# **PHOTONICS** Research

# **Dispersion-limited versus power-limited terahertz** communication links using solid core subwavelength dielectric fibers

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Terahertz (THz) band (0.1-10 THz) is the next frontier for ultra-high-speed communication systems. Currently, most of communications research in this spectral range is focused on wireless systems, while waveguide/ fiber-based links have been less explored. Although free space communications have several advantages such as convenience in mobility for the end user, as well as easier multi-device interconnectivity in simple environments, fiber-based communications provide superior performance in certain short-range communication applications such as multi-device connectivity in complex geometrical environments (ex., intra-vehicle connectivity) and secure communications with low probability of eavesdropping, as well as secure signal delivery to hard-toreach or highly protected environments. In this work, we present an in-depth experimental and numerical study of the short-range THz communications links that use subwavelength dielectric fibers for information transmission and define the main challenges and trade-offs in the link implementation. Particularly, we use air or foamcladded polypropylene-core subwavelength dielectric THz fibers of various diameters (0.57-1.75 mm) to study link performance as a function of the link length of up to  $\sim 10$  m, and data bit rates of up to 6 Gbps at the carrier frequency of 128 GHz (2.34 mm wavelength). We find that depending on the fiber diameter, the quality of the transmitted signal is mostly limited either by the modal propagation loss or by the fiber velocity dispersion (GVD). An error-free transmission over 10 m is achieved for the bit rate of 4 Gbps using the fiber of smaller 0.57 mm diameter. Furthermore, since the fields of subwavelength fibers are weakly confined and extend deep into the air cladding, we study the modal field extent outside of the fiber core, as well as fiber bending loss. Finally, the power budget of the rod-in-air subwavelength THz fiber-based links is compared to that of free space communication links, and we demonstrate that fiber links offer an excellent solution for various short-range © 2020 Chinese Laser Press applications.

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#### **1. INTRODUCTION**

The terahertz (THz) frequency spectrum (0.1–10 THz) holds high promises for many applications that include communications [1], imaging [2], sensing [3], and spectroscopy [4]. In communications, in order to meet the bandwidth demand set by the next generation of wireless systems, a shift in the carrier frequency toward the THz band is unavoidable [4,5]. THz communications have been already demonstrated in the context free space wireless links that profit from the presence of several low-/ modest-loss atmospheric transmission windows [6]. Although there are many advantages of wireless communications including convenience in mobility for the end user, ease in scaling up the network, flexibility of device interconnectivity, etc., they also possess many challenges. Particularly, due to high directionality of the THz beams, THz wireless links are known for their high sensitivity to alignment errors, thus requiring careful positioning of the transmitters and receivers [7]. Moreover, reliable communications in non-static environments (ex., between moving objects) require complex beam steering solutions. The situation is further exacerbated in geometrically complex environments (such as inside vehicles and buildings), where highly complex channel modeling is required. Moreover, free space links have higher chances of eavesdropping, thereby increasing the risks for secure communications [8]. Finally, atmospheric weather conditions such as rain, snow, and fog, play a major role in affecting the performance and reliability of the wireless THz links. In view of these limitations of wireless THz communications, short-range THz fiber links  $(\sim 10 \text{ m})$  can offer an alternative solution as THz fibers present a closed highly controlled propagation environment, can span complex geometrical paths, and can offer reliable coupling to receiver and transmitter for both static and dynamic applications. One interesting area of application for THz fiber links is in reliable onboard connectivity and intra-vehicle communications for military and civil transportation. In Fig. 1, we show the schematic of various communication modalities within and between the airborne vehicles, as well as place of THz fibers in such applications. For example, a high-speed THz data link with a moving vehicle can be established using a tracking ground station or another vehicle. A high power and high gain transmitter antenna can be used for such a long distance communication [9]. Given high directionality of the THz signals, multiple antenna modules have to be installed on the vehicle surface to cover several possible directions of communication. Next, received THz signals have to be demodulated and interpreted using expensive and environmentally sensitive signal processing units, which should be preferably located deep inside the vehicle.

This type of scenario in which THz signals are detected using multiple antennas and then are relayed over the complex geometrical paths to a central processing unit can profit greatly from flexible THz fiber links. Another scenario is using THz fiber links for reliable delivery of high-speed data through partially blocked or geometrically complex areas, which is of importance for hard-to-reach or highly protected environments such as enclosures for aggressive environments (ex., bioenclosures) and protected structures (ex., shelters and bunkers), as well as for intra- and inter-device THz communications in which different parts of the same system can be conveniently linked using flexible fibers. Finally, THz fiber links can be used as a backup solution for short-range wireless communications in case of sudden deterioration of the atmospheric conditions,



**Fig. 1.** Schematic of the THz wireless and fiber communication links for reliable and versatile intra-/inter-vehicle communication applications.

which can be of particular importance for places with harsh weather.

In designing an efficient THz fiber communication link, the fiber parameters such as transmission loss, bend loss, dispersion, coupling strength, and ease of handling play a significant role. Furthermore, the degree of complexity in the fiber fabrication process determines the cost and commercialization opportunities. While the fiber loss and coupling strength limit the communication link distance, the maximum achievable bit rate can also be limited by the fiber dispersion. Therefore, low transmission loss and low dispersion are the primary concerns for the THz fiber designs. We start by reviewing several types of existing THz fibers. The choice of waveguide material is one of the key factors in achieving THz guidance with low loss and low dispersion. In the case of metallic waveguides, the finite conductivity of metallic layers leads to ohmic losses, whereas in dielectric waveguides the loss is mainly due to material absorption. Independently of the materials used, longer THz waveguides (over 1 m) are frequently designed to use modes predominantly guided in the low-loss dry air region. Most recently in Ref. [10], bare metal wires in air were proposed as open waveguides for 5G communication applications; however, such waveguides suffer from high coupling losses and difficulty in mechanical handling due to wire waveguide open structure. Low-loss, low-dispersion, and efficient coupling can be achieved using two-wire plasmonic THz waveguides; however, longer (over 1 m) two-wire waveguides are inconvenient in practice due to challenges in packaging and handling [11]. This is because in the two-wire plasmonic waveguides, the air gap between the two metallic wires should be precisely maintained along the whole fiber length, which is difficult to achieve in long fiber links. While encapsulating the two metallic wires within a porous dielectric cladding using fiber drawing offers a solution to the mechanical stability and handling problem, this also leads to additional losses and dispersion due to coupling of a plasmonic mode to the dielectric cladding [12].

Alternatively, by selecting proper dielectric materials with low absorption loss [Teflon, polyethylene, polypropylene (PP), cyclic olefin copolymer, to name a few] and engineering the waveguide structure to expel the mode into the low-loss dry air region, highly efficient THz waveguides can be demonstrated [13-31]. In general, dielectric THz waveguides or polymer microwave fibers (PMFs) fall under one of the three main categories: hollow core waveguides [anti-resonant reflecting optical waveguides (ARROWs) or photonic bandgap (PBG) waveguides] [13-19], porous core waveguides [that use total internal reflection (TIR) or PBG guidance] [20-24], and solid core waveguides (TIR guidance) [25-28]. In the hollow core dielectric tube fibers, the finite thickness of a thin tubular cladding determines the bandwidth of the low-loss ARROW guidance regime, while such waveguides are generally multimode and can support many core and cladding modes. By increasing the size of the hollow core, the propagation loss can be further minimized (in expense to beam quality) as guided modes propagate almost completely in the low-loss air core [13]. Although the cladding modes can be suppressed and the transmission bandwidth can be improved by introducing lossy tubing material such as PMMA, in such fibers one still excites

multiple core modes, which becomes problematic for long link THz communications due to intermode dispersion and intermode interference [15]. Similarly, in the hollow core THz fibers, by arranging alternative layers of high and low refractive index (RI) cladding materials (Bragg fibers) or by introducing judiciously designed (periodic or aperiodic) arrays of air inclusions in the cladding (PBG fibers), the loss and the transmission bandwidth can be improved when compared with the tubebased ARROW fibers [3,14,16,19,32-35]. Moreover, effectively single mode regime can be achieved in long sections of such fibers, which can significantly reduce effective fiber dispersion. Additionally, low loss and low dispersion can be achieved when using spatially variable dense arrays of subwavelength air holes both in the core and cladding regions (porous fibers) [20,21]. Apart from the circular and hexagonal porous structure [20], honey-comb [36] and rectangular [37] porous geometries were introduced for which the dispersion is comparable to the THz microwires (subwavelength rod-in-air fibers). Similarly, using dispersion flattened porous THz waveguides, an ultra-wide transmission bandwidth (>1 THz) [38], which is comparable to the free space THz wireless channel, can be achieved for short distances. Finally, porous fibers with graded density of pores have been demonstrated to significantly decrease intermode dispersion when operated in the multimode regime [39]. Both hollow core and porous fiber, however, are challenging to fabricate as they rely on precise arrangements of air inclusions in a polymer, glass, or crystalline matrix [35]. Fabrication of most of such fibers involves drawing under pressure thermo-polymer or glass-based preforms with drilled or 3D printed air inclusions. Achieving and maintaining target porosity throughout the length of the fiber requires careful calibration and monitoring of the entire drawing process, which is often challenging due to small dimensions of structured preforms used in such drawings. Recently, an alternative method for the fabrication of THz microstructured and PBG fibers was detailed in Ref. [35], where over meter-long monocrystalline sapphire fibers were grown directly from the melt using structured dies. Alternatively, such fibers could be 3D printed directly using infinity 3D printing techniques, which was recently demonstrated in Ref. [40], in which authors continuously printed several meters of a wagon-wheel highly porous ARROW fiber using PP.

