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Experimental Demonstration of 5 Gbps Data Transmission Using Long Subwavelength Fiber at 140 GHz

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ABSTRACT— **We present the experimental demonstration of real-time data transmission using a long subwavelength dielectric fiber in the Terahertz (THz) frequency range. A commercial 3D printing filament made of polypropylene material with the diameter of 1.75 mm is used as the solid core fiber for signal transmission. A photonics-based THz communication system operating at the carrier frequency of 140 GHz is used to characterize the fiber. The fiber is butt coupled in both emitter and detector antenna to minimize the free space coupling loss. The performance of the fiber is measured by recording the bit error rate (BER) for the transmitted data rate of 5 Gbps with a pattern length of 2^{31}-1. By fixing the decision threshold to 0 mV, the BER of 10^{-7} is recorded for the fiber length of 3 m and 5 m respectively at the emitter photocurrent value of 8 mA. A successful error free data transmission using a 1 m fiber with the diameter of 670 µm is demonstrated. In addition, the effect of bending in a graded index porous fiber made of low density polyethylene is also studied.**

Index Terms — **Millimeter wave measurements, Terahertz communications, optical waveguides, Transmission lines measurements**

I. INTRODUCTION

Research in Terahertz (THz) frequency spectrum (100 GHz-10 THz) is advancing in several applications that includes communications [1], imaging [2] sensing [3] and spectroscopy [4]. To meet the bandwidth demand in high speed wireless communications, a shift of the carrier frequency towards the THz band is particularly interested [5]. So far, THz communications have been mainly demonstrated in free space wireless links due to the presence of several atmospheric transmission windows [4]. Furthermore, bulk optical components are necessary to collimate and focus the THz beam at the transmitter and receiver respectively. Particularly, the THz wireless links are very sensitive to alignment errors which requires careful positioning of the antenna. The atmospheric weather conditions such as rain, snow, fog etc. play a major role in affecting the performance of a wireless THz link. Also, it is difficult to integrate the THz communication system with other components for signal processing applications in the case of wireless transmission. Therefore, a low loss THz transmission line is preferred.

In the past years, several designs of THz waveguides have been proposed and demonstrated [5-12]. The choice of waveguide material is one of the major obstacles in achieving THz guidance with low loss and dispersion. In the case of metallic waveguides, the finite conductivity of metallic boundaries leads to higher ohmic losses whereas in dielectric waveguides, the loss is mainly due to material absorption [7]. By selecting proper materials with low absorption loss (Teflon, polyethylene, cyclic olefin copolymer to name a few) and engineering the waveguide structure, a highly efficient THz guidance can be achieved [13-16]. THz fibers with subwavelength dimension offers low loss when compared with the bulk material where most part of the modal field propagates in air [17]. Such fibers can be used to increase the communication link distance with high performance [18]. As the propagating fundamental mode in the subwavelength fiber is loosely confined and possesses low losses, efficient THz components such as directional coupler, power divider, band pass filter etc. can be realized for real-time signal processing applications [19]. The application of dielectric waveguides for high speed data transmission have been demonstrated recently [20, 21]. An error free transmission of 2.5 Gbps data over the link distance of 7 m has been demonstrated using a capillary waveguide made of Teflon at the carrier frequency of 120 GHz [21]. Similarly, in [22] ortho-mode sub-THz interconnect channel for planar chip-to-chip communications using silicon dielectric waveguide has been investigated. All these studies suggest that dielectric waveguides for THz communication link is a promising technique for high bit rate transmission.

In this work, we demonstrate the real-time data transmission using a long polypropylene (PP) fiber at the carrier frequency of 140 GHz. Among other polymers, PP is one of the cost-effective materials with low loss and low dispersion over a wide THz frequency range with a refractive index of ~1.5 [23, 24].

II. EXPERIMENTS

A commercial 3D printing PP material (Verbatim) with the diameter (d) of 1.75±0.05 mm is used as a solid core fiber for THz transmission. Another PP fiber with subwavelength dimension is drawn by reducing its size from 1.75 mm to 670±30 µm using a 3D printer (MakerBot Replicator). The temperature of the extruder is set to 220˚C which is the process temperature of PP fiber for the extrusion. Though the nozzle size of the 3D printer is 400 μm, a fiber with ~670 μm is drawn by slowing down the pulling process. However, the uniform length of the subwavelength fiber is limited to 1 m due to fixed extrusion time of the 3D printer.

