

Fabrication of Low Loss and Near Zero Dispersion Suspended Core Polypropylene Fibers for Terahertz Communications Using Infinity 3D Printing Technique

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Abstract

In this work we explore infinity 3D printing technique to fabricate continuous several-meter-long low-loss near-zero dispersion suspended-core polypropylene fibers for application in terahertz communications. The novel filament deposition modeling (FDM)-based infinity printing technique allows continuous fabrication of unlimited in length fiber sections of complex transverse geometries using advanced thermoplastic composites, and in our opinion is poised to become a key technique for advanced terahertz fiber manufacturing. Furthermore, particular attention in our work is paid to process parameter optimization for printing with low-loss polypropylene plastic, as well as an in-depth comparison between fibers printed using standard FDM 3D printers and infinity 3D printers.

Introduction

The terahertz (THz) spectral range (0.1 THz-10 THz) has attracted widespread attention in many practical applications, such as sensing [1-4], imaging [5-9], security [10-13] and communication [14-17]. In the communications, the global IP traffic is increasing exponentially and is expected to reach 396 exabytes per month by 2022 [18]. Among the total traffic, more than 85% will be utilized by video, gaming and multimedia applications. Establishing wireless link for transmitting such a large volume of data will be a convenient mode for the end users. According to Shannon theorem, for a given signal-to-noise ratio, the maximum data rate that can be reached is limited by the channel bandwidth [19]. To break the shackle, one way is to design the communication system with high signal spectral efficiency using advanced modulation techniques. However, there is an upper limit beyond which the spectral efficiency cannot be improved. Another method to achieve high bit rate is to utilize higher bandwidth. Therefore, shifting the carrier frequency towards THz spectral range is the promising solution. However, there are several challenges in the free space wireless THz links such as high path loss [20], the demand for high-gain antennas [15], low tolerance in alignment [21], etc., limits the THz communication to a short distance. Similarly, due to highly directional nature of the THz beams, the performance of the point-to-point non-line-of-sight (NLOS) communication will be significantly reduced. One of the solutions to improve the performance in the NLOS link is by installing the reflectors [22, 23] along the transmission path until achieving a reasonable signal in the detector. On the other hand, the

THz waveguides can be an alternative solution to the NLOS links due to its compact structure and flexibility in handling and manipulations. Further, the THz fibers are immune to external electromagnetic interference and eavesdropping. Therefore, the combination of the THz wireless links and THz fibers can offer a reliable performance in the next generation communication system. For an efficient communication link, the THz fiber must possess low transmission loss, low bend loss, low dispersion and high excitation efficiency. In addition, the speed and cost of fabrication plays a significant role in the mass production and commercialization opportunities.

The choice of waveguide material is one of the key factors in achieving low loss and low dispersion. It can be classified mainly into two types: One is metallic and the other is dielectric waveguides. In the THz regime, metallic waveguides suffers from high Ohmic loss and weak modal confinement depending on the waveguide structure. For instance, the circular metallic hollow waveguides [24, 25] and slot metallic waveguides [26, 27] can provide a strong mode confinement, but at the cost of higher Ohmic loss which limits the propagation distance. Moreover, it also suffers from huge dispersion near the cut-off frequency of the TE/TM mode guided in the kind of circular metallic hollow waveguide. In the case of parallel-plate metallic waveguides [28, 29], single wire waveguides [30-32] and two wires waveguides [33, 34], the fundamental mode exists for all frequencies and therefore the effect of dispersion is negligible, however, the modal confinement is weak along the direction of propagation. As the modes are loosely confined, any disturbance in the external environment leads to high radiation losses and thereby limiting the propagation distance.

In the case of dielectric waveguides, they have no Ohmic loss and negligible material dispersion, but suffer from the absorption loss caused by dielectric material and the dispersion mainly caused by waveguide structure. Although a dielectric slab waveguide with extremely low loss and negligible dispersion in the THz regime was fabricated with the high-resistivity silicon [35], however, the narrow application prospect that can only be applied in the chip scale field is the main limitation of its further development. Alternatively, micro-structured dielectric waveguides based on various polymers have come into vision. The great potential of these micro-structured polymer waveguides (MPWG) stems from low cost, low melting point, relatively low loss and easy accessibility of polymers. Furthermore, the waveguide dispersion can be effectively flattened by a reasonable design of the microstructure. In general, the MPWG can be divided into three categories based on the structure of the core: hollow core waveguide, porous core waveguide and solid core waveguide. The hollow core waveguide is famous for its extremely low loss and flat dispersion, making it very suitable for sensing applications. The main obstacles to its applications are the inflexibility due to the large dimension, and the limited bandwidth compared to the broad THz regime [36]. In comparison, the solid core waveguide can provide broader bandwidth THz wave propagation, but suffer

from the dilemma of material absorption loss. Applying materials with low loss characteristics, reducing the dimension of the solid core to compel mode field to propagate in lossless air, or adding some sub-wavelength discontinuous structures to the waveguide are the common methods to improve the performance of the solid core waveguide [37]. When it comes to porous core waveguide, it can provide almost constant lower loss and lower dispersion over a relatively wider frequency range compared with the solid core waveguide, and has a stronger resistance to bending [38]. The biggest challenge that restricts its development is that the high porosity and the high-precision pores arrangement make it inordinate difficult to fabricate. As mentioned before, in addition to the selection of material and the optimization of waveguide structure, another necessary condition that cannot be ignored to promote the development of waveguide applications is the efficient and inexpensive fabrication method. Otherwise, the waveguide that cannot be manufactured or is extremely difficult to be manufactured has to struggle in the theoretical stage even if its performance is excellent. In the last few years, several conventional methods are widely used in the fabrication of the MPWG, such as drill and draw technique [39-41] which can easily adjust the structural parameters of preforms with high accuracy by using computer numerical control (CNC) machining; stack and draw technique [42] which has advantages in fabricating waveguides with high porosity by stacking many tubes with large pores; casting and draw technique [43] which provides superiority over stacking since it is easier to adjust the porosity, arrangement of pores, and doesn't produce unnecessary gaps as stacking tubes. However, these conventional methods divide the manufacturing of waveguides into two steps, manufacturing preforms and drawing into waveguides, which inevitably increase the workload.

