3D-Printed Structured Optical Fibers for Terahertz Applications

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Abstract—In this work, prototype photonic crystal (PCF) and anti-resonant (ARF) terahertz fibers were designed, fabricated using FDM 3D printing from cyclic olefin copolymer (COC), and experimentally characterized. Several structured waveguide geometries inspired by photonic fiber concepts were developed and evaluated for the propagation of terahertz radiation. The measurements focused on transmission efficiency and field distribution at fiber output. It was found that both COC-based structures were capable of guiding THz radiation, with the best performance observed for the optimized PCF geometry. The results confirm the potential of COC 3D-printed structured fibers for rapid prototyping of terahertz waveguides.

Terahertz (THz) technologies are currently undergoing rapid development due to their broad applicability in imaging, spectroscopy, sensing, security screening, and material characterization [1–2]. Despite substantial advances in THz sources and detection systems, efficient and practical propagation of THz radiation remains a significant technological challenge. In most current systems, THz beams are transmitted in free space, resulting in bulky experimental arrangements that are highly sensitive to misalignment and difficult to integrate into compact platforms.

The development of dedicated THz waveguides offers a promising solution to this limitation; however, practical implementations remain constrained by material absorption losses, fabrication difficulties, and the limited availability of low-loss guiding structures [3–4]. Recent progress in additive manufacturing has demonstrated that 3D printing technologies, particularly fused deposition modeling (FDM), can provide a rapid and flexible route for prototyping terahertz waveguides with complex geometries. Among polymer materials suitable for THz applications, the cyclic olefin copolymer (COC) is particularly attractive due to its relatively low absorption, low refractive index, and compatibility with FDM processing [5].

Structured optical fiber concepts such as photonic crystal fibers (PCF) offer broad design flexibility by controlling geometric parameters, including air-hole diameter, periodicity, and structural arrangement [6]. Such microstructured fibers enable tailoring of propagation properties, including dispersion, modal behavior, and transmission bandwidth. In PCF structures, light can be guided either via modified total internal reflection or photonic bandgap mechanisms [7]. The further development of hollow-core photonic fibers introduced structures capable of guiding radiation predominantly in the air, significantly reducing material-related losses [8].

Among these, anti-resonant fibers (ARF) represent a particularly promising class of hollow-core waveguides. Their guiding mechanism relies on anti-resonant reflections from thin capillary walls surrounding the core, allowing efficient confinement of radiation within an air-filled central region [9]-[10]. This approach substantially reduces propagation losses while maintaining relatively simple structural geometries, making ARF especially attractive for THz applications, where material transparency remains a major limitation [11].

In this work, prototype terahertz PCFs and ARFs were designed, fabricated from COC using FDM 3D printing, and experimentally characterized to evaluate their feasibility and performance as practical THz propagation structures.

We designed the following prototype waveguides: three PCF structures and one ARF structure adapted for operation near 100 GHz. The designs were inspired by structured optical fibers known from VIS/NIR photonics, where periodic air-hole arrangements and hollow-core guidance enable control of modal properties and reduction of propagation losses. The PCF structures differed in internal air-hole arrangement to evaluate the influence of geometry on transmission efficiency, while the ARF design employed hollow-core anti-resonant guidance to maximize field confinement in air and reduce material absorption.

Fabrication was performed using Flashforge Inventor and Flashforge Dreamer printers equipped with 0.4 mm nozzles. Primary printing parameters included a nozzle temperature of 245°C, a bed temperature of 90°C, and a print speed of 50 mm/s. Despite technological constraints related to layer resolution, wall thickness, and geometric precision, all proposed PCF and ARF structures were successfully manufactured. The experimental samples preserved the essential structural features of their original designs, including periodic air channels and hollow-core geometries. Figure 1 presents the fabricated waveguides, including 3D design models and corresponding cross-sectional images, confirming the successful realization of complex waveguide architectures through 3D printing.

