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Characterization of hybrid waveguide for Terahertz guidance

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ABSTRACT: It has been reported that the conventional two-wire waveguide is a good candidate for guiding the Terahertz (THz) wave. However, the waveguide may not be suitable for some practical purposes because of its environmental sensitivity and bulky setup. In this study, we proposed the hybrid waveguide as an alternative THz waveguide. The waveguide structure is mainly composed of transparent dielectric material to a THz wave with a central square of air gap flanked by a pair of copper wires along the waveguide axis. The waveguide is robust due to the mechanical support of the metal wires. At the same time, the dielectric cover can prevent any environmental disturbance that could affect the wave propagation properties. The numerical studies of the proposed waveguide were carried out by commercial software COMSOL Multiphysics, which is based on finite element analysis. The simulation results show that the proposed hybrid waveguide can provide low loss and low dispersion due to the guidance mechanism of the surface plasmon wave propagation similar to the conventional two-wire structure. Using two identical copper wires with the radii, the air hole width, and the center-to-center distance given as 150, 300, and 600 µm, respectively, results in the linearly polarized THz wave confined within the central square of the air gap. The effective refractive index of the proposed waveguide fundamental mode is 1.34 at the operating frequency of 0.2 THz. In addition, high modal energy is confined, and a low absorption loss is achieved.

KEYWORDS: THz waveguide, hybrid waveguide, 3D printed waveguide

INTRODUCTION

Terahertz (THz), T-ray, or T-wave is the part of the electromagnetic spectrum with frequencies from 0.1–10.0 THz [1]. Regarding wavelength, the THz waves are in the gap between 0.3 and 0.03 mm. These frequencies are between 2 well-researched electromagnetic (EM) wave ranges, infrared (IR) and microwave. Hence, to guide the THz wave, the well-developed waveguides for both IR and microwave propagations play crucial roles in the research field of THz waveguide fabrication and development [2].

The dielectric waveguide is widely used to guide the EM wave in the IR regime [3]. However, in the THz frequencies, the conventional mechanism for the radiation confinement (Total Internal Reflection: TIR) and common dielectric materials (glass) typically used in the IR range results in high absorption and dispersion. The high absorption in THz can be overcome by using transparent materials in THz radiation such as cyclic olefin copolymer (COC) and cyclic olefin polymer (COP), commercially known as TOPAS and Zeonex, respectively [4]. In the case of the dispersion effect, some alternative mechanisms to guide the THz wave, for example, Bragg structure [5], photonic band gap structure [6], or anti-resonance structure [7, 8], have been proposed. These mechanisms effectively provide the THz waveguide with almost a flat dispersion in a specific range of the THz frequencies. However, those waveguides do not support broadband waveguide applications in THz since the mechanisms allow only a narrow frequency band to propagate. In addition, the dielectric waveguide is not as good as the metal waveguide because some physical disturbances can cause twisting or bending while being utilized.

In the microwave and RF frequencies, the metallic waveguide is a typical structure that guides the waves. However, they are known to have a high absorption similar to the dielectric waveguide in guiding the THz wave. Because of this problem, the air medium known to have low absorption in a wide range of EM waves can be used in the metallic waveguide [9]. To achieve the non-dispersion effect along the waveguide, the 2 metallic waveguide structures such as parallel plate waveguide (PPWG) [2] and two-wire waveguide (TWWG) are good candidates [3]. In addition, the metallic waveguide supports the linearly polarized field in the guided mode, which results in high coupling efficiency compared to the other waveguide. Regarding structural simplicity, tolerance to bending, and functional similarity to the existing cables used to transmit the signal, TWWG is a good choice for guiding the THz wave. Nevertheless, the air space between the wires, which allows the high modal energy propagation, is prone to physical disturbances from environments, leading to worsening waveguide performance. This influence hinders the implementation of TWWG into practical applications.