With the significant development of the Rapid Prototyping (RP) technique, such as Stereolithography (SLA), Continuous Liquid-Interface Production (CLIP), Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM), direct and efficient production of MPWG have gradually become a reality. In recent years, numerous THz waveguides manufactured directly by RP technique without further drawing process have been proposed, such as plasmonic waveguide [44], hollow core waveguide based on Kagome photonic crystal structure [45], hollow core Bragg waveguide with defect layers for surface sensing [46], pentagram hollow core anti-resonant waveguide [47], double pentagonal nested hollow core waveguide [48]. Moreover, FDM technique became the most fashionable one in directly printing MPWG due to that the wavelength of THz wave is comparable to the printing resolution. In addition, the FDM technique can be applied to variety of polymer materials, such as Poly(methyl methacrylate) (PMMA) [49], Polyethylene Terephthalate Glycol (PETG) [50, 51], Acrylonitrile Butadiene Styrene (ABS) [51-54], Polystyrene (PS) [55, 56], Polycarbonate (PC) [57], Polylactic Acid (PLA) [2, 58], High Density Polyethylene (HDPE) [59] and Polypropylene (PP) [60, 61].

To our knowledge, the first all-polymer micro-structured waveguide manufactured directly by FDM technique was proposed in 2015, a hollow core waveguide with negative curvature was directly 3D printed with ABS polymer. By characterizing the proposed waveguide with a diameter of 2.5 cm and a length of 10 cm, mode guidance from 0.1 THz to 1.1 THz was demonstrated [53]. In the same year, a hollow core Bragg ABS waveguide with a diameter of 2.28 cm and a length of 9.3 cm was directly 3D printed through a 150 μm nozzle, which was demonstrated low loss propagation over the frequency range higher than 0.35 THz [54]. Subsequently, in 2016, a rectangular PS waveguide with a side length of 0.15 cm for guiding the THz wave at 120 GHz was directly 3D printed to a maximum length of 50.6 cm by using multiple bending structures. An attenuation of about 6.3 dB/m was obtained by characterizing several rectangular waveguides of different length [56]. In 2018, an anti-resonant PC waveguide with half-elliptical cladding elements was designed and fabricated through a commercial FDM printer in order to minimize the required structural dimension for a desired value of loss. Several waveguides of different sizes with the same design were used for characterization, of which the longest length is 8.7 cm and the smallest diameter is about 1.5 cm. Two anti-resonance windows with a loss of approximately 1 dB/cm was clearly observed, which demonstrated the THz guidance in the 3D printed waveguide across a relatively broad spectral range [57]. In 2019, a hollow core Bragg PLA waveguide was directly printed through a 400 μm nozzle to demonstrate the application potential of the waveguide-based resonant fluidic sensor in monitoring of the analyte refractive index [2]. In view of the foregoing, it's not difficult to find that most of the waveguides directly manufactured by FDM technique are hollow core waveguides, which is due to that a large core is generally required to ensure the THz waves propagate predominantly in the lossless air. Therefore, the hollow core waveguide with relatively large dimension is easier to be manufactured since the resolutions of current commercial 3D printers are mostly in hundreds of microns. However, the hollow core waveguide is more suitable for sensing applications rather than communications since it features of narrow transmission window and inflexible characteristic. For porous core waveguide, high porosity, high-precision pores arrangement, and small pore dimension are still huge challenges for its manufacture even with the FDM technique.

Thence, the solid core waveguide can be considered as a substitute with great potential that can be combined with FDM technique to boost its applications in THz communication system. Although the transmission loss in a solid core waveguide is relatively higher and is usually comparable to the material absorption loss, the improvement of waveguide performance is absolutely achievable. By designing a reasonable waveguide structure to compel mode field propagate mostly in lossless air and applying polymers with relatively low absorption loss, a solid core waveguide with low loss and low dispersion can be realized. Among the aforementioned various polymer materials suitable for FDM technique, PP has lead widespread concern due to its advantages of almost constant refractive index and lower

absorption loss in the THz regime [62]. Therefore, further research on the material to promote a full understanding of its characteristics and boost its combination with FDM technique is very valuable for THz communication. Especially, with the advent of infinite printers in recent years, it has become a reality to break the standard printer volume restrictions. The ability of continuous printing and long object printing of infinite printers will inevitably greatly promote the application of FDM technique in THz communication.

In this paper, we

Waveguide design and fabrication with standard and infinite 3D printers

Fig. 1 shows the ideal cross section of the proposed fiber. The blue regions represent the PP material, and the white regions are air. The cladding region is formed by three air holes with a radius of 3.69 mm which evenly distributed around the center of the fiber. The distance between the fiber center and the air hole center is 4.5 mm. The core region is suspended by three supporting bridges with a width of 0.4 mm. The inner and outer diameters of the fiber are set as 7.6 mm and 8.0 mm, respectively. It is worth noting that the design of the proposed fiber is based on being able to be fabricated with FDM technique in a low cost and efficient manner while having optimal performance.

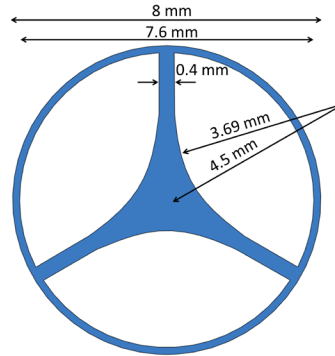


Fig. 1. The cross section of the proposed fiber

The FDM technique features of fabricating model through depositing molten material layer by layer, which will unavoidably increase the scattering loss. This leads to one of the main challenges in directly printing fibers is to maximize the transparency, which means minimizing the scattering loss. To achieve the best transparency, we need to minimize the generation of bubbles inside the printed model, which is making sure the extruded adjacent lines melt together as much as possible. Thus, we performed dozens of printings by adjusting different combinations of printing parameters to improve the model transparency. All the printings were performed with the commercially available FDM printer known as “Raise3D Pro2” because of its high position precision (0.78125 μm on X/Y axis), and high resolution in both horizontal (0.2 mm) and vertical (0.01 mm) directions. The material used in these

printings is 1.75 mm natural transparent PP filament due to its high transparency and lower absorption loss in the THz spectral range [62]. The temperature of extrusion and built template are set as 240 °C and 80 °C for all the printings. The extrusion width is 0.2 mm, same as the nozzle diameter. The infill density is fixed at 100% in order to get more material squeezed out, and thus reduce the generation of gaps between the extruded lines. One of the easiest infill patterns known as “Rectilinear” is adopted in the whole optimization process because of its reasonable amount of rigidity in all directions. A cylindrical slice with a diameter of 15 mm and a height of 4 mm was repeatedly printed to check the model transparency.