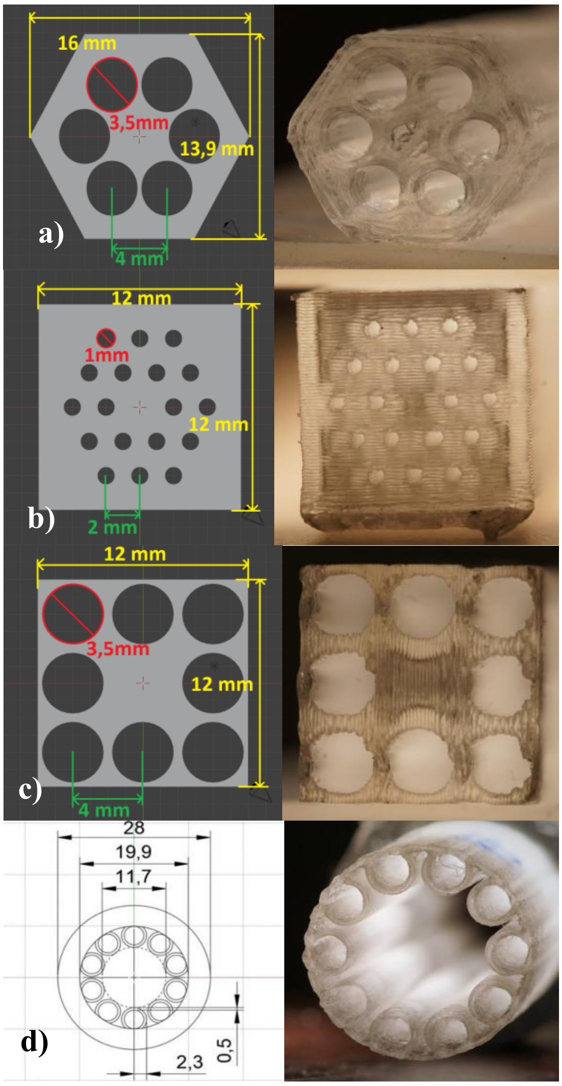

Fig. 1. 3D-printed COC THz waveguides: (a) PCF1, (b) PCF2, (c) PCF3, and (d) ARF, shown with corresponding 3D design models and cross-sectional images.

Due to build volume and process limitations, individual waveguide segments were restricted to approximately 100 mm in length, which positioned this study primarily as a rapid prototyping and proof-of-concept investigation rather than a full attenuation-scaling analysis over meter-scale lengths.

The transmission performance of the fabricated waveguides was evaluated using a terahertz measurement system based on tunable VDI WR5.1 (140-210 GHz) and WR10 (70–120 GHz) Schottky diode-based amplifier-multiplier chain sources. The experimental setup included beam-shaping components, such as toroidal and off-axis parabolic mirrors, enabling repeatable coupling of THz radiation into the tested waveguides. Output characterization was performed using either a TeraSense-1024 THz camera (32x32 pixels) to measure spatial field distributions or an Erickson PM4 THz power meter equipped with a horn antenna to analyze relative transmission efficiency. A schematic of the measurement arrangement is shown in Fig. 2.

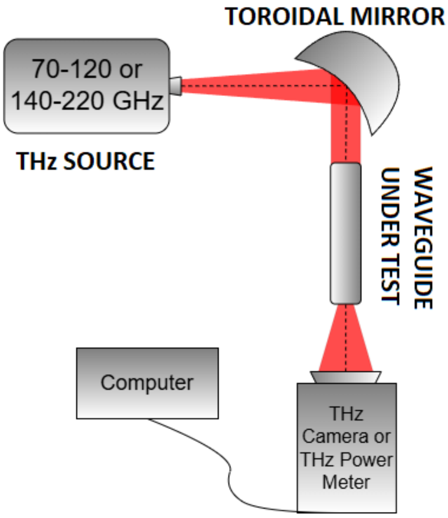

Fig. 2. Experimental setup for THz waveguide transmission and field distribution measurements.