In Table 1, according to the classification of the THz waveguide, the advantages and disadvantages of the dielectric waveguide and metallic waveguide based on operating frequency in the THz range are briefly summarized. In more detail, we suggest the comprehensive literature articles of THz waveguide

Table 1 Advantages and Disadvantages of the several THz waveguides.

		Dielectric waveguide[a]				
		(i)	(ii)	(iii)	(iv)	(v)
Advantage	– Simple waveguide structure	✓	–	–	–	–
	– Low material absorption	–	–	✓	✓	✓
	– Directly manufactured fabrication, for example 3D printer	✓	–	–	–	✓
Disadvantage	– High material absorption	✓	✓	–	–	–
	– Structure complexity	–	✓	✓	✓	✓
	– Narrow range THz in operating frequency	–	–	✓	✓	✓

		Metallic waveguide[b]		
		(a)	(b)	(c)
Advantage	– Simple waveguide structure	✓	✓	✓
	– Low loss and low dispersion due to a radial TM mode	–	✓	–
	– Low material loss and low dispersion due to transverse electromagnetic (TEM) mode	–	–	✓
Disadvantage	– Strong dispersion effect	✓	–	–
	– High coupling effective loss	✓	✓	–
	– Requirement of precisely optical components to experimental setup	–	–	✓
	– Sensitive to some physical disturbances in the environment	–	✓	✓

[a] Dielectric waveguide: (i) solid rod fiber [10], (ii) microstructured optical fiber [11], (iii) hollow core bandgap fiber [12], (iv) Kagome's structure waveguide [13], and (v) Antiresonance's structure waveguide [7, 8].
[b] Metallic waveguide: (a) circular metallic wire [14], (b) a bare metal wire [9], and (c) parallel plate waveguide (PPWG) and two-wire waveguide (TWWG) [15, 16].
Symbols ✓ and – represent the existent and non-existent features in each type of THz waveguides.

reviewed in [2–4, 17].

Hence, this work proposes the hybrid waveguide, composed of dielectric material and the 2 metal wires placed parallel to each other to guide the THz wave [17]. This proposed waveguide is designed to exploit the advantages of both dielectric and metallic waveguide structures, especially regarding waveguide characteristics such as low loss and low dispersion. In addition, using dielectric material as a cladding region in the TWWG can prevent environmental disturbances to this waveguide and fix the separated distance between metal wires, resulting in an effectively confined THz wave. To model and simulate the essential waveguide characteristics of the proposed hybrid waveguide for THz radiation, the finite element method (FEM) is applied by using COMSOL Multiphysics software.

MATERIALS AND METHODS

Guiding mechanism in the two-metallic wire based on plasmon waveguide

In this study, the THz surface plasmon waves (SPWs) propagate at the interface between metal and dielectric, which is air [18]. The two-metallic wire structure of the proposed hybrid waveguides can be directly excited with a simple THz dipole source, resulting in the fundamental transverse electromagnetic (TEM) mode equivalent to the SPWs propagating parallel to the interface between air and metal wires [2]. Similar to known surface waves on a planar dielectric-metal surface, the field associated with SPWs is enhanced into the media on either side of the interface. The SPWs extend considerable distances in the air due to low loss but only very short distances into the metal wires owing to the skin effect. The skin depth, a measure of the skin effect describing the penetration of a THz wave into a metal, is found to be much smaller than the wire radius [19] as found in the copper [2]. The skin effect relating to the effective resistance of the conductor restricts the propagation of the SPWs through the wires. Therefore, the propagation distance of surface waves is limited due to the wave attenuation from the resistance. The conductivity and the radius of the wire are found to affect the propagation distance of the surface waves [20]. In our study, the propagation distance of the surface waves in the conventional TWWG is in the order of hundred centimeters, while in the proposed hybrid waveguide, it is in the order of ten centimeters. The low propagation distance of our proposed waveguide is due to the material absorption surrounding the 2 copper wires.

