Continuous Fabrication of Microstructured Fibers for THz Communications Using Infinite 3D Printing

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Abstract: A microstructured suspended-core polymer fiber is designed and characterized experimentally for information transmission at 128 GHz carrier frequency. It is 3D printed using a 45° inclined extruder that enables continuous, length-unlimited fabrication of terahertz fibers.

1. Introduction

In the Terahertz (THz) spectral range, the conventional methods such as stack-and-draw and drilling are widely used for the fabrication of microstructured fibers (MSF). In these techniques, the microstructured preform must be fabricated and then drawn under pressure using the fiber drawing tower. It is a complex process which requires precise calibration and monitoring, particularly for longer fibers. On the other hand, 3D printing of MSF's enables robust fabrication with minimal supervision with the principal limitation being small fiber length limited by the printer build volume. In this work, a suspended core MSF is fabricated using a novel infinite 3D printing technique that allows continuous fiber fabrication without any limitations on its length. As an example, we use polypropylene (PP) material to fabricate and characterize fiber that features low loss and near-zero dispersion at 128 GHz.

2. Fiber design and theoretical demonstration

In Fig.1 (a) we show cross-section schematic of the suspended-core MSF optimized to have low modal loss and near-zero dispersion at the carrier frequency of our THz communication system (128 GHz). The core, outer layer and connecting bridges are formed by PP (blue color) and the inner cladding is air (white color). A negative curvature solid core with a diameter of 1.62 mm is suspended using three support bridges (0.4 mm). The cladding region is formed by three air holes with a radius of 3.69 mm which are symmetrically distributed around the fiber center. The distance between the fiber center and the air-hole center is 4.5 mm. The inner and outer diameters of the fiber are set to 7.6 mm and 8.0 mm, respectively. The numerical simulation has been carried out using COMSOL Multiphysics in which the refractive index and absorption loss of PP are 1.485 and 2.36 dB/m respectively [1].

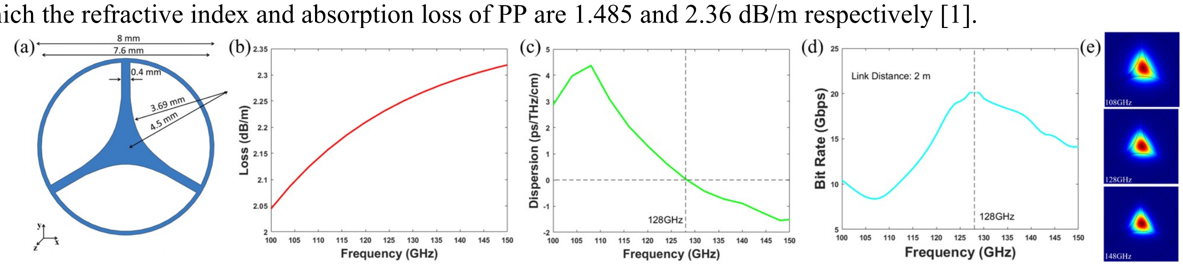

Fig. 1. (a) Schematic of the fiber cross-section, (b) modal losses, (c) dispersion, (d) bit rate and (e) normalized electric field distribution of the fundamental mode as a function of operation frequency near 128 GHz carrier.

As shown in Fig. 1(b), the theoretical loss of the fundamental mode is 2.04 – 2.32 dB/m (100 – 150 GHz), with 2.25 dB/m at the carrier frequency of 128 GHz. Moreover, modal dispersion [Fig. 1(c)] at 128 GHz is near-zero by design. Fig. 1(d) shows that the maximum bit rate of the signal transmission supported by the printed 2 meter-long fiber. This was estimated using a classic expression Bit rate$= 1/4\sqrt{|\partial^2\beta/\partial\omega^2|L}$, while at zero second order dispersion the maximum error-free bit rate is estimated using third order dispersion [1] Bit rate $= 0.324/\sqrt[3]{|\partial^3\beta/\partial\omega^3|L}$, where β, ω and L are the propogation constant, angular frequency and fiber length. Theoretically, we therefore estimate that the proposed fiber could support ~20 Gbps error-free bit rate transmission at 2 m-lengths, which is attractive for short-range fiber-assisted communications. The normalized electric field distributions of the fundamental mode at different frequencies are shown in Fig. 1(e). At higher frequencies, the modal field shows stronger confinement within the core.

3. Theoretical characterization of the infinite 3D printed fiber

The proposed fiber is 3D printed (1.4 meters long) using the 45° inclined extruder with the nozzle size of 0.25 mm using BlackBelt 3D Printer and is shown in fig.2 (a). The outer and inner diameters of this fiber are ~8.2 mm and

~7.7 mm, respectively. The thinnest part of the three bridges is ~0.5 mm. The suspended core has a diameter of about 1.53 mm, featuring a small hole defect (along the whole fiber length) in the center of the core.