Fig. 2. (a) Slices printed with different infill flow rates (increase from right to left). (b) Slices printed with different infill speeds (decrease from right to left). (c) Slices printed with different layer heights (decrease from right to left)

Fig. 2(a) shows that the transparency can be improved by optimizing the infill flow rate. The infill flow rates of these slices are set to 90%, 100%, 110% and 120% from right to left, respectively. It can be clearly seen that the transparency becomes better when increasing the infill flow rate from 90% to 110%, which is due to that the gaps between the extruded adjacent lines are minimized or eliminated since more material is squeezed out. However, the infill flow rate cannot be increased endlessly, otherwise it will cause material overflow and surface roughness increase, which leads to worse transparency. This can be clearly seen when increasing the infill flow rate from 110% to 120%.

The slices printed with different infill speeds of 180 mm/s, 120 mm/s, 30 mm/s and 10 mm/s are presented from right to left in Fig. 2(b). It's obvious that the transparency is the best when the infill speed is 30 mm/s since it more closely matches with the current feed rate. For a specific feed rate, a reduction in the infill speed will result in an increase in the width of the extruded lines, vice versa [60]. Therefore, the gaps between the adjacent lines will be minimized when an appropriate infill speed is applied to the model. It is worthwhile noting that over-extrusion will occur if the infill speed is set too low, resulting in increased surface roughness or printing failure. Conversely, excessively high infill speed will increase the gap between the adjacent lines, which leads to poor transparency.

As shown in Fig. 2(c), the layer height has a great influence on the transparency. Different slices with the layer heights of 0.19 mm, 0.17 mm, 0.15 mm and 0.13 mm are presented from right to left, which shows that the transparency is continuously improved as the layer height decreases until 0.15 mm. Same as the infill speed analyzed before, for a given feed rate, a decrease in the layer height leads to an increase in extrusion width, which results in better transparency. In general, a smaller layer height can provide higher printing quality and better transparency. But, with the continuous decrease of layer height, it will become more

time-consuming and may cause material overflow.

In a word, multiple printing parameters must be considered comprehensively in order to obtain the best printing results. In addition to the aforementioned parameters, some other parameters which have a certain influence on the printing quality need to be carefully optimized. For example, the extrusion temperature has a big impact on extrusion flow rate and the fusion between layers. Higher temperature results in higher flow rate and better fusion. The combination of printing speed and overlap has a great influence on the size of the subtle part, which is crucial for successfully printing the proposed fiber. Thinner shells and structures can be obtained when adopting higher printing speed and smaller overlap. In addition, the heavy warping which happens easily in the first several layers when printing with PP filament can be well solved by using the appropriate first layer printing speed and built template temperature. Therefore, the optimal printing parameters such as infill flow rate of 110%, infill speed of 30 mm/s, layer height of 0.16 mm, first layer printing speed of 50 mm/s, inner shell printing speed of 70 mm/s, overlap of 5%, extrusion temperature of 240 °C and built template temperature of 95 °C are adopted in the printing of the proposed fiber.

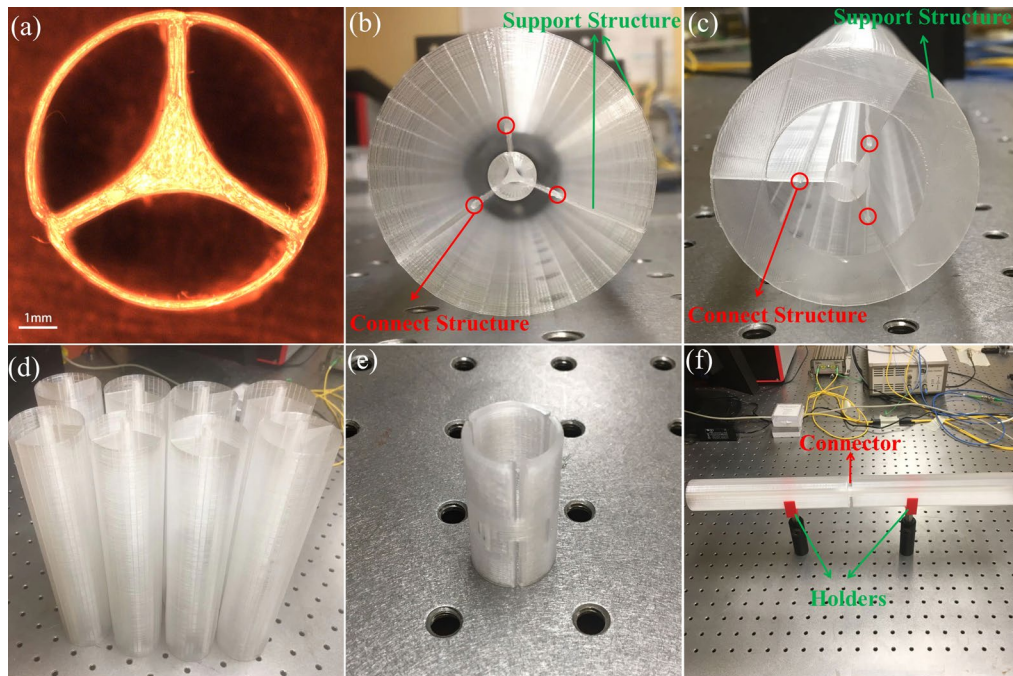


Fig. 3. (a) The cross-section microscopic image of the ideal fiber. (b) Top view of the ideal fiber. (c) Bottom view of the ideal fiber. (d) Side view of the ideal fiber. (e) The connector. (f) Two ideal fibers connected by one connector and two holders.