In solid core THz fibers, the transmission bandwidth is much larger than that in the hollow core fibers as the propagation mechanism is TIR. However, the transmission loss in such fibers is much higher and is generally comparable to the absorption loss of the fiber material. In order to minimize the transmission loss, one usually resorts to either subwavelength core dielectric fibers that are simple rod-in-air fibers or rod-in-foam fibers [26,41] or small solid core photonic crystal fibers (PCFs) with porous claddings [42]. The rod-in-air/ foam THz fibers with subwavelength size cores offer low loss and low dispersion guidance as a large fraction of the modal fields in such waveguides is guided in the low-loss air or foam regions [26-28,41]. In such fibers, scattering from inhomogeneities along the fiber length such as diameter variation, microand macrobending, and material density variation, is the dominant loss mechanisms due to weak confinement in the fiber core [43]. Scattering loss in such fibers can be somewhat mitigated by increasing the fiber diameter and realizing better confinement in the fiber core in the expense of the increased losses due to materials absorption. By choosing low-loss plastics for the core materials, as we show in the following, a good compromise can be found, and multi-meter THz fiber links can be realized. Therefore, despite of all these challenges, rod-in-air/ foam subwavelength fibers are a simple, but reliable platform for enabling various short-range THz communication applications. Furthermore, such fibers can be used to fabricate nontrivial signal processing components, such as directional couplers, power dividers, and bandpass filters, capable of realtime THz signal processing, which potentially allows building complete transmission/signal processing subsystems using the same base technology [44–46].

As discussed earlier, although simple rod-in-air subwavelength fibers are easy to fabricate and potentially offer low propagation loss and low dispersion, mechanical manipulation of such fibers and their integration into systems are problematic due to significant extent of the modal fields into air [47]. Therefore, for practical applications, such fibers have to be encapsulated in such a way as not to significantly affect the weakly core-bound guided modes, while allowing direct mechanical handling of the fibers. One solution to this problem is a wagon-wheel structure in which solid core is suspended in air using several deeply subwavelength bridges [27]. Fabrication of such fibers is, however, challenging due to complexity of the fiber cross section. Alternatively, solid subwavelength cores can be encapsulated using low-loss, low-RI (~1) dielectric foams, resulting in what we call throughout the paper rodin-foam fibers (see Fig. 2). In practical terms, high porosity low-loss material foams with deeply subwavelength air cells are virtually indistinguishable from the uniform air cladding, while providing the necessary mechanical stability and ease of manipulation [11,48]. Although, in principle, the dielectric foams can contribute to additional propagation losses, the effect is negligible for short distances (several meters) and lower THz frequencies (below 200 GHz) for many of the common foams.

Now, we briefly review some of the recent demonstration of THz communications using THz fibers [49–55]. In Ref. [54], an error-free transmission of 7.6 Gbps and 1.5 Gbps data over the link distance of 8 m and 15 m has been demonstrated using a hollow core waveguide made of Teflon at the carrier frequency of 120 GHz. The modal loss of the waveguide was 2.5 dB/m. The maximum bit rate at a longer link length here was mainly limited by the propagation loss. Recently, a 1 m



**Fig. 2.** (a) Schematic of the rod-in-foam subwavelength THz fiber. Fiber outer diameter is chosen to accommodate ~90% of the power guided by the identical rod-in-foam waveguide with infinite cladding. (b) Photograph of the rod-in-foam fiber.

expanded porous polytetrafluoroethylene THz fiber link has been established together with the resonant tunneling diode integrated with photonic crystal waveguide for 10 Gbps and uncompressed 4K video transmission [56]. For completeness, we note that one promising approach for high-speed THz interconnects at short distances (millimeters to few centimeters) for on-chip and inter-chip communications is based on silicon as the core material as such waveguides feature low transmission loss, high RI contrast, and strong confinement, as well as mature fabrication technology [57]. For example, in Ref. [58], an ortho-mode sub-THz interconnect channel for planar chip-to-chip communications using silicon dielectric waveguide has been investigated. By engineering the waveguide structure, silicon-based photonic crystal waveguides were proposed and demonstrated for efficient data transmission [59-61]. Moreover, by functionalizing silicon with other materials such as graphene, active components such as THz waveguide-based modulators can be fabricated [62]. Additionally, advanced shaped growth techniques [35,63] can be used to extend the use of low-loss, high RI monocrystalline materials such as silicon or sapphire to longer THz transmission lengths up to 1 m; however, application of such waveguides in THz communications has not yet been reported. In all these works, however, no in-depth analysis was presented as to the key reasons for the limitations in the transmission length and maximal bit rate in such fiber links. While, the most obvious reason for such limitations is often claimed to be fiber losses, in our following analysis, we conclude that fiber dispersion is another major factor that is often overlooked. In fact, we find that depending on the fiber design and operation frequency, one can be in the power-limited or dispersion-limited regime even in the case of short several-meter-long fiber links. From the practical point of view, in the power-limited regime, transmission is possible up to the highest communication bit rate supported by the available hardware even when approaching the maximal link length when signal strength becomes comparable to the noise level. In this regime, the eye diagram opening collapses along a single vertical direction, while no significant degradation in its overall form (skewedness) is observed. In the power-limited regime, negative effects of the modal loss dominate over those due to modal dispersion. In contrast, in the dispersiondominated regime, even for short fiber links when signal strength is significantly larger than the noise level, one cannot achieve maximal bit rate as allowed by the hardware. In this case, the eye diagram shows significant asymmetry and shape contortion due to modal group velocity dispersion and resultant pulse spreading. In the dispersion-limited regime, negative effects of the modal dispersion dominate over those due to modal loss.

In this work, we aim at deeper understanding of the limitations of the fiber link quality posed by the combined effects of the modal loss and dispersion. Without the loss of generality, we concentrate on a pure system of rod-in-air dielectric THz subwavelength fiber for short-range ( $\sim 10$  m) communication links with up to 6 Gbps data speeds. In fact, the rod-in-air fiber can be used in further studies as a performance benchmark for the more practical fibers such as rod-in-foam and suspended core fibers. In the following, we fix the carrier frequency at 128 GHz, while using fibers of various diameters to realize

power-limited or dispersion-limited transmission regimes. The dielectric fibers are made of low-loss PP material with three different diameters of 1.75 mm, 0.93 mm, and 0.57 mm. Both theoretical and experimental studies are then carried out, and a comparative analysis of the two is presented. Experiments were conducted using a photonics-based THz communication system reported in Refs. [64,65]. We then demonstrate that the limitation in the error-free link distance is mainly due to the modal loss for the 1.75-m-diameter fiber, while for the 0.93 mm and 0.57 mm diameter fibers, the link distance is limited due to modal dispersion. By optimizing the decision threshold, an error-free ~10 m-long link at 4 Gbps is achieved with the 0.57-mm-diameter fiber, while the argument is made for over 10 Gbps fiber links with over 10 m length when designing the fiber to operate near zero dispersion frequency (ZDF). Furthermore, study of the bending losses of the rodin-air fibers is presented, in which we conclude that even relatively tight bends of sub-10-cm radius can be well tolerated by such fibers. Finally, the power budget of the fiber-based link is compared with that of the free space links, and the case is made for the strong potential of the rod-in-air fibers in short-range communications. To the best of our knowledge, this is the first comprehensive study of all the major limiting factors and comparative advantages that relate to design and operation of shortrange fiber-assisted THz communications links.

#### 2. THEORY OF ROD-IN-AIR DIELECTRIC THZ FIBERS

Many polymers possess almost constant RI and low absorption losses at lower THz frequencies (<300 GHz). PP, in particular, has one of the lowest losses over the wide THz frequency range  $(<2 \text{ cm}^{-1} \text{ below 1 THz})$  [66–68]. Moreover, this material is compatible with 3D printing using the cost-effective fused deposition modeling (FDM) technique that opens many exciting opportunities in design and manufacturing of various 3D patterned bulk optical components and photonic integrated circuits. Due to the importance of PP material for THz application, in our studies we therefore used PP filaments of three different diameters (D = 1.75 mm, 0.93 mm, and 0.57 mm) as rod-in-air fibers. The filaments having smaller diameters (0.93 mm and 0.57 mm) were extruded using an FDM printer. Optical characterization of the fibers was then carried out using an in-house photonics-based THz communication system detailed in Refs. [64,65] that operates at 128 GHz carrier frequency. Complex RI of PP was measured using THzcontinuous wave spectroscopy system (see Appendix A.1). Mode analysis of the rod-in-air fibers was carried out using commercial finite element software COMSOL Multiphysics. The goal of this work is to establish limiting factors in transmission of high bit rate data streams over long distances; therefore, modal loss, group velocity dispersion, coupling efficiency, and bending losses are the key parameters to model.