Initial experiments focused on comparing three PCF geometries in the 140–220 GHz range. Average transmission efficiencies were determined from measurements at multiple frequencies, allowing for a direct comparison of structural performance. The results are shown in Table 1. Among all variants tested, PCF2 demonstrated the highest average transmission efficiency and good repeatability in fabrication, establishing it as the reference PCF structure for further analysis.

Table 1. Average coupling and propagation efficiency of THz radiation for the investigated PCF structures.

Structure type	Sample	Average efficiency
PCF1	PCF1	0.40
PCF2	PCF21	0.56
	PCF22	0.51
PCF3	PCF31	0.37
	PCF32	0.35
	PCF33	0.32

Field distribution measurements were performed using the THz camera to evaluate propagation quality and modal confinement in the fabricated PCF and ARF structures. As shown in Fig. 3, intensity distributions recorded at 95 GHz for the reference beam (without waveguide), the PCF, and the ARF structures demonstrate that both waveguides provide significantly stronger central confinement of THz radiation compared to the broader free-space beam profile.

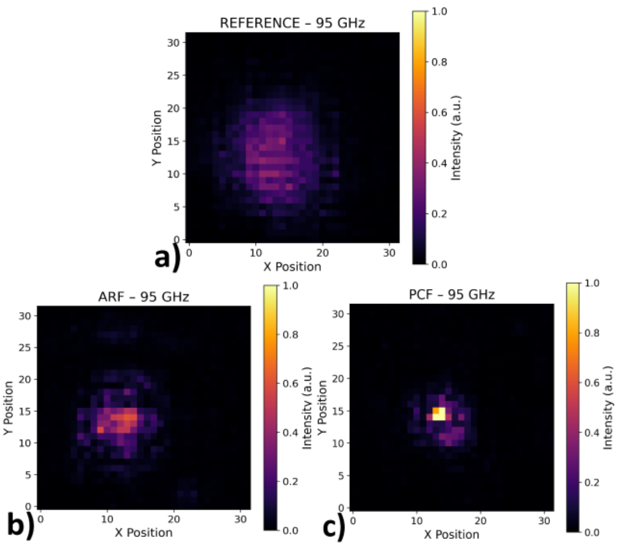

Fig. 3. THz radiation intensity distributions at 95 GHz for the reference beam (a), ARF waveguide (b) and PCF waveguide (c).

The PCF structure exhibited effective core-guided propagation, while the ARF structure showed strong field localization within the hollow core, consistent with anti-resonant guidance. These results confirm that both fabricated waveguide architectures effectively enhance electromagnetic field concentration and support efficient THz propagation with predominantly fundamental-mode characteristics.

To evaluate the influence of material properties on THz propagation, additional ARF waveguides with identical geometry and 10 cm length were fabricated from COC, PLA, and PET-G filaments. Average transmission efficiencies were determined over the 70 to 120 GHz range with the COC-based waveguide as a reference. As summarized in Table 2, all tested materials exhibited a very similar propagation performance.

Table 2. Comparison of average THz propagation efficiency for ARF waveguides fabricated from different materials (COC as a reference).

Material	Relative efficiency
COC	100 %
PLA	98 %
PET-G	102 %

These results indicate that, for anti-resonant THz waveguides, structural geometry and fabrication quality play a more significant role than intrinsic material differences. The weak dependence on material confirms the practical advantage of ARF designs, where dominant air-core propagation reduces the impact of polymer absorption losses.

The presented results confirm that FDM 3D printing is a viable method for rapid prototyping of structured THz waveguides. Both the COC-based PCF and ARF designs successfully enabled terahertz propagation, demonstrating their applicability as practical THz transmission structures. Field distribution measurements confirmed predominantly fundamental-mode guidance, with effective central confinement observed in both waveguide types. In the case of ARF structures, propagation occurred mainly within the air core, significantly reducing the influence of material absorption. This air-guiding mechanism indicates that anti-resonant designs may be fabricated effectively not only from specialized THz polymers such as COC but also from more conventional, widely available materials, provided that sufficient geometric precision is maintained. These findings highlight the strong potential of structured 3D-printed waveguides for future low-cost and accessible THz photonic systems.

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