Fig. 3(a) presents the cross-section microscopic image of the printed fiber. The outer and inner diameters are around 8.0 mm and 7.6 mm, respectively. A solid core with a diameter of approximately 1.6 mm is suspended by three bridges with a width of about 0.42 mm. For

convenience, the printed fiber is named as “ideal fiber” since its dimension is almost the same as the proposed fiber.

The top of the ideal fiber is shown in Fig. 3(b), from which it can be seen that the fiber is connected to a 0.2 mm thick outer shell through three thin walls. The width and length of the three thin walls are set as 0.4 mm and 2.1 mm, respectively. The outer shell and three thin walls work as the support structure in order to reduce the shaking when printing at higher heights, thereby improving printing accuracy. An annular strip with a width of 10 mm and a thickness of 0.4 mm is added to the bottom of the model to provide better stability [Fig.3(c)]. PP tape is applied in the printing process for the purpose of sticking the model well on the built template.

As shown in Fig.3(b) and (c), three protruding parts which work as connect structure are added to the three thin walls in order to perfectly fit the connector [Fig. 3(e)]. The height and outer diameter of the connector are set as 30 mm and 16mm to ensure the ideal fibers can be well connected together. Several fibers with the length of 25 cm were printed out [Fig. 3(d)], and these fibers can be connected together in order to get longer length for the subsequent experiments. As shown in Fig. 3(f), two of them are connected together by one connector and two holders.

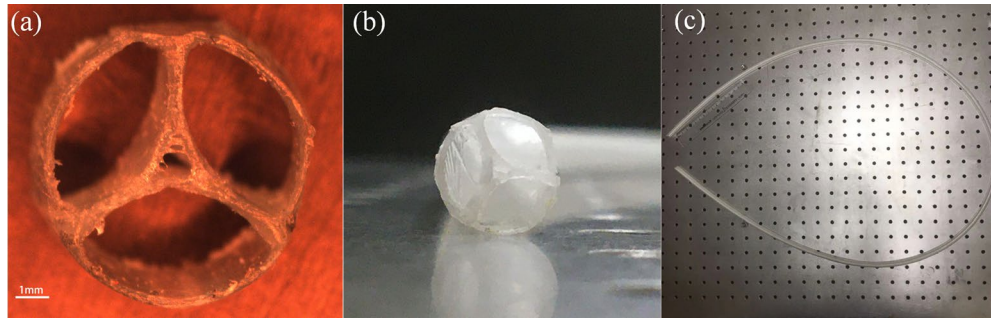


Fig. 4. (a) The cross-section microscopic image of the non-ideal fiber. (b) Top view of the non-ideal fiber. (c) Side view of the non-ideal fiber.

As shown above, longer fibers can only be obtained by connecting multiple pieces of short fibers through a well-designed connector and structure, which is due to the volume limitations of standard commercial 3D printers. This brings greater difficulty and more uncertainty to subsequent experiments, and it is unavoidable to generate more losses due to connections. In recent years, 3D printer has experienced significant progress thanks to the tremendous efforts invested in this technique, which leads to that the infinite 3D printer comes into vision. A company called “BlackBelt 3D BV” is the leader in the infinite 3D printing technique, whose printer makes the infinite printing a reality in a sense as long as you have enough filaments. Long prints or series production can be achieved by continuously printing on a sliding belt through a 45° inclined extruder. Thanks to the contribution of the BlackBelt team, a PP fiber with a length of about 1.4 m was obtained, which was fabricated by their infinite 3D printer

through a 0.25 mm nozzle. The cross-section microscopic image and different views of the fiber are shown in Fig. 4. The outer and inner diameters of this fiber are roughly 8.2 mm and 7.7 mm, respectively. The thinnest part of the three bridges is around 0.5 mm. Unfortunately, it can be clearly seen that the suspended core with a diameter of about 1.53 mm has some pores which should be completely solid. Accordingly, this fiber is named as “non-ideal fiber” because of the large deviation from the proposed fiber compared with the aforementioned fiber printed by a standard printer.

Theoretical demonstration of the suspended-core PP waveguides

Modal propagation in the straight waveguides

The simulations of the two fibers were numerically studied with the commercial finite element COMSOL Multiphysics software. We directly used the ideal cross section proposed in Fig. 1 to simulate the printed ideal fiber since its dimension is very close to the proposed fiber. For the non ideal fiber, firstly, a high resolution microscope was used to take high definition photos of the different parts of fiber cross section. Then, the complete cross-section picture was obtained through image stitching technology. Subsequently, a two dimensional model of the cross section is built by importing the complete cross-section picture into a solid modeling computer-aided design (CAD) software, and finally imported into COMSOL Multiphysics to perform the material definition and simulations. For convenience, the simulated values of refractive index and absorption coefficient of the PP material are set to 1.485 and 2.36 dB/m [61], respectively. Since the purpose of this study is to design and manufacture an optical fiber which can be applied in a photonics-based THz communication system operating at a carrier frequency of 128 GHz, several parameters that have a great impact on high bit rate transmission, such as modal loss, group velocity dispersion, excitation efficiency and bending loss are the focus of our simulations.