Mathematical approaches determining the propagation properties of a hybrid waveguide

The propagation parameters of the waveguide used to determine the quality of the THz waveguide are the dispersion and attenuation properties. This section shows the analytical expression for these properties in terms of the waveguide geometry. Due to the dispersion and attenuation values depending on the complex effective refractive index of the waveguide, the solving

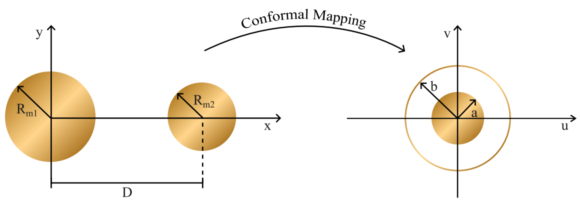


Fig. 1 The conformal mapping from the complex structure of the two-wire waveguide to a simpler equivalent structure of the co-axial waveguide.

technique for finding the effective refractive index of the waveguide is crucial. Following the report [21], the perturbation technique of boundary conditions can be used to solve for the index values of the waveguide.

In Fig. 1, the metal wires with different radii R_{m1} on the left and R_{m2} on the right are shown with the center-to-center distance, D. ε_m and ε_d represent relative permittivities of the metal and dielectric material, respectively. Using only perturbation techniques cannot solve the effective refractive index of the waveguide as a function of geometry parameters due to the complex structure. By using conformal mapping, known as the Mobius transformation, the complex geometry can be transformed into a simpler structure, which can simply be solved for the effective refractive index of the waveguide, as shown in Fig. 1.

The expressions for the transformed parameters are given as follows [21]:

$$x_1,\ x_2 = \frac{1}{2D}\left[\left(D^2+R_{m1}^2-R_{m2}^2\right) \mp \sqrt{\left(D^2+R_{m1}^2-R_{m2}^2\right)^2-4R_{m1}^2D^2}\right], \quad (1)$$

and

$$a = \left|\frac{R_{m1}+x_1}{R_{m1}+x_2}\right|, \quad b = \left|\frac{R_{m2}+D-x_1}{R_{m2}+D-x_2}\right|. \quad (2)$$

Hence, the effective refractive index of the two-wire waveguide is given as

$$n_{\mathrm{eff}}-n_d \approx \frac{n_d}{2k_0\sqrt{-\varepsilon_m}}\frac{1}{x_2-x_1}\frac{a+\frac{1}{a}+b+\frac{1}{b}}{\ln\frac{b}{a}}, \quad (3)$$

where n_d represents the refractive index of cladding [21] in the case of the conventional two-wire waveguide, n_d is the refractive index of air given by 1. Eq. (3) will be used to study the characteristics of the THz waveguide in our work for the next section.

Hybrid waveguide structure

The hybrid waveguide comprises 2 identical copper wires parallel to each other along the waveguide axis and surrounded by dielectric cladding. The initial

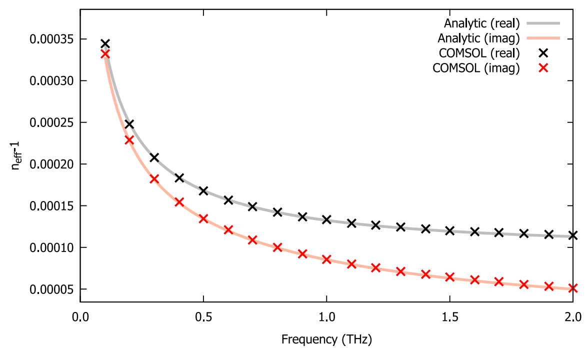


Fig. 2 Comparison of the effective refractive index of the conventional two-wire waveguide between analytical and numerical methods. The solid lines represent analytical values of effective refractive index −1. The black cross symbol is the real part of the index value, while the red cross symbol is the imaginary part.

geometry parameter (R_m) is designated as the radius of the copper wire. The center-to-center distance between the wires is given by D. The diameter of the dielectric cladding is L. By guiding the terahertz wave with a low material absorption, the rectangular air hole is introduced between the copper wires, as shown in Fig. 4 (bottom row) with a dimension of width (W_a) and height (H_a), respectively. In our study, TOPAS is used as the dielectric cladding to minimize the environmental impacts that can degrade the waveguide optical properties. Note that the TOPAS dielectric region in the waveguide structure is considered a cladding region, and the central air hole, which confines the THz surface wave between 2 metallic wires, is classified as a core region.