A finite element method-based software, COMSOL Multiphysics, version 4.2 is used to theoretically study the characteristics of the fiber. The power flow distribution of the fundamental mode in a PP fiber with the diameter of 1.75 mm (PP-1) and 670 μm (PP-2) at the carrier frequency of 140 GHz is shown in fig.1. In the case of PP-1 most of the power propagates inside the solid core (fig. 1a) whereas in PP-2, the mode is loosely coupled to the fiber and propagates mainly in air reducing the material absorption loss (fig. 1b). The effective modal index of PP-1 and 2 is 1.302 and 1.0001 respectively.

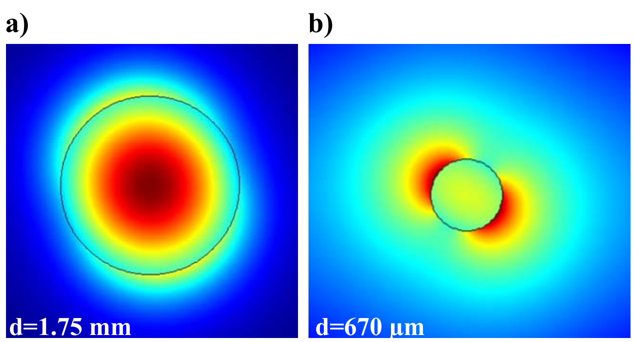

Fig.1. The power flow distribution of fundamental mode in a) PP-1 and b) PP-2 at the carrier frequency of 140 GHz

The fiber is experimentally characterized using a photonics-based THz wireless communication system as shown in fig.2. The detailed description of the system is presented in [25]. Briefly, two-independently tunable distributed feedback laser operating in the infrared C-Band with slightly different center frequency are used to optically drive the photomixer.

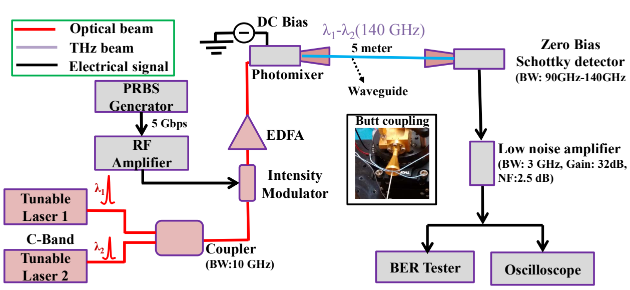

Fig.2. Schematic of the photonics-based THz communication system. Inset: Butt coupling of fiber to the antenna and held

The laser beams are combined using a 3 dB coupler and intensity modulated (ASK) using an external electro-optic Mach-Zehnder modulator. A baseband signal source of pseudo random bit sequence (PRBS) with bit rate of 5 Gbps and pattern length of 2^{31}-1 is used. The modulated laser beams are amplified using an erbium doped fiber amplifier (EDFA) and injected into the waveguide coupled uni-traveling-carrier-photodiode (UTC-PD) photomixer (NTT Electronics) for THz generation. The wavelength of the laser beams is adjusted so that the frequency difference between them is 140 GHz. The choice of the carrier frequency is determined by the output THz power and responsivity of the detector antenna. In the receiver section, a zero bias Schottky diode is used to detect and demodulate the baseband signal. The baseband signal is then amplified using a high gain low noise amplifier and the bit error rate (BER) is measured using the test equipment (Anritsu -MP2100B). The output THz power of the photomixer is proportional to the DC bias voltage and input optical power. In fig.3, the THz output power at the carrier frequency of 140 GHz is presented which is recorded by fixing the DC bias voltage to -2 V. The nominal photocurrent of the photomixer is 7 mA where the corresponding THz power is ~-5 dBm at 140 GHz.

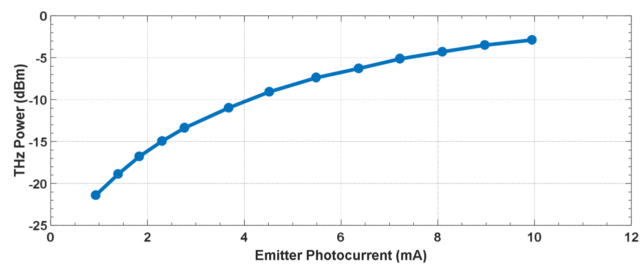

Fig.3. THz output power from the photomixer at the carrier frequency of 140 GHz (Courtesy of NTT Electronics).