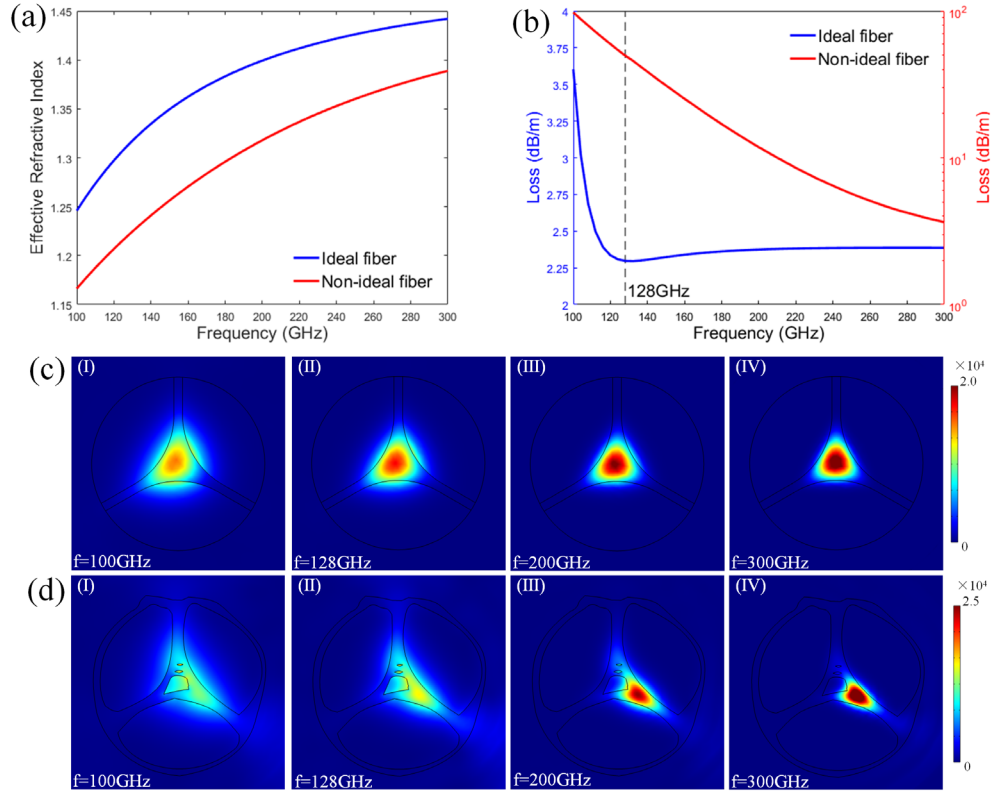


Fig. 5. (a) Effective refractive index of the fundamental mode versus frequency. (b) Total Loss of the fundamental mode versus frequency. Normalized electric field distributions of the fundamental mode for (c) ideal fiber and (d) non-ideal fiber at different frequencies.

We first studied the modal propagation of the two fibers fabricated above in the spectral range of 100 GHz-300 GHz. The effective refractive indexes of the fundamental modes for the two fibers are shown in Fig. 5(a). It shows that the effective refractive indexes monotonically increase with the frequency. To explain this phenomenon persuasively, the normalized electric field distributions of the fundamental modes for the two fibers at different frequencies are shown in Fig. 5(c) and (d). It can be clearly found that the monotonically increase of the effective refractive index is due to the fact that the fundamental mode is confined in the solid core more and more as the frequency increases. The fundamental mode of ideal fiber has a larger effective refractive index resulting from the ideal fiber has a completely solid core which leads to stronger confinement. In terms of the non-ideal fiber, due to its relatively weaker confining ability, a large part of the mode field is expanded in the air or leaks out through the bridges.

In addition, the diagram of total loss versus frequency is shown in Fig. 5(b). For the ideal fiber, the lowest total loss of 2.3 dB/m can be obtained around the frequency of 128 GHz. Different from the variation of effective refractive index, the situation gets slightly complicated when it

comes to the total loss, the curve of total loss presents an interesting phenomenon which is that the total loss decreases monotonically first and then increases monotonically.

For the ideal fiber, in the lower frequency range, the mode field is slightly delocalized [Fig. 5(c) I] which leads to lower absorption loss and higher radiation loss since the mode field propagates dominantly through the lossless air and can easily radiate out from the fiber. When the frequency is increased, the mode field will slightly shrinks [Fig. 5(c)II] resulting in a slight increase in absorption loss and a significant reduction in radiation loss, which leads to the slight reduction of total loss. The situation is completely reversed when the frequency comes to higher frequency range. The mode field continuously shrinks and is strongly confined around the suspended solid core [Fig. 5(c)III] which cause that the increase in material absorption loss will be considerably greater than the reduction in radiation loss. Therefore, the total loss increases. When it comes to even higher frequency range, the mode field is almost completely confined within the solid core [Fig. 5(c)IV], resulting in absorption loss comparable to the material absorption coefficient and extremely low radiation loss.

For the non-ideal fiber, the absorption loss increases since the mode field continuously shrinks with increasing frequency, which can be clearly seen in Fig. 5(d). However, it experiences a high radiation loss resulting from its relatively weaker confinement capability. Therefore, as the frequency increases, the reduction in radiation loss is always more significant than the increase in absorption loss. Accordingly, the total loss decrease monotonically as the frequency increases.

Excitation efficiency optimization and single mode behavior demonstration

Then, the excitation efficiency of the fundamental modes excited by the WR-6 waveguide flange of the THz emitter is thoroughly studied. It can be calculated through the ratio of the mode field overlap integrals with the following equation:

$$C = \frac{\iint (E_{mode}^* \times H_{wg} + E_{wg} \times H_{mode}^*) dx dy}{\sqrt{\iint 2Re(E_{wg}^* \times H_{wg}) dx dy} \sqrt{\iint 2Re(E_{mode}^* \times H_{mode}) dx dy}} \quad (1)$$

where E_{mode} and H_{mode} are the transverse electric and magnetic fields of modes guided by the fiber, E_{wg} and H_{wg} are the transverse electric and magnetic fields of the output beam from the WR-6 waveguide flange. In order to obtain the maximum excitation efficiency, we need to ensure that the mode field distribution of the WR-6 waveguide flange has the largest overlap with that of the fundamental modes guided by the two fibers, which is determined by their relative position and the operation frequency. Fig. 6(a) and (b) present the excitation efficiency of the fundamental modes for the two fibers as a function of the relative position at the carrier frequency of 128GHz. The X-axis and Y-axis represent the values where the center of the WR-6 waveguide flange deviates from the center of the fiber.