According to the complex geometry of the proposed hybrid waveguide, a numerical approach is employed to solve the complex problems. The numerical method used to demonstrate the feasibility of the proposed waveguide structure is the finite element method (FEM). The commercial software COMSOL Multiphysics, which is software based on FEM widely used to solve complex phenomena in physical and engineering problems, is utilized. The Mode Analysis in Radio Frequency (RF) module in two-dimensional (2D) is chosen in this work due to the symmetry of the waveguide-cross section along the waveguide axis.

Optical properties of dielectric and metallic materials

Many dielectric materials are used to make the waveguide in the visible-to-IR electromagnetic range. However, some of them are unsuitable for THz radiation due to their high absorption. With such a crucial characteristic, the TOPAS and Zeonex are widely selected as the dielectric materials for the waveguide in the THz regime. In our numerical analysis, the

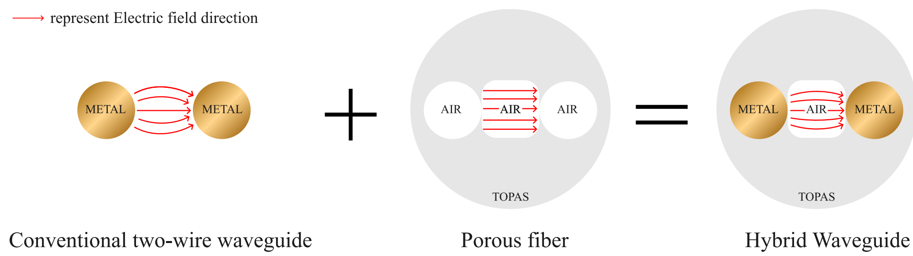


Fig. 3 The hybrid waveguides which are considered to be equivalent to conventional two-wire and porous waveguides. Also, the combination of the electric fields from both structures gives rise to the supported fundamental mode in the hybrid waveguide.