# A. Effective Index, Modal Losses, and Excitation Efficiency

The normalized electric field distribution |E| of the fundamental HE<sub>11</sub> mode (normalized to 1 W of carrying power) for the PP fibers of different diameters at 128 GHz is shown in



**Fig. 3.** Normalized electric field profile |E| of the fundamental mode at the carrier frequency of 128 GHz: (a) 1.75 mm fiber, (b) 0.93 mm fiber, and (c) 0.57 mm fiber. (d) The power fraction of the fundamental mode within the aperture of a variable diameter. (e) The effective refractive indices of the guided modes, and (f) the corresponding modal absorption losses for the rod-in-air fibers of different diameters at the carrier frequency of 128 GHz. As a reference, the bulk refractive index and absorption loss of the fiber polypropylene core are 1.485 and 2.36 dB/m, respectively, at 128 GHz.

Figs. 3(a)-3(c). The normalized power fraction of the fundamental mode contained within the aperture of a variable diameter centered around the fiber is presented in Fig. 3(d). Clearly, for the fibers of larger diameter, the modal field is mostly confined within the fiber, while for smaller diameters the modal fields are strongly present in the low-loss air cladding, which is also the reason for the lower absorption losses of smaller diameter fibers. In Fig. 3(e), we present the effective refractive indices of the fundamental fiber guided modes as a function of the fiber core diameter at 128 GHz operation frequency, and the corresponding modal absorption losses (in straight fibers) are presented in Fig. 3(f). At the carrier frequency of 128 GHz, the fiber operates in a single mode regime up to the fiber diameter of 1.63 mm. For a 1.75 mm fiber, one expects excitation of three modes (HE<sub>11</sub>, TE<sub>01</sub>, and TM<sub>01</sub>), while in practice, excitation of TE<sub>01</sub> and TM<sub>01</sub> does not happen as such modes are incompatible by symmetry with the mode of a WR-6 waveguide (THz emitter waveguide flange) that is centered with respect to the fiber input facet. Thus, all the waveguides used in this work are effectively single mode.

We next study excitation efficiency of the fiber fundamental modes using external THz sources. Generally, the excitation efficiency is maximized when the size of the source field distribution is comparable to that of the fiber mode. In our experiments, the subwavelength fibers are butt coupled to the conical horn antenna that is connected to the WR-6 waveguide flange of the THz emitter. The horn antenna is a mode converter with the tapered structure that converts the fundamental  $TE_{10}$  mode of a rectangular waveguide to the Gaussian-like mode at the output. Coupling efficiency can be further optimized by properly positioning the fiber input end inside of the horn antenna. While many coupling scenarios have been considered in the literature [56,69,70,71], they all essentially result in a similar coupling efficiency as achieved by a simple free space coupler that uses a single plano-convex lens. The schematic of such a coupler is shown in the inset of Fig. 4(a). By optimizing the lens parameters (focal length, diameter) so as to match the size of the focused Gaussian beam with that of the fiber mode (or alternatively by matching the numerical apertures of the lens with that of the fiber), one can optimize excitation efficiency of the fiber guided modes.



**Fig. 4.** Excitation efficiency by power of the fundamental  $HE_{11}$  mode of a rod-in-air fiber of three different diameters. (a) Excitation efficiency versus Gaussian beam diameter. (b) Excitation efficiency as a function of frequency for the optimized Gaussian beam diameter. Inset in (a), schematic of a simple free space coupler.

Next, we use the transfer matrix theory and a mode matching technique to estimate excitation efficiency of the fiber fundamental mode with the focused linearly polarized Gaussian beam generated by such a coupler/taper at the input facet of a fiber [72,73]. In Fig. 4(a), the excitation efficiency (by power) of the fundamental mode for rod-in-air fibers of three different diameters is presented as a function of the Gaussian beam diameter  $(1/e^2)$ . The maximum excitation efficiency and the corresponding Gaussian beam diameter for all three fibers at 128 GHz carrier frequency are summarized in Table 1. Similarly, by using the optimized Gaussian beam size, the fundamental mode excitation efficiency is calculated as a function of frequency, which is presented in Fig. 4(b). The bandwidth of the excitation efficiency is one of the critical parameters that determines the maximum channel capacity. Even if we disregard the frequency dependent sensitivity of the receiver and assume dispersionless transmission, the maximal channel bandwidth in the fibers is still limited by the frequency dependent transmission loss and excitation efficiency. Therefore, maximizing the THz communication link bandwidth is a very challenging problem as it depends on a large number of factors from emitter/receiver hardware to the fiber design. In the particular case of our fibers, as seen from Fig. 4(b), over 90% excitation efficiency of the fiber fundamental mode with the bandwidth of at least 20 GHz is achieved for 1.75 mm and 0.93 mm fibers, whereas for 0.57 mm fiber, the bandwidth of ~10 GHz with the excitation efficiency of 80% is achieved. Although the available transmission bandwidth (in terms of excitation efficiency) is sufficient for the transmission of greater than 10 Gbps data (ASK modulation), the maximal bit rate is limited by the group velocity dispersion, which is discussed in Section 2.C.

From the data presented earlier in this section, we can now estimate the maximal fiber link distance given a  $\sim$ 35 dB power budget that is typical for our optics-based THz communication system (for the moment we ignore modal dispersion and bending loss). Thus, received power at the end of the fiber link can be estimated using the following expression:

$$P_r = P_t \cdot C^2 \cdot e^{-\alpha_{\rm wg}L},\tag{1}$$

where  $P_r$  is the power at the receiver end,  $P_t$  is the power at the transmitter end, C is the input/output power coupling efficiency per facet (see Fig. 4), and  $\alpha_{wg}$  is the modal propagation loss by power. The modal loss  $\alpha_{wg}$  for all three fibers is obtained from the numerical simulation [see Fig. 3(f)] as 2.2 dB/m, 0.62 dB/m, and 0.01 dB/m for 1.75 mm fiber, 0.93 mm fiber, and 0.57 mm fiber, respectively. The transmitter power is -6.6 dBm (~218  $\mu$ W, which is used in our experiments), and the received power after propagation along the distance L is shown in Fig. 5.

Table 1. Maximum Excitation Efficiency and ItsCorresponding Gaussian Beam Size for the Fibers ofDifferent Diameters

| THz Fiber     | Maximum Excitation<br>Efficiency, C | Gaussian Beam<br>Diameter |
|---------------|-------------------------------------|---------------------------|
| 1.75 mm fiber | 0.97                                | 1.85 mm                   |
| 0.93 mm fiber | 0.96                                | 3.2 mm                    |
| 0.57 mm fiber | 0.90                                | 32.7 mm                   |



**Fig. 5.** Power budget considerations for the fiber links of variable distance and 6 Gbps data transmission rate used in our experiments. Transmitter THz power is -6.6 dBm (~218  $\mu$ W). The signal loss level for the error-free data transmission is experimentally found at -20 dBm, and the absolute noise floor is -34 dBm.

The signal loss level for the error-free transmission of data with the bit rate of 6 Gbps is found to be  $\sim$ -20 dBm (10  $\mu$ W), while the absolute noise level below which transmission is impossible is found to be at  $\sim$ -34 dBm (0.4  $\mu$ W) (see Appendix A.4). From these measurements and from Fig. 5, we can estimate maximal distances of the fiber links capable of error-free 6 Gbps data transmission, which are 5 m for the 1.75 mm fiber and 20 m for the 0.97 mm fiber. Note that transmission with errors is possible up to  $\sim$ 10 m in 1.75 mm fiber and 43 m in 0.97 mm fiber. Finally, we note that while for 0.57 mm fiber the power budget considerations limit transmission distances to  $\sim$ 1 km range, in practice, the dispersion and bending loss result in much shorter fiber link distances of several tens of meters.

#### **B. Bending Losses**

The bending losses of the guided modes of the rod-in-air THz fibers are calculated using both numerical simulation and analytical approximations. The numerical simulations were carried out using the 2D axis-symmetric model in COMSOL Multiphysics. Here, the radiating wave propagates in the azimuthal direction,  $\phi$ , and the electric field is expressed as

$$E(r,\phi,z,t) = E(r,z)e^{j(\omega t - \beta r_0\phi)},$$
(2)

where  $r_0$  is the fiber bending radius, while  $\beta$  is the leaky mode propagation constant. The computational cell is a rectangle with a circular fiber core positioned at  $r_0$  from the axis of rotation, while the other boundaries are perfectly matched layers terminated with a perfect magnetic conductor. Furthermore, we use reflection symmetry with respect to the horizontal plane crossing the fiber center together with the perfect electric conductor or perfect magnetic conductor boundary conditions at the plane to calculate bent fiber modes of two polarizations [electric field at the symmetry plane directed parallel (*Y* polarization) or perpendicular (*X* polarization) to the bend axis]. Fiber materials are considered lossless for this simulation.