III. Results and Discussion

A. Solid core waveguides

Before characterizing the fiber, the THz transmitter and receiver with slightly different height and angle is placed at 0.5, 1 m, 3 m and 5 m apart. As there is no collimating and focusing optics, it is confirmed that no stray THz beam is received in the detector. Therefore, the signal reception will be purely due to fiber only.

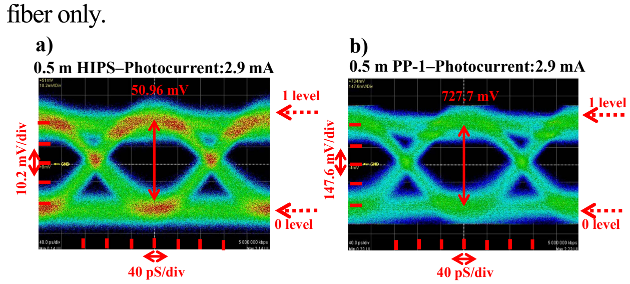

Fig.4. 5 Gbps eye pattern in a 0.5 m a) HIPS and b) PP-1 waveguide.

We used a standard 3D printing filament as the THz waveguide in our experiments. Therefore, the choice of using polypropylene fiber (PP-1) for data transmission is verified by comparing it with high-impact polystyrene (HIPS) fiber (diameter of 1.75 mm) and length 0.5 m each. An eye pattern for the data rate of 5 Gbps is recorded for the emitter photocurrent of 2.9 mA as shown in fig.4. An eye amplitude of 727.7 mV and 50.96 mV is recorded for PP-1 and HIPS waveguide respectively. Therefore, it is concluded that the performance of the THz waveguide made of PP is superior than HIPS due to lower absorption loss in the target frequency range.

Next, PP-1 of length 5 m is butt coupled at both emitter and detector antenna to minimize the free space coupling loss. To hold the fiber steadily, we designed and fabricated several fiber holders. However, holding the fiber using a thin thread with fisherman's knot is simple and effective (Inset of fig.1). By fixing the DC bias to -2 V, the optical power is varied using EDFA, while the BER is measured as a function of the photocurrent of the photomixer. To record a highly consistent BER in short measurement duration, we choose the target BER of 10^{-12} in our experiments. For the target BER of 10^{-12}, and 5 Gbps bit rate, the duration of a single measurement is calculated as measurement time = 1/(target BER · bit rate) ≈ 200 sec. The decision threshold is fixed as 0 mV and BER is recorded for PP-1 with a length of 5 m followed by 3 m as shown in fig.5. It is observed that a high bit errors were recorded for 5 m fiber when compared with 3 m fiber which is mainly due to material absorption loss. Within the forward error correction (FEC) limit (BER ~10^{-3}), the photocurrent for 3 m and 5 m fiber is 3.2 mA and 4.4 mA respectively. Although we measure a higher eye amplitude in a 3 m fiber, the performance is not improved beyond the photocurrent of 5 mA. This is due to the vertical asymmetry (digital 1 and 0 have unequal amplitude from the threshold value) of the eye pattern as presented in fig.5. The small vertical asymmetry arises from the optical modulation itself which could be due to slight variation in the operating bias point of the electro-optic modulator.

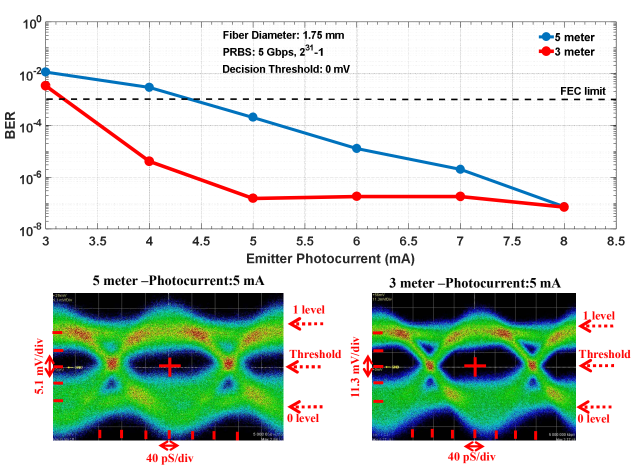

Fig.5. Measured BER as a function of the emitter photocurrent for 3 m and 5 m PP PP-1.