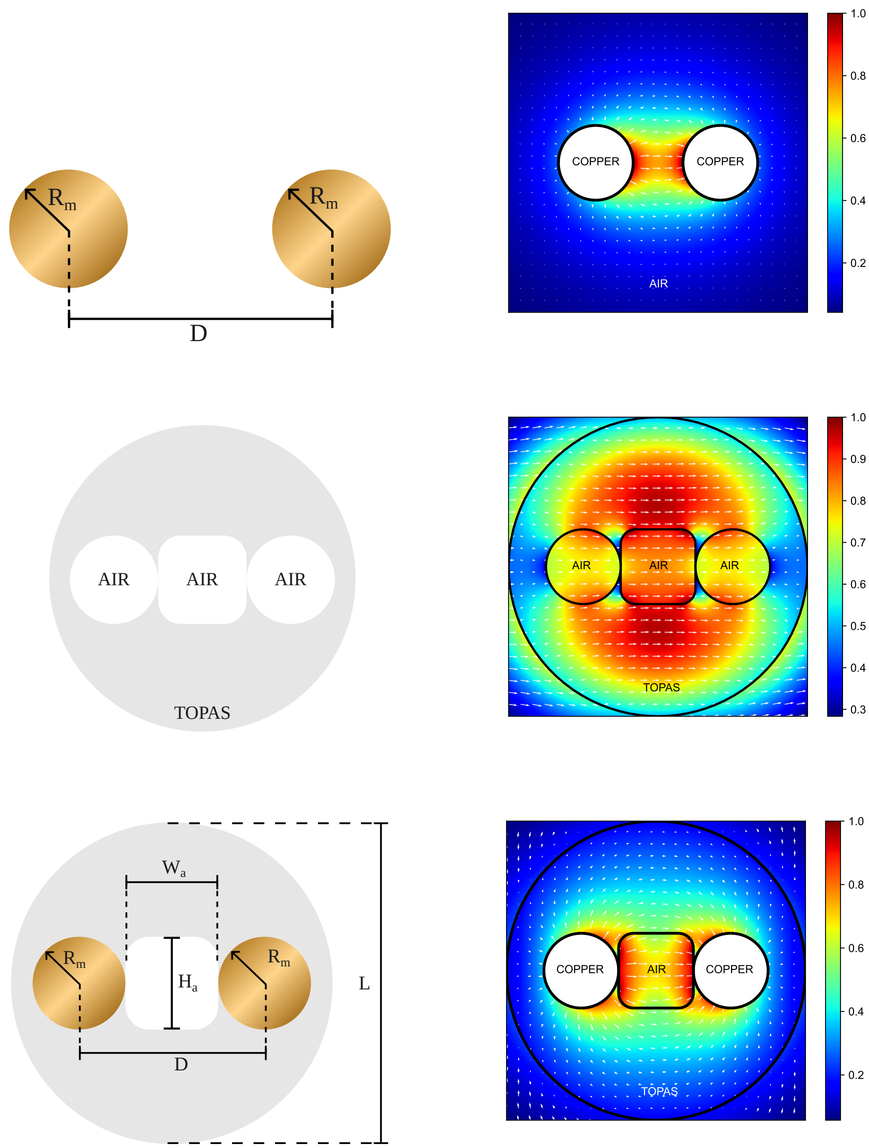


Fig. 4 The waveguide configurations and corresponding cross-sectional electric field distributions supported by a conventional two-wire waveguide (top row), a porous waveguide (middle row), and a hybrid waveguide (bottom row). The color bar represents a strength magnitude of electric field.

TOPAS was chosen as the dielectric structure of the hybrid waveguide. Regarding the optical properties, the refractive index of TOPAS is frequency independent and equal to 1.5258, while the absorption material loss is frequency dependent on the operating THz range [8].

Copper is a good candidate for metal wire due to its high conductivity and low skin depth compared to the other metal waveguides for THz guidance. In our simulation, the relative permittivity (ε_m) as a function of the copper frequency is described by the Drude model as [22].

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + \mathrm{i}\omega\omega_\tau}, \tag{4}$$

where ω_p and ω_τ represent the plasma frequency and the damping frequency of copper obtained from [22] with the values of 73.2 cm^{-1} and 59600 cm^{-1}, respectively, and the ω represents the angular frequency of the operating THz wave. The values of the optical properties of copper based on the Drude model will be used in our work.

RESULTS AND DISCUSSION

The accuracy of the numerical method for simulation study

In our study, we benchmarked the accuracy of the results obtained from COMSOL Multiphysics, the primary tool for our simulation study, by comparison with the analytical results. So, firstly, our study started with comparing the propagation parameters obtained from the analytical method and the numerical method for the conventional two-wire waveguide (equivalent to the hybrid waveguide in which metal wires are surrounded by air) to test the accuracy. The initial geometrical parameters are as follows: the radius of the copper wire is 150 µm, and the center-to-center distance is 500 µm. The optical properties of the copper wire were described in the previous section, while the relative permittivity of air is given as 1. The comparison of the results from the 2 methods is shown in Fig. 2. The numerical study performed in this work used a perfectly matched layer (PML) to absorb all fields outside the waveguide. The mesh size in the model structure is also considered independent of the characteristic of the studied waveguide by following the mesh independence process. The result shows that the values of the effective refractive index of the conventional two-wire waveguide are in good agreement with each other. The results confirm the accuracy of the simulation model adopted in our study.