Bending losses of the fiber fundamental mode  $\alpha_{bend}$  in dB/m are computed for the bending radii *R* in the range of 4–30 mm. The calculated and fitted values of the bending loss are presented on the logarithmic scale in Fig. 6(a) as solid and dashed curves for *X* and *Y* polarizations, respectively. In the inset of Fig. 6, the normalized electric field profile of the bent



**Fig. 6.** (a) Bending losses of the 1.75 mm, 0.93 mm, and 0.57 mm fibers for different bending radii and polarizations. The solid curve corresponds to the *X*-polarized leaky mode, and the dashed curve corresponds to the *Y*-polarization leaky mode of a bend modeled using COMSOL software. The dotted lines correspond to the analytical estimations of the bending loss given by Eq. (3). (b) The group velocity dispersion of the fundamental *X*-polarized leaky mode of the 1.75 mm fiber as a function of the bending radius. (c) The field distributions correspond to those of the bent leaky modes for fibers of different diameters and bending radius of 3 cm.

fundamental mode for the bending radius of 3 cm is presented. For 1.75 mm fiber, the bending loss becomes smaller than the modal absorption loss in a straight fiber (~2.2 dB/m) for bending radii as small as  $\sim 2$  cm or larger. At the same time, for the 0.93 mm fiber bending radius should be larger than  $\sim 10$  cm in order for the bending loss to be smaller than the modal absorption loss (~1 dB/m). We note that optical performance of both fibers (1.75 mm and 0.93 mm) is quite robust with respect to bending as in many practical applications bending radii superior to 2-10 cm can be easily accommodated; however, using fibers of smaller diameters becomes challenging. This is due to the fact that for smaller core diameters, the fundamental mode is only weakly confined to the fiber core leading to higher radiation losses due to bending. For example, as seen from the inset of Fig. 6 for the 0.57 mm diameter fiber at 3 cm bending radius, the leaky mode of a bend has a much stronger contribution of the radiation continuum to its modal field distribution when compared to the leaky modes of the fibers of larger core diameters. Therefore, while straight 0.57-mm-diameter fiber features very low absorption loss <0.1 dB/m, at the same time it is strongly affected by the radiation loss due to micro- and macrobending.

Bending loss can also be estimated analytically using the classical expression for the bending loss of step-index fibers in the regime of weak modal confinement [74,75],

$$2\alpha = \frac{\sqrt{\pi}\kappa^2 \exp\left(-\frac{2\gamma^3 R}{3\beta_z^2}\right)}{2\sqrt{R}\gamma^{\frac{3}{2}}V^2 K_{m-1}(\gamma a)K_{m+1}(\gamma a)},$$
  

$$\kappa = \sqrt{k_{\text{core}}^2 - \beta_z^2}, \quad \gamma = \sqrt{\beta_z^2 - k_{\text{clad}}^2},$$
  

$$V = ka\sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}, \quad k = \frac{2\pi}{\lambda},$$
(3)

where  $2\alpha$  is the power loss coefficient, *a* is the fiber radius, *R* is the bending radius,  $\beta_z$  is the modal propagation constant in a straight fiber, and *K* represents the modified Bessel functions where *m* is the azimuthal mode number corresponding to the subscript LP<sub>*mn*</sub>. As HE<sub>11</sub> corresponds to the LP<sub>01</sub> mode within scalar approximation, we use m = 0 in Eq. (3). The propagation constants  $\beta_z$  of the fundamental modes at 128 GHz for all three fibers are obtained from numerical simulations using COMSOL. Estimated bending losses using analytical expression Eq. (3) are presented in Fig. 6(a) as dotted lines and show reasonable correspondence with the losses of the bent leaky modes described earlier.

# C. Modal Group Velocity Dispersion and Maximal Bit Rate Estimation

Next, we study modal group velocity dispersion and maximum error-free bit rate for the three fibers assuming a 10-m-long fiber link. The link length of 10 m is chosen to be long enough to be of practical importance, while making sure that all the fibers have no more than 25 dB loss (by power) over the link distance. In general, the maximum bit rate in the communication link is limited by the pulse dispersion and propagation loss. The dispersion parameters  $\beta_2(\frac{\partial^2 \beta}{\partial \omega^2})$  and  $\beta_3(\frac{\partial^2 \beta}{\partial \omega^3})$  are the second- and third-order derivate of the propagation constant ( $\beta = \frac{2\pi n_{\text{eff}}}{\lambda}$ ) with respect to the angular frequency  $\omega$ , which is used to characterize the degree of pulse broadening in fibers.

Particularly, considering only the second-order modal dispersion, the maximum bit rate *B* (for ASK modulation) supported by the fiber of length *L* can be estimated using Eq. (4), which is derived by requiring that ~95% of the power of the broadened pulse form still remains within the time slot allocated to logical "1" [76]. In Fig. 7(a), the  $\beta_2$  of all the three fibers is presented along with their single mode cutoff

**Fig. 7.** (a) Second-order dispersion  $\beta_2$  of the fundamental mode for 1.75 mm, 0.93 mm, and 0.57 mm fibers. The dashed vertical line corresponds to the single mode cutoff frequency of respective fibers. (b) The maximum bit rate supported by the fibers in a 10 m link with zero modal loss.

frequency  $f_{mr}$  We see that dispersion [ $\beta_2$ ] of the 0.93 mm fiber [~40 ps/(THz · cm)] is much higher than those of the 1.75 mm and 0.57 mm fibers at 128 GHz carrier frequency, thus significantly limiting maximal bit rates for the 0.93 mm fiber. Moreover, dispersion of the 1.75 mm fiber is near zero at 128 GHz, thus promising very high bit rates at this carrier frequency. The estimated bit rates for different fibers and different carrier frequencies are presented in Fig. 7(b). At 128 GHz and a 10-m-long fiber link, the maximum error-free bit rates of 4.7 Gbps and 1.2 Gbps are predicted for fibers of 0.57 mm and 0.93 mm diameter,

$$B = \frac{1}{4\sqrt{|\beta_2|L}}.$$
 (4)

It is important to mention that 1.75-mm-diameter fiber has a ZDF (at which  $\beta_2 = 0$ ) in the immediate vicinity of 128 GHz carrier frequency used in our experiments. The maximum error-free bit rate  $B_{\rm ZDF}$  supported by such a fiber at ZDF is, thus, limited by the third-order dispersion  $\beta_3$ , and can be estimated using Eq. (5) [76]. Applying Eq. (5) to all the three fibers operating at their respective ZDFs and assuming a link distance of 10 m, we estimate for  $B_{\rm ZDF}$  in the 10–20 Gbps range (see Table 2). We thus conclude that, by optimizing the fiber diameter to achieve low dispersion at a given carrier frequency, 10 m fiber links can be realized with rod-in-air fibers capable of over ~10 Gbps error-free bit rates per channel, which is sufficient for many practical THz fiber-based communication applications,

$$B_{\rm ZDF} = \frac{0.324}{\sqrt[3]{|\beta_3|L}}.$$
 (5)

Finally, we note that dispersion of a bent fiber can be different from that of a straight fiber, especially at smaller bending radii. In Fig. 6(b), for example, we show dispersion of the fundamental X-polarized leaky mode of a bent 1.75 mm

Table 2.ZDF for 1.75 mm, 0.93 mm, and 0.57 mm Fibersand Their Maximal Supported Bit Rates Estimated UsingThird-Order Dispersion

| THz Fiber     | Zero Dispersion<br>Frequency (ZDF) | Bit Rate at ZDF<br>for a 10 m Link |
|---------------|------------------------------------|------------------------------------|
| 1.75 mm fiber | 128 GHz                            | 9 Gbps                             |
| 0.93 mm fiber | 241 GHz                            | 13.8 Gbps                          |
| 0.57 mm fiber | 393.5 GHz                          | 19.2 Gbps                          |

fiber. At large bending radii, dispersion approaches zero (that of a straight fiber), while at bending radii smaller than several cm it grows rapidly and can become as large as  $\sim 10 \text{ ps/(THz} \cdot \text{cm})$ . Additionally, ZDW can shift to a somewhat different value in bent fibers, which should be considered when designing fiber links.

#### 3. EXPERIMENTAL CHARACTERIZATION OF THE ROD-IN-AIR SUBWAVELENGTH FIBERS

#### A. THz Communication System, Fiber Holding Method, and Principal Measurement Challenges

The experimental characterization of the fibers was carried out using an in-house photonics-based THz communication system reported earlier in Refs. [64,65]. The schematic and the experimental setup of the THz communication system are shown in Figs. 8(a) and 8(b), respectively. Particularly, two independently tunable distributed feedback lasers (TOPTICA Photonics) operating in the infrared C-band with slightly different center frequencies are used to optically drive the photomixer. The laser beams are combined using a 3 dB coupler and are intensity modulated (ASK) using an external electro-optic Mach-Zehnder modulator. A baseband signal source of pseudo random bit sequence (PRBS) with a varying bit rate from 1 Gbps to 6 Gbps and pattern length of  $2^{31}$  – 1 is used. The modulated laser beams are amplified using an erbiumdoped fiber amplifier (EDFA) and injected into the waveguide coupled uni-traveling-carrier-photodiode (UTC-PD) photomixer (NTT Electronics) for THz generation. In the receiver section, a zero bias Schottky diode (WR8.0 ZBD-F) is used to detect and demodulate the baseband signal. The baseband signal is then amplified using a high gain low noise amplifier (LNA), and the bit error rate (BER) is measured using the test equipment (Anritsu-MP2100B).

