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Guidance of Terahertz Wave over Commercial Optical Fiber

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***Abstract*—This work proposes a new flexible terahertz subwavelength fiber using commercial optical fiber as the core medium. The proposed dual-band fiber allows the optical signals to propagate in the innermost two layers and the THz signal to distributed over the optical fiber and mostly in the lossless foam cladding. The propagation loss at 1550 nm and 500 µm are 0.2 dB/km and 0.034 dB/mm, respectively. The proposed fiber is compact and cost-effective, making it a promising candidate for optical and terahertz fusion sensing, imaging, and nonlinear optoelectronics applications.**

I. INTRODUCTION

THE characteristic scales of terahertz (THz) waves (0.1~10 THz ≡ 0.03~3 mm ≡ 0.414~41.4 meV) in the dimensions of time, space and photon energy are closely related to many unique phenomena in nature, so there are abundant scientific research opportunities and industrial applications in the fields of communication, imaging, sensing, and spectroscopy. THz fibers or waveguides interconnect different functional modules in THz systems, and are vital if high stability, reliability, and flexibility are required in the systems when comparing with the free-space transmission of THz wave.

Recently, based on the guidance mechanism, step-index fibers, anti-resonance fibers, and photonic-crystal fibers have attracted much attention for efficient guidance of THz wave. Among various THz fibers, foam-cladded dielectric-core subwavelength fibers have been reported as strong candidates for the guidance of THz wave over few meters with low loss [1, 2]. This work presents an expanded polystyrene (EPS) foam cladded optical-fiber-core fiber which allows optical and terahertz signals to propagate over it simultaneously, which opens the opportunities for optical and terahertz fusion sensing, imaging, and nonlinear optoelectronics applications.

II. RESULTS

The proposed THz subwavelength fiber with bare optical fiber as the solid core and EPS foam as the cladding is shown in Fig. 1. Standard commercial Corning SMF28e+ single-mode optical fiber is used as the core of the THz subwavelength fiber [3]. The protective polymer coating layer of the SMF28e+ fiber can be dissolved using an organic solvent, such as acetone. Benefiting from the mature optical fiber drawing techniques, the bare optical fiber, made up of doped silica as the core and pure silica as the cladding is extremely cost-effective and has minimum surface roughness which helps to reduce the scattering loss of THz subwavelength fiber. By enclosing the bare optical fiber with low-density EPS material, whose refractive index is near unit and absorption is extremely low [4], a step-index fiber with the subwavelength solid core can guide terahertz with low loss. With a large wavelength-to-diameter ratio, the energy of the propagating mode expands to the EPS foam, minimizing the fractional power delivered inside the relatively lossy silica core [5, 6].

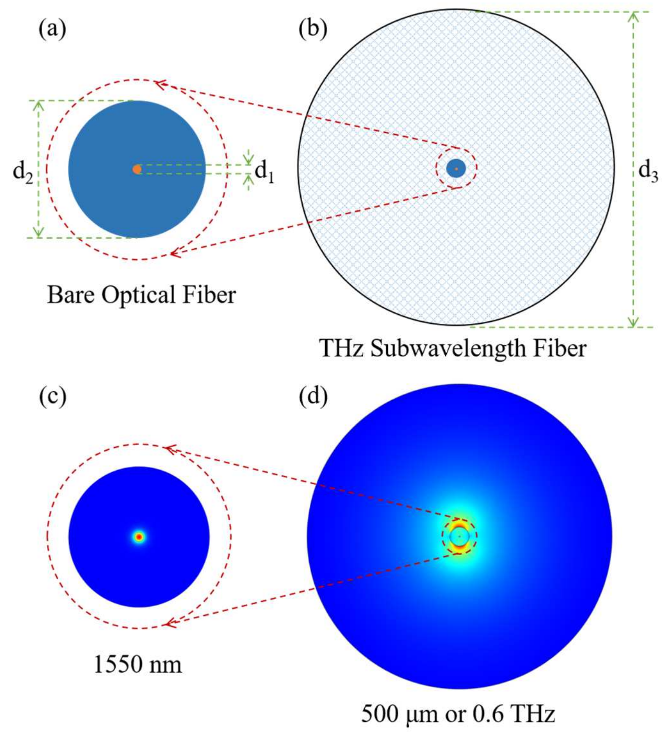

Fig. 1. Geometries and dominant modes in terahertz and optical dual-band fiber. (a) Standard commercial optical fiber with the outmost protective cladding layers being removed. d_1=8.2 µm and d_2=125 µm. (b) THz subwavelength fiber comprised of the bare optical fiber and the EPS foam cladding. d_3=2 mm. (c) Optical mode at 1550 nm. (d) THz mode at 500 µm or 0.6 THz.