Since the amplitude of digital 0 is close to the decision threshold point, the contribution of insertion error (digital 0 is mistaken as digital 1) is much higher to the total bit errors when compared with the omission errors (digital 1 is mistaken as digital 0) limiting the performance. However, the performance can be improved by optimizing the decision threshold.

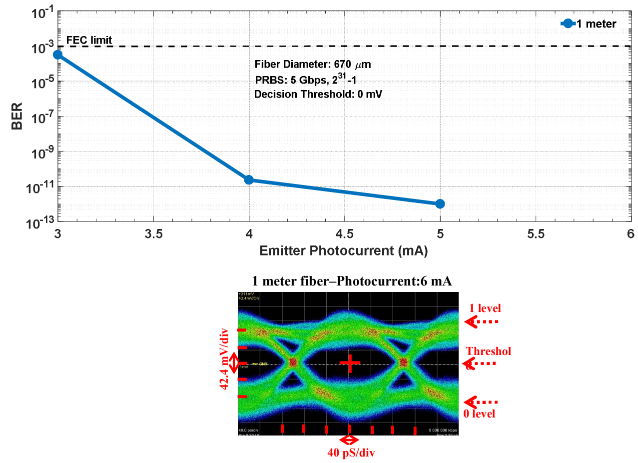

Fig.6. Measured BER as a function of the emitter photocurrent for 1 m PP PP-2.

Next, PP-2 of length 1 m is characterized for the same bit rate of 5 Gbps as shown in fig.6. As the mode field mainly propagates in air, the material absorption loss is almost zero. The fiber is tightly held at both emitter and detector antenna without any bend and therefore the total loss (including the bending loss) is minimized in a short 1 m fiber link. Beyond the photocurrent value of 5 mA, we did not observe any errors within the measurement duration of 200 sec.

B. Porous waveguides

Next, we investigated the effect of bending in a graded index porous waveguide (GI-PW) which is fabricated using low density polyethylene (LDPE) [26]. The porous waveguides are particularly interested to reduce the material loss and dispersion. The BER was measured for the data rate of 6 Gbps in a GI-PW of length 22 cm as shown in fig.7. The inset in the fig.7 shows the schematic of the bending experiment.

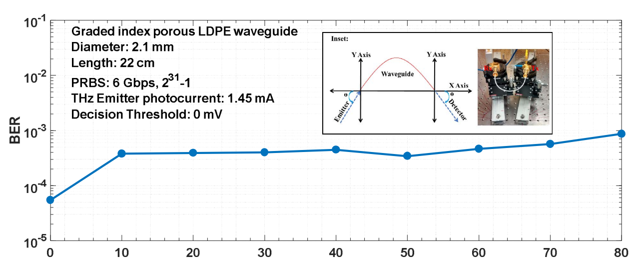

Fig.7. Measured BER as a function of bending angle in GI-PW.

Both the emitter and detector antenna were rotated at the same angle. In order to observe the effect of bending in the GI-PF, the emitter photocurrent was set to 1.45 mA which results in the BER slightly above the FEC limit. It is found that, even at the waveguide bending angle of 80 degrees (θ), the variation in the BER is minimal when compared with straight fiber (θ =0 degree). Mostly, the THz integrated circuits and devices can be linked using a short length waveguides. Therefore, such THz fibers can be easily integrated in the real-time applications.

V. CONCLUSION

To conclude, we have experimentally demonstrated the real-time data transmission using polypropylene THz fiber of length up to 5 m. We observe that an error free data transmission with the data rate of 5 Gbps can be achieved for the fiber with subwavelength dimension at the carrier frequency of 140 GHz. Furthermore, we investigated the performance of GI-PW and found negligible effect due to bending at various angles. Such fibers can be used in the indoor applications such as data centers, device-to-device communications, KIOSK systems to name a few. Also, it is possible to construct passive THz components such as directional coupler, band pass filter etc. In the future work, we are focusing on to increase the THz fiber link length to at least 10 m.

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