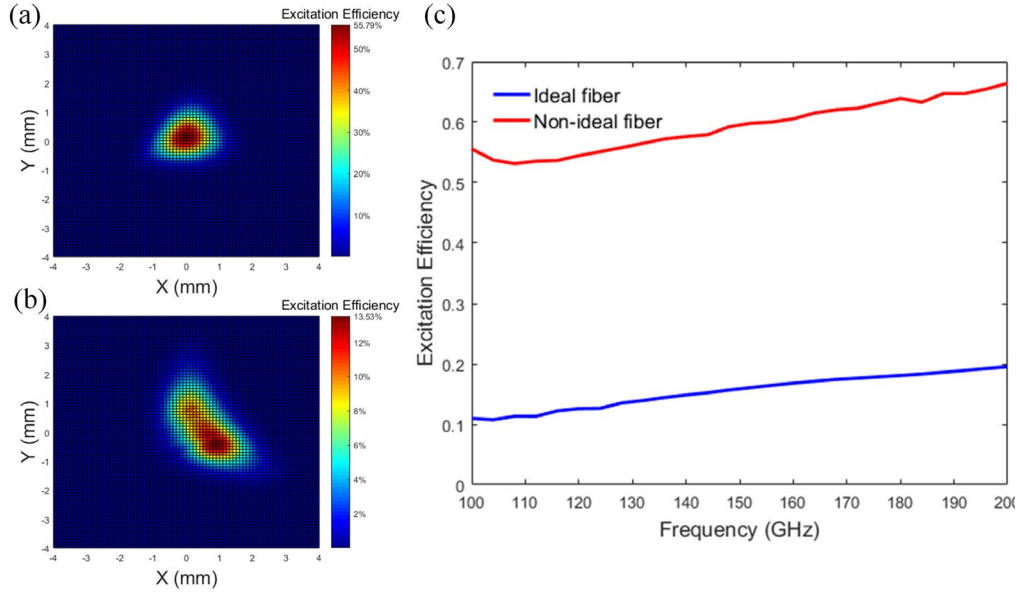


Fig. 6. Excitation efficiency of (a) ideal fiber and (b) non-ideal fiber versus relative position. (c) Excitation efficiency of the two fibers versus frequency by adopting the optimal relative positions.

As seen from Fig. 6(a) and (b), the maximum excitation efficiencies of the fundamental modes at 128GHz are 55.79% ($X=0$ mm, $Y=0.1$ mm) and 13.53% ($X=0.8$ mm, $Y=-0.5$ mm) for the two fibers, respectively. Subsequently, the excitation efficiency of the fundamental modes calculated as a function of frequency by adopting the aforementioned optimal relative positions is shown in Fig. 6(c). For the ideal fiber, over 50% excitation efficiency of the fundamental mode is achieved over the entire spectrum of 100 to 200 GHz. In comparison, the maximum excitation efficiency of non-ideal fiber in the entire spectrum can only reach close to 20%. In addition, the excitation efficiency of the two fibers will generally increase as the frequency increases. However, for the ideal fiber, the excitation efficiency decreases slightly with increasing frequency in the spectrum below 110 GHz. This is presumably due to that the above-mentioned optimal relative position is obtained at the carrier frequency of 128 GHz, which may cause a reduction in the mode field overlap when the mode field shrinks with increasing frequency. Therefore, it's necessary to adjust the relative position in the experiment to obtain the maximum excitation efficiency for different carrier frequencies.

To ensure high bit rate transmission for THz communication system, it's essential to make sure the fiber works in the single mode regime or have a single mode behavior. However, the fiber we designed can support multi modes at the carrier frequency of 128 GHz. Fortunately, the fiber is still able to have a single mode behavior.

The two main reasons for determining whether the fiber has single-mode behavior are the excitation efficiency which can determine how much power each mode can obtain from excitation, and the modal loss coefficient which can determine the survivability of each mode

in the fiber. In our case, there're four modes in addition to the fundamental mode need to be considered because they either have a modal loss coefficient comparable to the fundamental mode or have a relatively high excitation efficiency. The normalized electric field distributions of the two modes with modal loss coefficients comparable to the fundamental mode [HE₁₁, Fig. 7(a)] are shown in Fig. 7(b) and (c). The guiding mechanism of the two modes is total internal reflection.

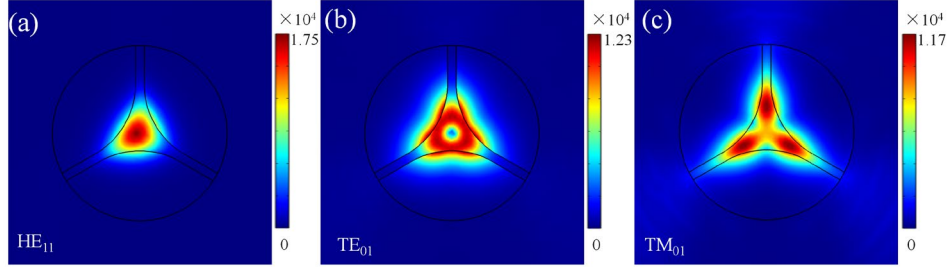


Fig. 7. Normalized electric field distributions of different modes for the ideal fiber at the frequency of 128GHz. (a) HE₁₁ mode. (b) TE₀₁ mode. (c) TM₀₁ mode.

Since the TE₀₁ mode [Fig. 7(b)] is strongly confined around the suspended solid core like the fundamental HE₁₁ mode [Fig. 7(a)], their modal loss coefficients are in the same order, which are 2.33 dB/m and 7.33 dB/m obtained from the numerical simulation. In terms of the TM₀₁ mode [Fig. 7(c)], it has a modal loss coefficient of 32.59 dB/m, which is not particularly high when applied to short-link THz communication system. So, both TE₀₁ mode and TM₀₁ mode may compete with the HE₁₁ mode. To verify this, the excitation efficiencies of the TE₀₁ mode and TM₀₁ mode are calculated to be 0.06% and 0.18% with equation (1), which are far smaller than the excitation efficiency of the HE₁₁ mode (55.79%). Therefore, it's demonstrated that the two modes cannot compete with the HE₁₁ mode or even cannot be excited at all.