The largest rod-in-air fiber used in our experiments is the 1.75 mm fiber, which is a commercial 3D printing PP filament (Verbatim) with a diameter of  $1.75 \pm 0.05$  mm. The 0.93 mm fiber was fabricated by reducing the diameter of the 1.75 mm PP filament using a 3D printer (Raise3D Pro2). The temperature of the extruder was set to 220°C, and a 1 mm nozzle was used for the extrusion. A motorized spinning tool is used to precisely control the diameter of the filament that is extruded from the nozzle by adjusting the drawing speed. Thus, fabricated fiber had  $0.93 \pm 0.03$  mm diameter along the 8 m length. Similarly, a 10-m-long  $0.57 \pm 0.03$  mm fiber is fabricated by using the same 1 mm nozzle at increased drawing



Fig. 8. (a) Schematic of the photonics-based THz communication system. Inset, butt coupling of the THz fiber with the horn antenna using fisherman's knot assembly. (b) Photograph of the 6-m-long 1.75 mm diameter rod-in-air fiber THz communication link.

speed. While characterizing fiber links, a stable and consistent fiber coupling must be used. This is of particular importance for subwavelength fibers that can have significant modal presence in the air cladding. In our experiment, we used butt coupling with the fiber ends judiciously positioned inside the horn antenna. To counter the weight of the free-hanging fiber, the fiber is held tightly using an arrangement of two fisherman's knots made of thin threads and positioned at both emitter and detector ends [see inset of Fig. 8(a)]. Additionally, rodin-air fibers do not preserve the in-coupled light polarization state as the light propagates along the fiber. The birefringence is caused by local imperfections in the rod shape (ellipticity, for example), as well as material property fluctuations, which alter the polarization state of the propagating field. Stochastic polarization rotation becomes an issue for fiber links longer than several meters and must be considered while aligning the fiber at the detector side. The optimal alignment is achieved by rotating the fiber end at the detector side until a maximum signal amplitude is recorded.

# **B.** Measuring Fiber Propagation Loss Using Cutback Technique

The modal propagation loss of the PP fiber is studied experimentally using the THz communication system and a cutback method, which is then compared to the theoretical values [see Fig. 3(f)]. Without the loss of generality, here we detail only the measurement for the 1.75 mm fiber, while smaller diameter fibers can be characterized in a similar manner. First, the detector electronics are calibrated for direct power estimation from the eye pattern as discussed in the Appendix A.3. Second, a 1-m-long 1.75 mm fiber is butt coupled at both emitter and detector antenna by direct insertion into the horn antenna linked to the WR-6 hollow rectangular waveguide flange. By fixing the DC bias voltage of the emitter to -2 V, the infrared optical power is increased using EDFA, and the eye pattern for 1 Gbps is recorded using the test equipment. When the emitter photocurrent reaches 4 mA, the eye pattern starts clipping indicating that maximum threshold of the oscilloscope is reached. Therefore, in the following modal loss measurement, the emitter photocurrent is fixed to 4 mA, which corresponds to the THz power of -11.5 dBm ( $\sim 70 \mu$ W). Next, the 1.75 mm fiber of length 5 m is butt coupled at both emitter and detector antenna. The eye amplitudes for three bit rates (1 Gbps, 3 Gbps, and 6 Gbps) were recorded. Then, the fiber is cut back from the detector side with a step of 0.5 m, and the eye amplitude is recorded until the fiber reaches 1 m as shown in Fig. 9(a). At each cutback length, the fiber is carefully inserted into the detector horn antenna, while the position of the fiber tip is minimally adjusted to achieve the largest opening in the eye diagram. The recorded eye amplitude is then fitted using the form  $a \cdot \exp(-bx)$ . In Fig. 9(b), the estimated THz power is presented in logarithmic scale. It is observed that the modal loss of 1 Gbps, 3 Gbps, and 6 Gbps is 2.10  $\pm$ 0.37 dB/m,  $2.00 \pm 0.39 \text{ dB/m}$ , and  $1.96 \pm 0.40 \text{ dB/m}$ , respectively, which agrees well with the theoretically estimated absorption loss.

#### C. Modal Field Extent in the Air

As mentioned earlier, subwavelength fibers can have significant modal presence in the air cladding. In practice, one has to choose the size of fiber cladding (foam, for example) in such a way as to incapsulate most of the modal field. Experimentally, to measure the extent of modal field into air, we place the fiber in the center of a circular metallic aperture of the variable



**Fig. 9.** Measuring propagation losses of a 1.75 mm fiber using cutback technique. (a) Measured eye amplitude for 1 Gbps, 3 Gbps, and 6 Gbps signals as a function of the fiber length. (b) Power loss estimation using detector pre-calibration and recorded eye amplitude.



**Fig. 10.** (a) Fraction of the modal power inside the aperture of a variable diameter. Inset, circular aperture centered around the rod-in-air fiber. Photograph of the THz subwavelength fibers with polystyrene foam cladding: (b) 1.75 mm fiber with 5 mm diameter foam cladding (100% of power); (c) 0.93 mm fiber with 6 mm diameter foam cladding (90% of power); (d) 0.57 mm fiber with 45 mm diameter foam cladding (90% of power).

diameter (1–25 mm). The eye amplitude for 1 Gbps bit rate is then recorded as a function of the aperture diameter, from which the fraction of the received THz power is estimated [see Fig. 10(a)] by normalizing with respect to the corresponding value measured for the fully open aperture. From this measurement, we conclude that 90% of guided power for the 1.75 mm and 0.93 mm fibers is contained within the circles of ~2 mm and ~6 mm, respectively, and thus define characteristic sizes of the claddings to be used with practical fiber designs. At the same time, the corresponding size for the 0.57 mm fiber is theoretically estimated to be ~45 mm and could not be measured directly due to small size of the used aperture. At the same time, the measured results agree well with the numerical simulations [see Fig. 3(d)].

As mentioned earlier, one of the major challenges posed by the rod-in-air subwavelength fibers is the difficulty in their handling to significant presence of the modal field in the air cladding. To counter this problem, and to enable easy handling and manipulation of such fibers in practical installations, one can insert the subwavelength THz fiber core, for example, in a circular/square-shaped low-loss foam that features RI close to that of air. In our experiments, we realized some of such fibers using polystyrene foams with RI of 1.0104 and losses <1 dB/m [11]. In Figs. 10(b)–10(d), we present photographs of several THz subwavelength fibers with fiber diameters of 1.75 mm, 0.93 mm, and 0.57 mm surrounded by the polystyrene foam cladding of size 5 mm, 6 mm, and 45 mm, respectively, which are chosen from Fig. 10(a) to guarantee that 90% of the modal power is confined within the cladding.

#### 4. BIT ERROR RATE MEASUREMENTS

The BER measurements were carried out to study the fiber link performance under the laboratory environment. In the measurements, the emitter photocurrent was set to 7.5 mA, which corresponds to the THz power of –6.6 dBm (~218  $\mu$ W). A non-return to zero (NRZ) PRBS with the bit rates between 1 Gbps and 6 Gbps and a pattern length of  $2^{31}$  – 1 was used as a baseband signal. For the target BER of  $10^{-12}$  (error-free detection), the duration of a single measurement was 1/(target BER  $\cdot$  bitrate) ~ 1000 s. Furthermore, the decision threshold is optimized so that insertion error (digital 0 is mistaken as digital 1) and omission error (digital 1 is mistaken as digital 0) are approximately the same.

#### A. BER Measurement for the 1.75 mm and 0.93 mm Fibers at 8 m Link Length

First, we identify the maximal fiber length of the 1.75 mm fiber for BER measurements in our system. For that, we consider the eye pattern and observe that beyond 8 m of fiber length, the eye amplitude becomes comparable to the 0 and 1 noise levels, thus resulting in impractical BER values. Therefore, the maximum link length is fixed at 8 m. Similar to the modal loss measurement, an 8-meter-long 1.75 mm fiber is butt coupled to the emitter and detector units using fisherman's knots to hold the fiber in place. The BER measurement is carried out for the 1.75 mm fiber by varying the bit rate from 1 Gbps to 6 Gbps. At each bit rate, the decision threshold is optimized so that both insertion and omission errors are the same.

The total BER of the 8 m link is presented in Fig. 11 (blue solid line). Similarly, for the purpose of comparison, the BER measurements of the 8-m-long 0.93 mm fiber link is carried out. In our measurements, we did not observe any error (for optimized decision threshold) for the bit rates below 2.4 Gbps, within the measurement duration. At the same time, we were not able to measure BER for the bit rates beyond 2.8 Gbps due to high group velocity dispersion of the guided mode. The BER recorded for the bit rates between 2.4 Gbps and 2.8 Gbps is presented in Fig. 11 (red solid line). The inset in Fig. 11 shows the recorded eye patterns for both the 1.75 mm and 0.93 mm fibers.

From the eye patterns, we can judge the effects of modal loss and modal dispersion on the fiber link performance. Thus, in the case of 1.75 mm fiber, the eye amplitude is much smaller than that for the 0.93 mm fiber indicating that 1.75 mm fiber link performance is limited by the modal absorption loss. The error-free operation for the 1.75 mm fiber is observed for link lengths shorter than 5 m (input THz power is  $\sim$ 218  $\mu$ W) and bit rates of up to 6 Gbps [currently limited by the THz communication system, and the input THz power is  $\sim 218 \ \mu W$ (-6.6 dBm)]. At the same time, even at the link distance of 8 m, the measured BER of  $10^{-5}$  is well below the forward error correction (FEC) limit  $(10^{-3})$ . As the eye patterns for the 1.75 mm fiber stay relatively symmetric even for longer fiber links (8 m) and at high bit rates (6 Gbps), we believe that such a fiber can support at least 9 Gbps up to 10 m (as predicted theoretically), by compensating modal absorption losses with higher input powers [above ~550 µW (-2.6 dBm)]. In contrast, for the case of 0.93 mm 8-m-long fiber, although its absorption



Fig. 11. Measured BER versus bit rate for the 1.75 mm and 0.93 mm fibers, and the link length of 8 m. Inset, eye patterns for the two fibers at various bit rates.

loss is much lower than that of the 1.75 mm fiber due to much higher group velocity dispersion in such fibers [~40 ps/(THz  $\cdot$  cm)], the maximal bit rate is limited to only 3 Gbps. This is also confirmed by the shapes of the eye patterns for the 0.93 mm fiber that show significant shape degradation at higher bit rates, while also featuring almost 10 times higher powers of the received signals in the case of the 1.75 mm fiber.

