Abstract—We experimentally demonstrate single-mode broadband THz propagation in hollow core waveguides fabricated with a 3D printer with metallic inclusions. The measurement data obtained from the Terahertz (THz) Time Domain spectroscopy experiments show low loss guidance and low dispersion characteristics, and these are in very good agreement with the results obtained from numerical simulations of the investigated waveguides.

I. INTRODUCTION

Parallel wires have been demonstrated as THz waveguides with low loss [1,2]. Recently, we have reported hollow core waveguides with metallic inclusions and the waveguides are fabricated using a drawing tower [2]. In this letter, we report on our work on fabrication of hollow core waveguides with a commercial 3D printer that allows us to test various waveguide designs fast and inexpensively [4, 5]. The versatile designs of our waveguide allow us to investigate THz radiation characteristics in the two, three and four copper wires attached to the hollow core 3D printed waveguides.

Fig. 1 shows the schematic of the THz time-domain spectroscopy (THz TDS) setup that we used to investigate our waveguides [7]. The specially-designed lenses, the symmetric-pass lenses with a focal length of 75mm (NA=0.33) are used to achieve good mode-matching with the fundamental mode \( \text{HE}_{11} \) in the waveguide [2, 3].

II. RESULTS

The fabricated fibers have a core diameter of 3 mm, and the core is surrounded by 12 air holes each with a diameter of 0.35 mm. The copper wires are manually inserted into the selected voids, as shown in Fig. 2(b). Fig. 2(a) shows the temporal signals obtained from the different wire configurations in these waveguides for a 50 mm length. We also measured 100 mm length of these waveguides. Fig. 2(c) shows the \( \text{HE}_{11} \) mode distribution in the waveguides for 0.7 THz, simulated with the finite difference frequency domain solver by MODE Lumerical Solutions using the measured values for the refractive index and attenuation constant of the polymer used in the fabrication.

Fig. 2. (a) The measured THz waveform for reference (inset), and for 50 mm length of two-wire, three-wire, and four-wire configurations. Compared to the reference signals, we observed there is a time delay of the peak, 1 picoseconds (ps) for 50 mm and 2 ps for 100 mm length. (b) The photograph of the waveguide with copper wires inserted. The metal wires are seen as brown dots, and the polymer cladding has a yellow tint. The arrow in (b) indicates the polarization of the input THz field. (c) From top to bottom, the normalized intensity mode profile at 0.7 THz in linear scale from the numerical simulations in two-, three- and four-wire configurations respectively.

Fig. 3. The measured (grey dot line) and calculated (solid red line) attenuation coefficient for two-wire (a), three-wire (b), and four-wire (c) configuration.

Fig. 3(a-c) shows the experimentally determined and simulated loss coefficients respectively for the two-, three-,
and four-wire configurations. The measured attenuation coefficients are obtained from comparing the Fourier-transformed amplitude spectrum of different lengths of the waveguides with that of the reference signals. We observed the trend of low attenuation at high frequencies for all types of wire configurations in our waveguides. For the frequency range from 0.5 to 1 THz all waveguides show losses between 0.1 cm\(^{-1}\) and 0.5 cm\(^{-1}\). In all wire configurations, the attenuation spectrum shows modulation pattern resulting from the anti-resonant reflecting optical waveguide (ARROW) characteristics [6]. Our simulation and measurement data show that the HE_{11} mode is no longer guided in our waveguides for frequency below 0.3 THz. From our measurements, we have achieved an average coupling efficiency of 62\%, 60\%, and 50\%, respectively for two-, three-, and four-wire configurations. Our measurement data agree with the simulation results that predict the reduction in the coupling efficiency in the four-wire configuration in comparison to that of the two and three-wire configurations due to effect of the metal wires on the mode field distribution.

Further, we numerically calculated the field behavior of the simulated mode profiles. The modeintensity distribution at 1/e\(^2\) threshold is fitted with a spatial-elliptic function that yields the radii of the major and minor axis of the fitted ellipse. The direction of the major axis is always along that of the polarization of the electric field. In the two- and three wire configurations, there is only small difference, in the range of 2-4\%, between the radii of the major and minor axes for the frequency range of 0.4 - 1 THz, while for the four-wire configuration this difference reaches 7 - 10 \% for the same frequency range. The reason for this increase is identified as a result of increasing field amplitude of the plasmonic mode excited on the two wires that werealigned parallel to the electric field. Additionally, we also try to turn the position of two-wire configuration waveguide 90° from its original position. This action yields higher attenuation and reduces the coupling efficiency by 10\% in average. Furthermore, when we change the position of three wires from the isosceles into the equilateral configuration, the attenuation increases and the coupling efficiency is reduced by 5\% in average. The plasmonic effect can also be observed on the three wires with equilateral arrangement but with a lower field magnitude than that of the four-wire configuration.

In Fig 4 (a-c), we plotted the effective phase index (n_{eff}) of the guided mode, obtained from extracting the phase details of the measured waveforms. The effective phase index of the HE_{11} mode is less than unity, an indication that the mode in these waveguides is essentially guided in air. We also calculated the group velocity dispersion (GVD) β parameter, the second derivatives of β with respect to ω, where β = k/ln_{eff}k is the mode propagation constant. The very good agreement between the predicted and the measured data are shown in Fig 4 (d-f) for the two-wire, three-wire, and four-wire configurations, respectively. We like to point out that the simulations do not contain any fitted parameters. We observe low dispersion with a magnitude of less than 5 ps.THz \(^{-1}\)cm\(^{-1}\) in the frequency range from 0.4 THz to 1.0 THz for all our waveguides.

### III. SUMMARY

We demonstrated broadband single-mode THz guidance in hollow core waveguides fabricated using a 3D printer with metal wires. We observed low loss THz propagation of about 0.2 cm\(^{-1}\) at 1 THz. We experimentally achieved high coupling efficiencies of up to 62\% for our waveguides. All wire configurations in these waveguides yield an effective phase index in the range of 0.98 to 1, and β parameters of less than 5 ps.THz \(^{-1}\)cm\(^{-1}\) in magnitude for the frequency range of 0.4-1 THz. The measured n_{eff} and β value are in very good agreement with the predicted values obtained from simulations.

### REFERENCES