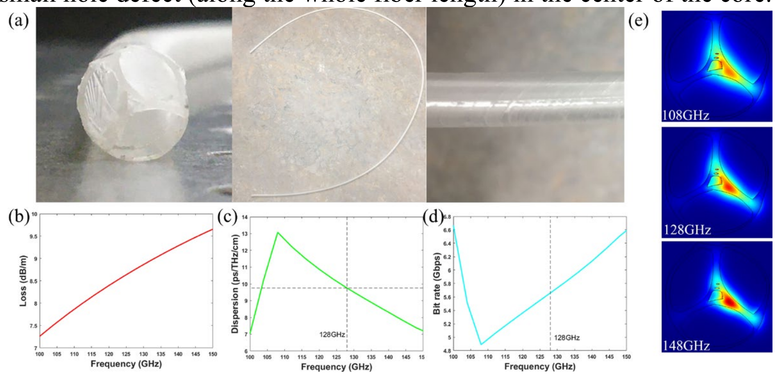

Fig. 2. (a) The cross-section, top view and side view of the fabricated fiber using an infinite 3D printer. The (b) loss, (c) dispersion, (d) bit rate and (e) normalized electric field distribution of the fundamental mode as a function of the operation frequency.

Then, a two-dimensional model of the fiber cross-section is obtained from the fiber microscope image and used for numerical simulations. The fiber features a loss of 8.78 dB/m [Fig. 2(b)] and dispersion of 9.759 ps/THz/cm [Fig. 2(c)] at 128GHz. Thus, the maximum bit rate supported by this fiber using basic ON-OFF keying is predicted to be 5.66 Gbps [(Fig. 2(d)]. The differences in loss and dispersion between the designed fiber and a 3D printed one are due to a defect in the fiber core that pushes the modal field into the air and cladding regions [Fig. 2(e)]. Further optimization of the 3D printing process is therefore in order to improve fiber fabrication, but is beyond this work.

4. Experimental characterization of the infinite 3D printed fiber

The 3D printed suspended core MSF is further characterized using an in-house THz communication system detailed in [2]. The fiber transmission loss is measured using a standard cutback method. The bit error rate (BER) is measured for bit rates from 1 Gbps to 6 Gbps. It is noted that the fiber is butt-coupled to the waveguide flange at the input end and is undisturbed throughout the experiments to maintain the optimal excitation conditions.

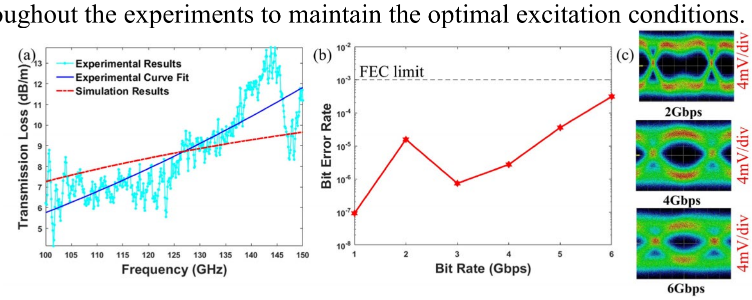

Fig. 3.Experimental characterization of the 3D printed fiber. (a) Transmission loss vs frequency, (b) Bit Error Rate vs Bit Rate and (c) measured eye patterns for different bit rates for a 0.75 m-long fiber.

The transmission loss is measured from 100 GHz – 150 GHz and is presented in Fig. 3(a). The measured loss at 128 GHz is 8.86 dB/m which agrees well with the theoretical results (8.78 dB/m). The BER measurements are carried out using a 0.75 m-long 3D printed fiber section and results are presented in Fig.3 (b). We see that, the fiber can transmit up to 6 Gbps with the BER value much lower than the forward error correction (FEC) limit (10^{-3}). Similarly, the eye patterns show good symmetry and clear openings can be observed even at 6 Gbps [see Fig. 3(c)]. In fact, for this fiber the experimental BER is limited by the low output THz power of our communication system (~218 µW at 128 GHz) and relatively high losses of the infinite 3D printed fiber.

In summary, a suspended core MSF is proposed and fabricated using an infinite 3D printer. The experimental characterization is carried out to validate the theoretical analysis. Furthermore, the THz communication link at 128 GHz is established using a 0.75 m-long fiber and a 6 Gbps operation with BER below FEC limit is demonstrated. We conclude that, infinite 3D printed terahertz MSFs can be a viable option for building the next generation fiber-assisted THz communication systems.

4. References

[1] K. Nallappan, Y. Cao, G. Xu, H. Guerboukha, C. Nerguizian, and M. Skorobogatiy, "Dispersion Limited versus Power Limited Terahertz Transmission Links Using Solid Core Subwavelength Dielectric Fibers," *Photonics Research,* vol. 8, no. 11, pp. 1757-1775, 2020.

[2] K. Nallappan, H. Guerboukha, C. Nerguizian, and M. Skorobogatiy, "Live Streaming of Uncompressed HD and 4K Videos Using Terahertz Wireless Links," *IEEE Access,* vol. 6, pp. 58030-58042, 2018.