#### **B. BER Measurement for the 0.57 mm Fiber at 10 m** Link Length

We now consider the 0.53 mm fiber that is theoretically predicted to have a very small absorption loss and a relatively small value of dispersion [ $\sim$ 4 ps/(THz  $\cdot$  cm)]. As predicted theoretically, an error-free transmission of up to 4.7 Gbps can be achieved using 0.57 mm 10-m-long straight fiber link. Experimentally, we use the same arrangement as discussed earlier, and then conduct BER measurements for data bit rates between 1 Gbps and 6 Gbps and a fiber length of 10 m. Error-free transmission with an optimized decision threshold is observed up to 4 Gbps (measured in steps of 1 Gbps) as shown in Fig. 13, which is in good agreement with theoretical predictions. The inset in Fig. 12 presents the eye patterns for 1, 2, and 6 Gbps bit rates. Although propagation loss of the 0.57 mm straight fiber is much lower than those of the 1.75 mm and 0.93 mm fibers, due to considerable modal diameter of the 0.57 mm fiber (~45 mm), a significant portion of the modal power is cut by the receiving horn antenna of 10.8-mm-diameter aperture.

### C. BER Measurement for the 1.75 mm Fiber and a $90^\circ$ Bend

The effect of bending on performance of the 8-m-long 1.75 mm fiber is studied using a 90° bend of 6.5 cm bending radius. The BER measurement (see Fig. 13) was carried out in a configuration similar to that of the straight fiber detailed earlier, while the fiber bend was realized by suspending the fiber using



Fig. 12. Measured BER versus bit rate for the 0.57 mm fiber and the link length of 10 m. Inset, eye patterns for 1, 2, and 6 Gbps bit rates.



**Fig. 13.** Measured BER for the 90° bending of 1.75 mm fiber with the bending radius of 6.5 cm versus bit rate. The schematic and experimental setup of the bent fiber are shown in the inset.

several knots and holders. For the chosen bending radius, we observe only a small increase in the measured BER of a bent fiber compared to that of a straight fiber, which is consistent with theoretical observation that bending loss of the 1.75 mm fiber at 6.5 cm bending radius is much smaller than the modal absorption loss, while dispersion of the mode of a bend at this bending radius is also small [<1 ps/(THz · cm)]. We note that performing a reliable measurement of the bending loss using subwavelength rod-in-air fibers is difficult as such fibers cannot be conveniently handled due to significant extent of the modal fields in air. Therefore, we defer a more detailed experimental study of the bending loss to future works, which will be conducted using rod-in-foam fibers placed into predesigned bending molds.

#### 5. POWER BUDGET COMPARISON OF THE ROD-IN-AIR THZ FIBER LINKS WITH THE FREE SPACE COMMUNICATION LINK

In this section, we highlight the advantages of fiber-based communication links by comparing them with the free space communications assuming a simple ASK modulation scheme. In free space optics, the power received at a distance L from the source is given by

$$P_r \approx P_t \cdot \frac{D_{\text{RX}}^2}{[D_{\text{TX}} + (L\theta)]^2} e^{-\alpha L},$$
  
$$\theta \approx 2 \cdot \frac{\lambda}{\pi w_0},$$
 (6)

where  $P_r$  is the received power,  $P_t$  is the transmitter power, and  $D_{\text{TX}}$  and  $D_{\text{RX}}$  are the aperture size of the source and detector antenna (lens diameter or horn antenna aperture, for example), respectively. The angle  $\theta$  is a full divergence angle of the beam,  $w_0$  is the beam waist size at the transmitter end, and  $\alpha$  is the air attenuation coefficient. The equation is valid in the far field region, i.e., at distances  $L > 2 \cdot D_{\text{TX}}^2 / \lambda$ . A typical power attenuation coefficient  $\alpha$  in air at the carrier frequency of 128 GHz is ~6.5 dB/km [77]. The received THz power using the fiber link can be estimated using Eq. (1). As a value for  $D_{\text{TX}}$  (assuming that  $D_{\text{TX}} = D_{\text{RX}}$ ), the aperture sizes of a standard horn antenna (10.8 mm) and a lens (2" optics: 50.8 mm) were considered. In free space communication, the received power is mainly limited by the divergence of the propagating beam.

By using a large-area lens or parabolic reflector antenna, it is possible to collect most of the transmitted energy. However, using large collecting optics is not favorable in many spacelimited applications. For the emitter power of 0 dBm (1 mW), the received power after distance L for both fiber and free space links is shown in Fig. 14. From this figure, we see that at shorter distances, fiber-based links are superior to free space beams in terms of received power due to fast divergence of the THz beams, while at longer distances, free space links are generally superior to fiber links due to smaller atmospheric losses compared to absorption losses of the fiber materials. From the figure, we see that when using a relatively small horn antenna (aperture size of 10.8 mm) at both emitter and detector sides, performance of the 1.75 mm fiber-based communication link is superior to that of a free space link in terms of the received power for the link lengths of up to 24 m. However, at this link



**Fig. 14.** Comparison between free space and rod-in-air fiber (straight)-based THz communication links at 128 GHz carrier frequency. The emitter power is set at 0 dBm.

distance, the received THz power is well below the noise floor (-34 dBm) for both free space and 1.75 mm fiber-based links. Moreover, even when using relatively bulky 2-inch optics (lens) for collimating and collecting the THz beam in free space, the performance of 1.75 mm fiber is still superior to a free space link of up to 8 m in length. By reducing the fiber diameter, the modal loss can be further reduced, thereby increasing the link distance. Alternatively, the noise floor and the minimal power required for the error-free transmission can be further improved as they depend on many factors including the type of modulation, responsivity of the detector, bandwidth and gain of LNA, etc. Although the link distance can be improved by using subwavelength fibers of smaller diameters or by better system design, the maximal achievable bit rate in the fiber links is still much lower compared to the free space THz communication links as fibers feature much higher group velocity dispersion than free space. The maximal bit rate in the free space THz links can be estimated by considering the dispersion of dry air  $[2.5 \times 10^{-4} \text{ ps}/(\text{THz} \cdot \text{cm})]$  [70].

In Table 3, we use both theoretical and experimental data (pertaining to our system) to summarize some estimates for the power budget and maximal bit rates of the fiber-based and free space THz communication links using the ASK modulation mechanism. Here we use the experimentally found -20 dBm as a minimal signal level to achieve the error-free transmission at 6 Gbps bit rates; moreover, since the ZDF for the 1.75 mm fiber is 128 GHz, third-order dispersion  $\beta_3$  is used to estimate the maximal bit rate, while for the 0.93 mm and 0.57 mm fibers, we use  $\beta_2$  instead. It is clear from Table 3 that, while the fiber-based communication links offer higher transmitted powers at shorter distances, nevertheless, they also consistently underperform in terms of the maximal achievable data rates compared to the free space links due to higher dispersion. To increase data transmission rates in fiber links, the modal dispersion (as well as modal loss) can be reduced by reducing the fiber diameter to deep subwavelength sizes; however, it comes with a higher sensitivity to bending and larger mode diameters. Alternatively, dispersion compensation techniques can be used to compensate for the fiber-link dispersion as we have recently demonstrated using strong hollow core waveguide Bragg grating [78]; however, such devices tend to have limited operation bandwidth, and further studies are necessary to establish feasibility of this approach. Alternatively, by using

| Table 3.  | Maximal Bit I              | Rate (ASK Modul  | ation) at Different | t Link Distances  | and Required Em  | nitter Power t | o Result |
|-----------|----------------------------|------------------|---------------------|-------------------|------------------|----------------|----------|
| in the -2 | 0 dBm Signal               | Power (Error-Fre | e Transmission) a   | at the Receiver E | nd for Both Free | Space and F    | iber     |
| Commun    | ication Links <sup>a</sup> |                  |                     |                   |                  |                |          |

| Link Distance, L                       |  | 8 m   | 15 m  | 30 m  |
|--|--|-------|-------|-------|
| Maximal bit rate in Gbps for           | Free space   | 560   | 410   | 290   |
| different link distances; carrier      | 1.75 mm fiber  | 10.5  | 8.4   | 6.7   |
| frequency is 128 GHz                   | 0.93 mm fiber  | 1.3   | 1     | 0.7   |
|  | 0.57 mm fiber  | 5.2   | 3.8   | 2.7   |
| Required transmitter power in          | Free space ( $D_{\text{TX}} = D_{\text{RX}} = 10.8 \text{ mm}, \alpha = 6.5 \text{ dB/km}$ ) | 26.3  | 31.8  | 37.9  |
| <b>dBm</b> so that the received signal | Free space $(D_{\text{TX}} = D_{\text{RX}} = 50.8 \text{ mm}, \alpha = 6.5 \text{ dB/km})$   | -0.57 | 4.9   | 11.0  |
| power is above the minimal             | 1.75 mm fiber, $\alpha = 2.2$ dB/m, $C = 0.97$   | -2.1  | 13.2  | 46.1  |
| -20 dBm level required for the         | 0.93 mm fiber, $\alpha = 0.62$ dB/m, $C = 0.96$  | -14.6 | -10.3 | -0.9  |
| 6 Gbps error-free transmission         | 0.57 mm fiber, $\alpha = 0.01$ dB/m, $C = 0.90$  | -19.0 | -18.9 | -18.8 |

"The carrier frequency is 128 GHz.

higher order modulation schemes such as orthogonal frequency division multiplexing (OFDM), the effect of dispersion can be minimized due to smaller bandwidth required at each carrier frequency [79]. This could potentially increase the bit rate several folds in longer THz fiber links.