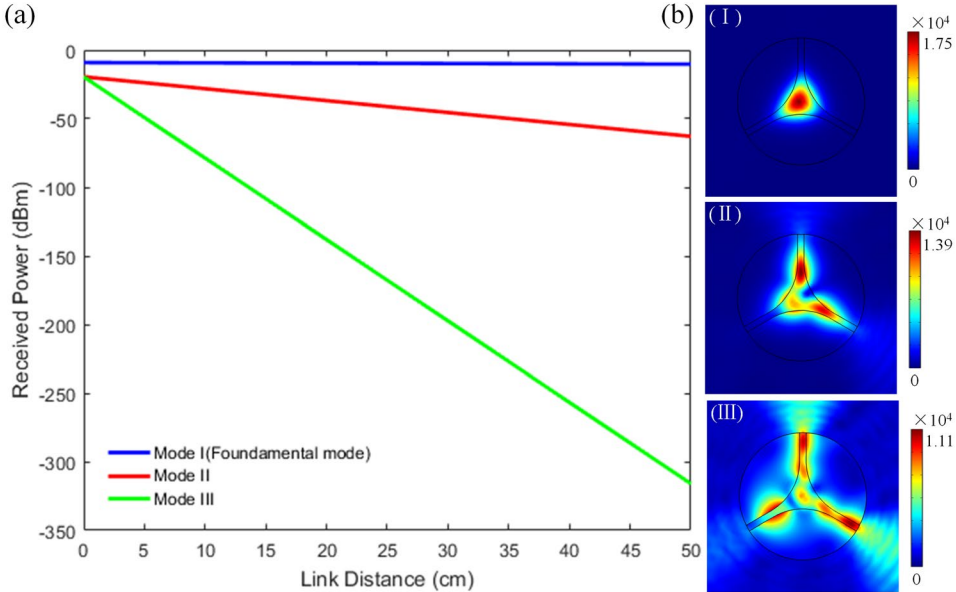


Fig. 8. (a) The received power of the three modes versus link distance for the idea fiber. (b) Normalized electric field distributions of the three modes for ideal fiber at the frequency of 128GHz

The other two modes whose guidance mechanism is anti-resonance reflection also need to be considered, because they have relatively high excitation efficiencies, which are calculated as 5.39% and 5.31%. The normalized electric field distributions of the two modes are shown in Fig. 8(b) II and III. In order to verify theoretically whether the two modes will affect the single mode behavior of the fiber, the received power of different modes versus link distance is calculated with the following equation:

$$P_r^i = P_0 |C_i|^2 e^{-\alpha_i L} \quad (2)$$

where P_r^i , C_i and α_i are received power, coupling coefficient and modal loss coefficient of each mode, P_0 is the output power of the WR-6 waveguide which is set as the input THz power used in our experiments (-6.6 dBm), L is the fiber link distance. Through numerical simulation, the modal loss coefficients for the three modes [Fig. 8(b)] are obtained as 2.3 dB/m, 87.06 dB/m and 593.45 dB/m, respectively. Accordingly, the received power for the three modes at different link distances is shown in Fig. 8(a). It can be found that the mode III will dissipate very quickly due to its high loss. Meanwhile the power of the fundamental mode will be 10^3 times more than the mode II at the link distance of 28 cm, which means the mode II has no possibility to compete with the fundamental mode. Therefore, it is fully demonstrated that the ideal fiber we fabricated can effectively guide only the fundamental mode at the carrier frequency of 128 GHz. The same is true for the non-ideal fiber, other modes except the fundamental mode either have extremely low excitation efficiency or dissipate quickly due to high modal loss.

Estimation of dispersion and maximum bit rate

In addition to the received power at the fiber end mentioned above, another important factor affecting the signal quality transmitted through optical fibers is dispersion [61]. While ensuring that the received peak intensity of the signal pulse is larger than the detection level of the receiver, it's also essential to ensure that the signal distortion due to dispersion is acceptable. As part of nonlinear optical effects, the dispersion can be derived from the propagation constant β which can be expanded in the Taylor series around a central angular frequency ω_0 as follows:

$$\beta(\omega) = \beta(\omega_0) + \beta'(\omega_0)(\omega - \omega_0) + \frac{1}{2}\beta''(\omega_0)(\omega - \omega_0)^2 + \cdots, \quad (3)$$

in which, it has been demonstrated that signal distortion at a specific propagation distance will vary with β'' which is the second derivative of the propagation constant [63]. The proper selection of the sampling number can effectively decrease the calculation error of β'' [64]. In our case, a total of 51 sampling points are applied in the frequency range from 100 GHz to

300 GHz to obtain a smoother dispersion curve. The dispersion (β'') for the two fibers is shown in Fig. 9(a). The dispersion for the ideal fiber at 128 GHz is 0.063 ps/THz/cm, which is very conducive to achieving high bit rate transmission. However, for non-ideal fiber, the dispersion at 128GHz can reach up to 9.044 ps/THz/cm, which will greatly affect the communication quality. Subsequently, the maximum bit rate ‘B’ supported by the two fibers at different frequencies are calculated with equation (4) [65], which is presented in Fig. 9(b).

$$B = \frac{1}{4\sqrt{|\beta''|}L} \quad (4)$$

where L is the fiber link distance which is set to 2 m. It can be clearly seen that the maximum bit rate of up to 70.56 Gbps can be obtained at 128 GHz for the ideal fiber, however, it can only reach 5.88 Gbps for the non-ideal fiber.

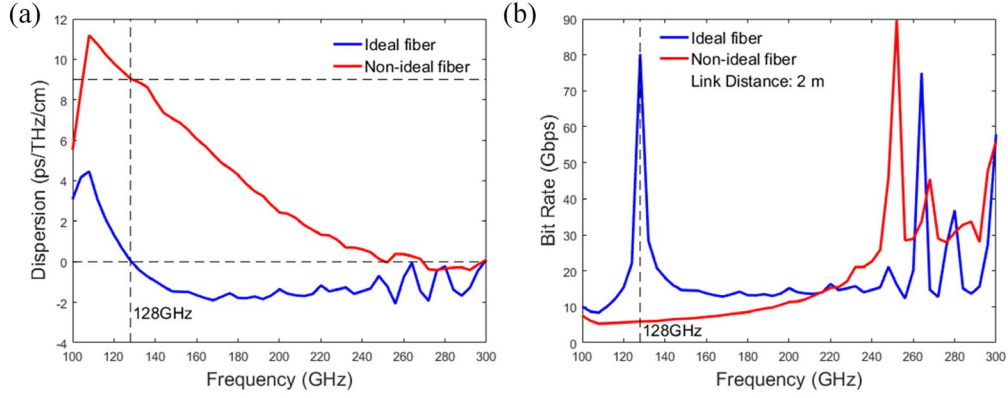


Fig. 9. (a) The second order dispersion of the fundamental mode versus frequency for the two fibers. (b) The maximum bit rate of the two fibers with a length of 2 m

Modal propagation in the bent waveguides

The modal radiation loss in the bent fiber occurs due to that the modal field of the cross-section which is orthogonal to the fiber axis cannot keep the same phase velocity during propagation. In our case, we bent the fiber into a planar arc of specific radius (R_b), which leads to that the phase velocity parallel to the fiber axis will varies with the distance from the center of the planar arc. At some distance from the center of the planar arc, the phase velocity can't continuously increase because it cannot exceed the speed of light, which means the modal field beyond this certain distance will radiate out from the fiber [66].

