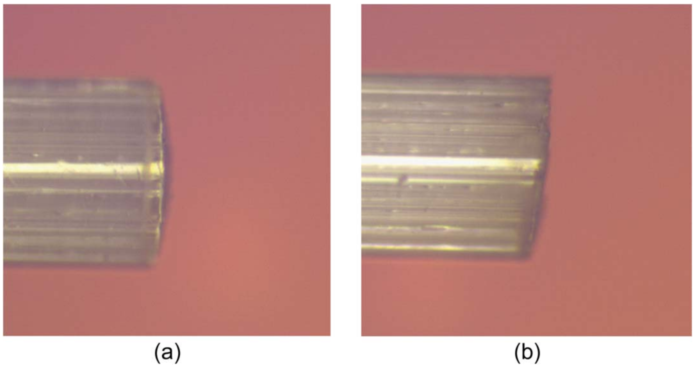

Fig. 4. Side view images of cleaved end-face of a TOPAS spider-web air-hole porous fiber using a UV laser. (a) With rotation and (b) without rotation.

It is worth highlighting that rotating the fibers during the cleaving process not only reduces the cleaving time to almost half but also results in a smoother end-face. Fig. 4(a) and (b) show the side view image of cleaved end-face of a TOPAS spider-web air-hole porous fiber with and without rotation, respectively. A slightly raised center have been observed in the side-view image of the fiber that has been rotated during the cleaving process, Fig. 4(a). The outer rings sit slightly lower compared with the center since they have been exposed to UV radiation longer than the central part. However, the end-face of the fiber is inclined at an angle for the case that the fiber has not been rotated during the cleaving process; see Fig. 4(b). This is attributed to the fiber relaxing asymmetrically as being cleaved from one side, causing the fiber to raise upwards toward the beam, resulting in an angled cleave. A slight blackening of the fiber end-face is also observed due to longer exposure of the fiber to the UV radiation during the cleaving process. This thermal build-up may be avoided by using lower repetition rates, as reported in [11]; however, this will come at the expense of increased cleave times. For the case when rotation is used, the center of applied tension changes continuously during rotation and results in a more even cleave with only a slight elevation toward the fiber center, as may be expected.

3. Conclusion and Discussion

Three different methods, using an SD saw, FIB milling, and a 193-nm UV laser, have been exploited for the cleaving of terahertz porous fibers made up of PMMA and TOPAS. The cleaves obtained using the SD dicing saw and UV laser are more than 500 times faster and free of ion deposition compared with those achieved by FIB milling. For PMMA porous fibers, both using a UV laser and FIB milling results in a good quality of end-face. Although the end-face of these fibers using the SD saw to cleave is chipped, the structure is well maintained. For TOPAS porous fibers, where the material has a lower glass transition temperature, only the UV laser technique is applicable. Using the dicing saw and FIB milling results in smearing the end-face and unreasonable cleaving time for TOPAS fibers, respectively. Moreover, the high reproducibility of UV laser cleaves place this technique as the best for cleaving of extremely porous polymer fibers. Overall, we observed that although the porosity of rectangular porous fiber is higher, the mechanical stability of this fiber is better compared with that of the spider-web porous fiber, and we attribute that to orthogonality of the struts.

The slight blackening of the UV laser cleaved fiber end-face [noticeable in Fig. 4(b)] may be due to oxidization during the cleaving process. A possible solution to this could be to carrying out the UV 193-nm laser cleaving process in an argon- or nitrogen-purged environment. This also will reduce the cleaving time further. It is also worth mentioning that the traces left from the UV laser cleaves on the cleaved end-face due to ablation can possibly be reduced by pressurizing one end of the fiber with an oxygen-free gas. The gas flow to the site of the cleave will blow away ablated material and reduce oxidization and blackening of the cleaved end-face of the fiber, even if it is not carried out in an oxygen-free environment. Further studies of the porous fiber stresses during the drawing process might reveal more information regarding the higher mechanical stability of rectangular porous fibers.

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