#### 6. CONCLUSION

In this work, we presented a comprehensive theoretical and experimental study of simple, yet practical dielectric rod-in-air/ foam THz fibers in view of their potential applications in short-range THz communication applications. The THz fibers under study were made of PP and featured three different core diameters of 1.75 mm, 0.93 mm, and 0.57 mm. Furthermore, THz communication link performance was characterized with fibers of lengths 8 m and 10 m as a function of the variable data bit rates from 1 Gbps to 6 Gbps at the carrier frequency of 128 GHz. Our main conclusion was that, depending on the fiber diameter, the communication links were operating either in the power-limited or dispersion-limited regime. Thus, the 1.75 mm fiber featured ~2.2 dB/m loss and zero dispersion at the carrier frequency, and it could carry the highest bit rate of 6 Gbps up to the maximal distance of 8 m only limited by the fiber absorption loss, while error-free transmission with such a fiber was observed up to 5 m link length. Modal field extent of the core-guided mode into air cladding was only several mm deep due to relatively strong confinement of the modal field in the fiber core. As a result, the 1.75 mm fiber was also well tolerant to bending with virtually no degradation in the link performance when inserting a 90° tight bend of 6.5 cm radius. Further encapsulation of the fiber with polystyrene foam of sub-1-cm diameter makes such a fiber an excellent candidate for practical short-range THz communication links due to its ease of handling and installation, as well as good optical properties and tolerance to perturbations such as bending. Similarly, the 0.57 mm straight fiber featured a very low absorption loss ~0.01 dB/m and a relatively small dispersion of  $\sim$ 3 ps/(THz · cm). The resultant performance was similar to that of a 1.75 mm fiber; however, maximal link length was rather limited by dispersion than by the modal loss. As a result, error-free transmission was realized for a 10 m link with up to 4 Gbps data rates, while signal strength was considerably higher than the noise level. One of the major disadvantages of this fiber is high sensitivity to bending and severalcm-deep penetration of the modal fields into the air cladding, thus making even the foam-cladded fibers inflexible and somewhat difficult to handle. Finally, the 0.93 mm fiber, while featuring relatively small absorption loss of <1 dB/m, also featured relatively high dispersion of  $\sim 40 \text{ ps}/(\text{THz} \cdot \text{cm})$ , thus significantly limiting the maximal supported bit rate even for a good signal strength. Aa a result, a maximal bit rate of only 2.4 Gbps was demonstrated for an 8 m fiber link. Finally, we compared the THz fiber communication links with free space links that use relatively small focusing optics (up to 5 cm diameter) and concluded that in this case fiber links are generally more efficient in terms of the power budget for short-range communications up to several tens of meters. Fiber links are also more reliable and easier to install, maintain, and reconfigure than free space links, especially in complex communication environments (on-board communications, for example). At the same time, free space communications outperform fiber-based links in terms of maximal bit rate as air features significantly lower dispersion than fiber.

#### **APPENDIX A**

#### 1. Complex Refractive Index Measurement of the Polypropylene Filament

The RI of the PP fiber is measured using the continuous wave (CW) THz spectroscopy system [78,80]. The schematic of the experimental setup is shown in Fig. 15, which is briefly explained as follows. The setup has two distributed feedback (DFB) lasers with slightly different center wavelengths and uniform power (~30 mW each) operating in the telecom region. A 50:50 coupler combines and splits the two wavelengths equally into the emitter and detector arm, respectively. Two single mode polarization maintaining fibers wounded with piezo actuators, which stretch in the opposite directions, were connected to both the arms for the measurement of phase. The symmetric arrangement of the fiber stretchers provides the additional path delay as well as uniform disturbance due to any variation in the external environment. The path lengths between the emitter and detector arms were balanced to have a flat phase. The generated THz waves, which are the frequency difference of the two lasers, were modulated using the bias voltage for lock-in detection. The THz beams were collimated



Fig. 15. Schematic of the CW THz spectroscopy system for RI measurements.

and focused into the detector using the parabolic mirrors. The generated photocurrent in the detector was recorded along with the phase information as a function of frequency. The sample was kept in the collimated THz path for the RI measurement.

The PP sample for RI measurement was prepared as follows. A circular slab of PP material was fabricated by melting the PP fiber in a crucible at a temperature of 240°C for 35 min followed by 20 min of cooling. The densities of the PP fiber and the fabricated slab after melting were 898.02 kg/m<sup>3</sup> and 869.92 kg/m<sup>3</sup>, respectively, with the difference of only <4%. Therefore, it is concluded that the melting process does not affect the density of the material, and no significant amount of air inclusions were introduced.

Three slabs with slightly different thicknesses d were fabricated and then polished on both sides to get a smooth surface. A cutback measurement technique was used to measure the real part of the RI using the CW THz system. Both the amplitude and phase were recorded after removing each slab. The unwrapped phase for different sample (PP) thickness is shown in Fig. 16(a). Using the phase information, the real part of the RI of PP is extracted using Eq. (A1), where  $n(\omega)$  is the frequency dependent real part of RI,  $\Phi(\omega, d)$  is the measured phase difference due to the presence of a sample, and c is the speed of light. The RI of PP was measured as 1.485 in the measured frequency range, which is shown in Fig. 16(b),

$$n(\omega) = 1 - \frac{\Phi(\omega, d) \cdot c}{\omega \cdot d}.$$
 (A1)

Although the real part of the RI of PP was measured using the CW THz spectroscopy system, extracting the imaginary part accurately requires thick sample (~in meters) due to very low PP material loss. Therefore, we used the modified THz

In spectroscopy, a heterodyning detection scheme is used, whereas in the communication system, a direct detection scheme using a Schottky detector is employed. To measure the PP loss, the data modulation unit was disabled; however, the bias to the emitter antenna was modulated at lower frequency (12 kHz) for lock-in detection. In the detector section, a trans-impedance amplifier was placed after the LNA where the voltage is amplified and converted to photocurrent, which is proportional to the received THz power. In order to measure the loss of the PP fiber, we used the 1.75 mm fiber, and a similar fiber holding arrangement was used as for the BER measurement, as well as a metallic aperture at the detector side that was closed around the fiber. By keeping the input coupling undisturbed, the fiber was cut from the detector side during the cutback measurement. The photocurrents of two fiber lengths (5 m and 1 m) were recorded from 100 GHz to 150 GHz as shown in Fig. 17(a). The fiber loss was then estimated using Eq. (A2) [see Fig. 17(b)],

$$\operatorname{Loss}\left(\frac{dB}{m}\right) = \frac{1}{L_5 - L_1} \cdot 10 \log_{10}\left(\frac{I_5}{I_1}\right), \qquad \text{(A2)}$$

where  $L_5$  and  $L_1$  are the fiber lengths and  $I_5$  and  $I_1$  are the corresponding THz photocurrents, respectively. We note that from Eq. (A2) one can now extract the bulk absorption loss of the PP material by dividing Eq. (A2) by a certain frequency dependent normalization function  $\xi(f)$ . Such a function can be computed numerically by assuming a certain frequency independent bulk absorption  $\alpha_b$ , then finding numerically the corresponding absorption loss of a 1.75 mm rod-in-air fiber  $\alpha_f(f)$  made of such a material, and then defining  $\xi(f) = \alpha_f(f)/\alpha_b$ . Such a function is universal as long as bulk loss used in simulations  $\alpha_b$  is small. Thus, extracted bulk absorption loss [black curve in Fig. 17(b)] can then be fitted using the second-order polynomial [Eq. (A3)], where f is the frequency in THz,

Loss 
$$\left(\frac{dB}{m}\right) = 236 \cdot 31 f [\text{THz}]^2 - 37.75 f [\text{THz}] + 3.32.$$
 (A3)

Finally, bulk absorption loss of PP at 128 GHz is estimated to be 2.36 dB/m.



Fig. 16. (a) Unwrapped phase for different PP slab thicknesses. (b) Refractive index of the PP fiber as a function of frequency.



Fig. 17. (a) THz photocurrent for different fiber lengths. (b) Absorption loss of the 1.75 mm PP fiber (blue) as well as inferred bulk absorption loss (black) and a corresponding square fit (red).