We performed the mode analysis with a 2D axis symmetric geometry in the COMSOL Multiphysics software. The modal electric field is expressed with the equation:

$$E(r, \varphi, z, t) = E(r, z)e^{j(\omega t - \beta R_b \varphi)} \quad (5)$$

where φ is the wave propagation direction which is in the azimuthal direction, R_b is the bending radius which is defined as the distance from the fiber axis to the center of the planar

arc, z is the propagation distance parallel to the fiber axis, β is the propagation constant of the mode. The modal propagation analyses of the two bent fibers are performed with the parameter sweep of R_b which ranges from 10 mm to 60 mm with a step value of 2 mm. The effective refractive index of the fundamental mode with different polarizations (X-pol and Y-pol) versus bending radius is shown in Fig. 10(a), from which we can find that the effective refractive index monotonically decrease as the bending radius increases. It's because the fundamental modes of the two fibers are confined closer to the suspended core with the increasing bending radius rather than to the edge of the fiber, which can be clearly seen from the normalized field distributions of the fundamental modes at different bending radius [Fig. 10(c) and (d)].

Meanwhile, the calculated bending loss is presented in Fig. 10(b), in which the fluctuations are presumably due to the fact that the suspended core is not a central symmetric structure. For the ideal fiber, the bending loss becomes several orders smaller as the bending radius increases from 10 mm to 40 mm, resulting from that the fundamental mode (X-pol and Y-pol) becomes stronger confined in the fiber [Fig. 10 (c)]. Above 40 mm, the trend of the bending loss reduction slows down because the mode field has been tightly confined around the suspended core. Hence, we can conclude from the above analysis that the ideal fiber fabricated with a standard 3D printer has strong bending resistance. Its bending loss is almost negligible in the application of short link THz communication for bends as tight as 40 mm of radius. For the non ideal fiber, the bending loss is only reduced by less than one order of magnitude even when the bending radius is increased to 60mm. This is due to the fact that the suspended core of the non-ideal fiber is not completely solid resulting in a loose confinement on the X-polarized fundamental mode, which makes the mode easy to radiate out when bending the fiber [Fig. 10(d)]. For the Y-polarized mode, it is even easier to radiate out because it is confined in the material closer to the edge of the waveguide, which makes it easy for the Y-polarized mode to leak out through the material of the bridge [Fig. 10(d)]. Thus, we can conclude that the non-ideal fiber printed by an infinite printer is less resistant to bending than the ideal fiber with completely solid suspended core.

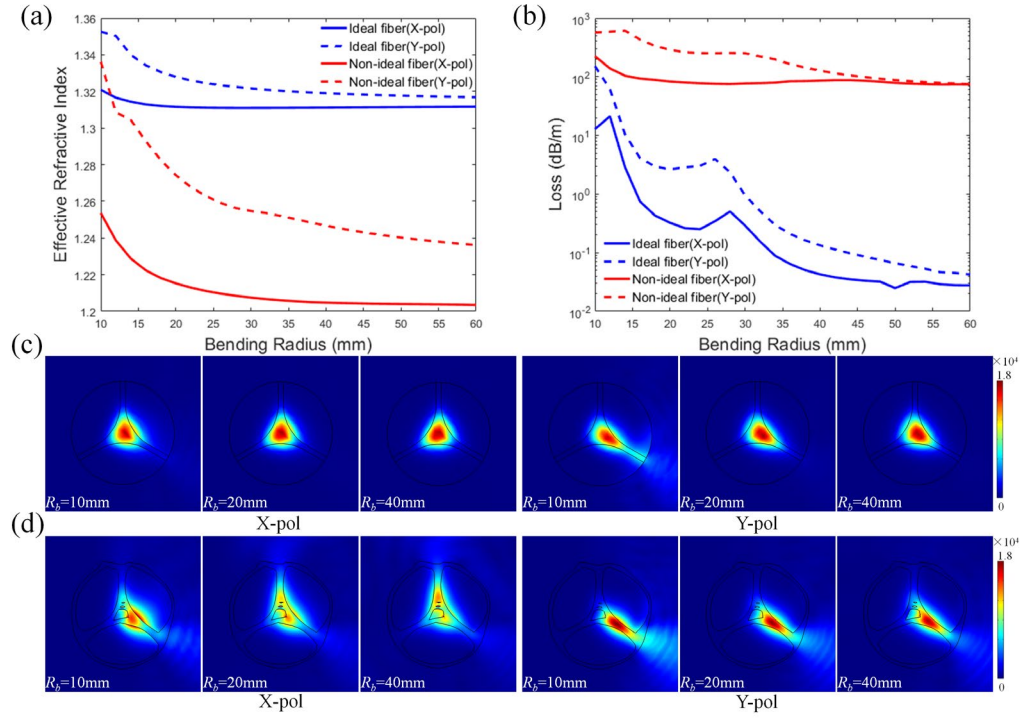


Fig. 10. (a) Effective refractive index of the fundamental modes with different polarizations versus bending radius. (b) Bending Loss of the fundamental modes with different polarizations versus bending radius. Normalized electric field distributions of the fundamental modes with different polarizations for (c) ideal fiber and (d) non-ideal fiber at different bending radius.

Conclusion

In this work we explored infinity 3D printing technique to fabricate continuous several-meter-long low-loss near-zero dispersion suspended-core polypropylene fibers for application in terahertz communications. Particular attention was paid to process parameter optimization for printing with low-loss polypropylene plastic, as well as an in-depth comparison between fibers printed using standard FDM 3D printers and infinity 3D printers.

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