The refractive index of the doped silica and pure silica at 1550 nm are 1.4707 and 1.4654, respectively. At 500 µm, since the wavelength is significantly larger than the diameter of the doped silica core, the doped silica core is regarded as the same as pure silica whose refractive index is 1.9488+0.0091i. The refractive index of the low-density EPS foam is measured to be 1.001+2.7833e-5i at 500 µm using THz time-domain spectroscopy, and it is basically dispersionless and lossless over the THz frequencies of interest. The dominant mode at 1550 nm and 500 µm calculated by COMSOL mode analysis solver are shown in Figs. 1 (a) and (b). The propagation loss of the SMF28e+ optical fiber at 1550 nm is less than 0.20 dB/km, and the propagation loss of the THz subwavelength fiber at 500 µm is 0.034 dB/mm.

At both optical and terahertz bands, the proposed fiber works as a single-mode fiber simultaneously. According to the formal product information sheet [3], the Corning SMF28e+ optical fiber works as an effectively single mode fiber between 1310 nm to 1625 nm with the propagation loss ranging from 0.23

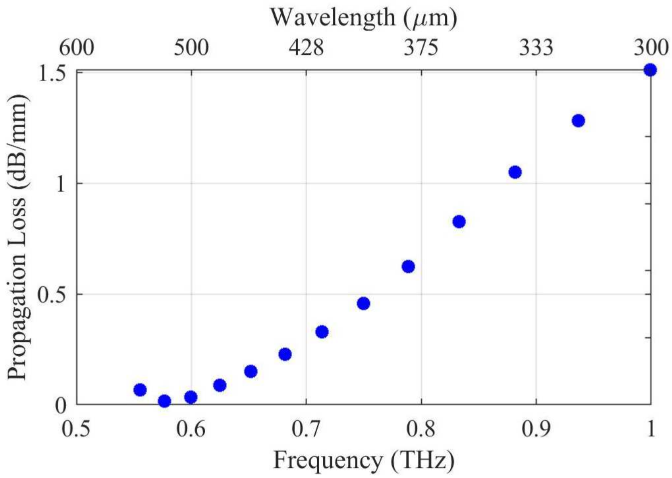

Fig. 2. The simulated propagation loss of the THz subwavelength fiber.

dB/km to 0.35 dB/km. At the same time, according to numerical simulation results obtained by COMSOL, the THz subwavelength fiber works as a strictly single-mode fiber between 300 to 550 um (or 0.55 to 1 THz). The propagation loss is less than 1.51 dB/mm across the frequency range between 0.55 to 1 THz, with a minimum of around 0.018 dB/mm at 0.58 THz, as shown in Fig. 2. At the long wavelength end, the guided HE_{11} mode is weakly confined and the electric field reaches the outmost absorbing boundary, which increases the propagation loss. This explains why the propagation loss becomes higher at frequencies lower than 0.58 THz. By increasing the thickness of the cladding foam layer, the propagation loss will be lowered, especially at long wavelengths.

III. Summary

This paper presents a novel flexible terahertz subwavelength fiber using commercial optical fiber as the core medium. At both optical and terahertz bands, the proposed fiber works as a single-mode fiber simultaneously, as the optical mode is confined in the innermost two layers, and the THz mode takes the bare fiber as the core and the foam layer as the cladding forming a typical step-index fiber. The proposed dual-band fiber is low loss at both bands. Our work paves the way for optical and terahertz fusion sensing, imaging, and nonlinear optoelectronics applications.

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References

[1]. K. Nallappan, Y. Cao, G. Xu, H. Guerboukha, C. Nerguizian, and M. Skorobogatiy, "Dispersion-limited versus power-limited terahertz communication links using solid core subwavelength dielectric fibers," *Photonics Research*. vol. 8, pp. 1757-1775, November, 2020.

[2]. H. Guerboukha, G. Yan, O. Skorobogata, and M. Skorobogatiy, "Silk foam terahertz waveguides," *Advanced Optical Materials*, vol. 2, pp. 1181-1192, December, 2014.

[3]. Corning Inc., "Corning® SMF-28e+® Optical Fiber," Corning.com, Sept. 2019. [Online]. Available: https://www.corning.com/optical-communications/worldwide/en/home/products/fiber/optical-fiber-products/smf-28e-.html. [Accessed: 30 June 2021].

[4]. G. Zhao, M. Ter Mors, T. Wenckebach, and P. C. M. Planken, "Terahertz dielectric properties of polystyrene foam," *Journal of the Optical Society of America B*, vol. 19, pp. 1476-1479, June, 2002.

[5]. L. J. Chen, H. W. Chen, T. F. Kao, J. Y. Lu, and C. K. Sun, "Low-loss subwavelength plastic fiber for terahertz waveguiding," *Optics Letters*, vol. 31, pp. 308-310, February, 2006.

[6]. M. Roze, B. Ung, A. Mazhorova, M. Walther, and M. Skorobogatiy, "Suspended core subwavelength fibers: towards practical designs for low-loss terahertz guidance," *Optics Express*, vol. 19, pp. 9127-9138, April, 2011.