The dispersion of THz fibers can be measured using both CW and time-domain THz spectroscopy systems as detailed in Refs. [15,78,81]. In Ref. [81], it was demonstrated that for subwavelength fibers in particular, experimentally measured dispersion agrees well with the theoretical estimations; therefore, in our work, only the theoretically calculated dispersion values were used to estimate the maximal bit rate for all the three fibers.

#### 2. Selection of the THz Carrier Frequency

The choice of carrier frequency is determined by the output THz power and responsivity of the detector antenna. In Fig. 18(a), the THz power versus frequency measured using a calibrated powermeter (PM3-Erickson powermeter, Virginia Diodes) is presented. Similarly, the corresponding developed DC voltage (without data modulation) was recorded [see Fig. 18(b)] using the oscilloscope (Anritsu-MP2100B). Both these measurements were carried out independently by keeping the DC bias voltage (-2 V) and photocurrent (7.5 mA) of the emitter antenna constant. A higher DC voltage was recorded for the frequency of 130 GHz. However, we observe a better eye pattern at 128 GHz, which was also verified by doing the frequency sweep from 125 GHz to 135 GHz.

### 3. Calibration of Detector Electronics for Direct THz Power Estimation

The calibrated calorimetric THz powermeter is standard when measuring the absolute power over the broad frequency range. In communications, such THz powermeters are integrated with hollow rectangular metallic waveguides for direct coupling with an electronic source. However, for fiber-based links, the absolute power measurement is challenging due to fluctuations caused by coupling consistency issues between the fiber and a waveguide flange. In fact, we found that using horn antenna coupled to a Schottky diode as a detector allows efficient and more consistent optimization of the coupling conditions at the fiber/detector side. Therefore, we first calibrated the detector antenna for direct power measurement using the received digital signal in the communication system. To calibrate the zero bias Schottky diode (ZBD) detector for direct power measurement, we proceed as follows. The data modulation unit in the communication system is disabled for the purpose of power measurement. First, the THz output power was measured using calorimetric THz powermeter by fixing the output frequency at 128 GHz and the DC bias voltage to -2 V. The infrared optical input power to the emitter antenna was varied, which is controlled in terms of the photocurrent. The measured THz power as a function of the photocurrent is shown in Fig. 19(a).

Second, the THz emitter is butt coupled to the ZBD by removing the horn antenna attached to it. Similar to the above measurement, the emitter photocurrent was varied, which is proportional to the THz output power, and the developed DC voltage (without the LNA) in the ZBD was measured by the oscilloscope with a load resistance of 50  $\Omega$ . The developed DC voltage as a function of emitter photocurrent is shown in Fig. 19(b). Then, the photocurrent in Figs. 19(a) and 19(b) was replaced with the THz power as shown in Fig. 19(c). The measurement in Fig. 19(c) was fitted using the second-order polynomial,

$$P[\mu W] = 0.0552 \cdot V[mV]^2 + 5.2346 \cdot V[mV] + 4.8216,$$
(A4)

where P is the THz power in microwatts and V is the developed DC voltage in millivolts. Since the LNA is connected after



**Fig. 18.** (a) THz output power from the photomixer versus frequency and (b) developed DC voltage in the detector corresponding to the input THz power shown in (a).



**Fig. 19.** (a) Measured THz power and (b) developed DC voltage in the ZBD at the frequency of 128 GHz by varying the input infrared optical power. (c) Developed DC voltage in the ZBD versus THz power at the frequency of 128 GHz. (d) Relation between the developed DC voltage from the ZBD for the coupled THz signal, eye amplitude, and digital one level of the 1 Gbps eye pattern at the carrier frequency of 128 GHz.

ZBD during the real-time communication measurements, the additional amplification factor needs to be considered. The LNA was AC coupled, and therefore we could not measure the amplification of the DC voltage. Therefore, the data modulation unit was enabled, and the 6 Gbps eye pattern was recorded using the high-speed oscilloscope before and after LNA for the THz power of -16.98 dBm ( $\sim 20 \mu$ W). The eye amplitude of the 1 Gbps eye pattern without and with LNA is 9.35 mV and 430.66 mV, respectively. The voltage gain in dB is given below:

Gain = 
$$20 \cdot \log_{10} \left( \frac{430.66}{9.35} \right) = 33.26$$
 dB. (A5)

Similarly, the gain factor of the LNA is calculated as below:

Gain factor = 
$$10^{\frac{\text{Gain}}{20}} = 10^{\frac{33.26}{20}} = 46.02.$$
 (A6)

The DC voltage developed in the ZBD by varying the emitter photocurrent [see Fig. 19(b)] is recorded when there is no data modulation, which is shown in Fig. 19(d) as a blue solid line. It means that the measured DC voltage is the same as logical 1 of the modulated signals (for binary modulation). In our experiments, the digital logical 1 is represented as +1, and logical 0 is represented as -1. Therefore, measuring the eye amplitude and dividing it by 2 is equivalent to the DC voltage measured when there is no modulation as shown in Fig. 19(d) (red line and green line). The developed DC voltage in the ZBD is referred to here as mean DC voltage recorded when the data modulation unit is disabled. We see a small deviation between the mean DC voltage and eye amplitude/2, which could be due to the amplifier noise and minor discrepancy in estimating the eye amplitude. To summarize the calibration process, the measured eye amplitude is divided by  $92.0512(2 \times 46.0256)$ and used in Eq. (A4) to estimate the received THz power.

# 4. Noise Floor and Error-Free Detection Using THz Communication System

The following experiment has been carried out to measure the effect of signal level on the BER in our communication system and in order to characterize the noise floor and minimal signal power necessary for error-free detection (BER  $< 10^{-12}$ ). In the THz receiver unit, we have used the LNA with the bandwidth of 3 GHz. Therefore, the bit rate in the communication system is limited to the maximum of 6 Gbps (ASK modulation). In this measurement, the emitter antenna was butt coupled to the ZBD. The output from the LNA was connected to the test equipment (oscilloscope and BER tester). The DC bias voltage to the emitter antenna was set to -2 V. The emitter photocurrent was varied by increasing the infrared optical power to vary the THz signal power in the system. The eye pattern and BER with optimized decision threshold for the bit rate of 6 Gbps were then recorded. Since the emitter and detector were butt coupled, the received THz power is considered the same as the transmitted THz power, which is extracted from Fig. 19(a).

From Fig. 20, for the received THz power of  $\sim -20$  dBm (10  $\mu$ W) and higher, we did not observe any errors within the measurement duration for the optimized decision threshold.



**Fig. 20.** BER measurement in our communication system as a function of the received signal power for the bit rate of 6 Gbps.



**Fig. 21.** Eye pattern of 6 Gbps data for the emitter power of (a) 0.8  $\mu$ W (-30.96 dBm), (b) 0.6  $\mu$ W (-32.21 dBm), and 0.4  $\mu$ W (-33.97 dBm).

Therefore, the signal level of -20 dBm for 6 Gbps is defined as a minimal signal power required for the error-free transmission in our THz communication system.

The noise floor of our THz communication system is measured by decreasing the emitter power, while the mean and standard deviations of one level and zero level of the 6 Gbps data were recorded from the eye pattern. The noise floor is considered as the THz power at which the distance between the mean one and zero levels equals the average of standard deviations of the one and zero levels. In Fig. 21, we show the eye pattern of the 6 Gbps data recorded for various emitter powers. The noise floor for 6 Gbps data in our system was  $\sim -34$  dBm.

#### 5. Modal Properties of Rod-in-Foam Fibers

The RI of highly porous foams (polystyrene foam, for example) is close to that of air. Therefore, the modal propagation properties of fibers with foam cladding (such as mode size and dispersion) are similar to those of fibers with air cladding. In Fig. 22, we show normalized electric field profiles of the fundamental modes of the rod-in-foam fibers of different core diameters, which look very similar to those of air-clad fibers shown in Fig. 3. The main effect of the foam claddings is in the additional transmission losses due to foam material absorption and scattering on the foam microstructure. Therefore, by replacing the air cladding of rod-in-air fibers with a foam, one should mostly observe changes in the modal propagation loss. Thus, considering, for example, the experimentally measured RI and loss of a polystyrene foam in the THz region as 1.0104 and 1 dB/m (see Ref. [11]), the total loss of the fundamental mode of the straight rod-in-foam fiber is then computed as 2.4 dB/m, 1.45 dB/m, and 1.01 dB/m for the fiber diameters of 1.75 mm, 0.93 mm, and 0.57 mm, respectively.



**Fig. 22.** Normalized electric field profiles |E| of the fundamental modes at the carrier frequency of 128 GHz for rod-in-foam fibers of various diameters. (a) 1.75-mm-diameter core and 5-mm-diameter foam cladding; (b) 0.93-mm-diameter core and 7-mm-diameter foam cladding; (c) 0.57-mm-diameter core and 50-mm-diameter foam cladding.

These losses should be compared to those of the air-clad fibers, which are 2.2 dB/m, 0.6 dB/m, and 0.01 dB/m for the same fiber diameters. As propagation of the fundamental mode in the 1.75 mm fiber is mostly inside of the PP core, the effect of the foam cladding is minimal, thus resulting in only 0.2 dB/m increase in the modal loss compared to the air-clad fiber. In contrast, for the smaller diameter fibers, a significant part of the mode propagates outside of the fiber core and in the foam cladding, which can potentially lead to significant increase in the modal losses and reduction of the maximal error-free link distance if the foam losses are important.

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