The confined electric field in a hybrid waveguide

Based on the configuration of the hybrid waveguide, the waveguide structure can be considered to be equivalent to a conventional two-wire waveguide and porous fiber, as shown in Fig. 3. The electric direction of a supported fundamental TEM mode in the hybrid waveguide has to correspond to the direction of electric fields of the supported fundamental TEM modes in both the conventional and the porous waveguides as demonstrated in Fig. 3. Due to the mixing structure of the hybrid waveguide, the supported mode in such a waveguide is quite complicated to classify. Note that the fundamental mode of the hybrid waveguide only corresponds to the supported mode by the conventional two-wire waveguide, as reported in [23].

Table 2 Initial parameters used in a numerical study of a hybrid waveguide in COMSOL.

Parameter	Value
Radius of metallic wire (R_m)	150 µm
Center-to-Center distance (D)	600 µm
Width of the square air hole (W_a)	300 µm
Diameter of TOPAS (L)	1.2 mm
Thickness of PML layer	1.5 mm
Relative permittivity of copper (ε_m)	$(-6.5747 - 72.1399\mathrm{i}) \times 10^5$
Relative permittivity of air (ε_d)	1
Operating frequency (f)	0.2 THz
Operating waveguide (λ)	1.5 mm
Refractive index of TOPAS (n_{TOPAS})	1.5258

By using the initial parameters shown in Table 2, the confined THz electric field distribution in a fundamental mode of conventional two-wire waveguide, porous waveguide, and the proposed hybrid waveguide are numerically calculated and shown in Fig. 4. In Fig. 4 (top row), a conventional two-wire waveguide configuration and its electric field distribution of the fundamental mode is presented. The THz field is clearly confined in the air gap between metal wires corresponding to the polarization parallel to the line connecting the wire centers [17, 21, 23, 24]. In addition, the simulation results also show fields above and below the gap regions are slightly curved. Therefore, the supported TEM mode experiences low loss propagation and non-dispersion effect.

The porous waveguide with 3 air holes is considered next. The cross-sectional structure of the porous waveguide is shown on the left of Fig. 4 (middle row). The electric field distribution at the operating frequency of 0.2 THz of the porous waveguide clearly corresponds to the fundamental mode of the linearly polarized THz wave in the horizontal direction, similar to the conventional two-wire waveguide.

In the hybrid waveguide (Fig. 4, bottom row), the configuration and electric field distribution are presented. Because the supported fundamental mode in a conventional two-wire waveguide and a porous fiber shown in Fig. 4 (top row and middle row) is linearly polarized in the horizontal direction, the corresponding supported fundamental mode in a hybrid waveguide is consequently the linearly polarized light aligning in the direction connecting between two-copper wires within the air gap. This characteristic is an advantage and also suggests that any desired propagation properties of the confined THz wave in the proposed hybrid waveguide can be tunable by designing the waveguide structures of either a conventional two-wire waveguide or a porous waveguide.

Optimization of hybrid waveguide

In this section, the optimum performances of the hybrid waveguide are investigated. The criteria for optimization are as follows: the propagating THz wave confined in the central air hole to provide the low absorption loss, the linearly polarized direction of the THz field for a better coupling efficiency, and strong field confinement. According to the composition of the hybrid waveguide, the varying geometrical structures of conventional two-wire and porous waveguides were investigated to obtain the required optimum performances in guiding the THz wave.

Effect of the conventional two-wire waveguide structure

The effect of the geometrical structure of the conventional two-wire waveguide was studied in terms of the center-to-center distance between metal wires and the radii of metal wires. The changing distance between copper wires can affect the SPR guiding condition [25], affecting the maintenance of the THz mode field between the 2 copper wires. Following the initial parameters in Table 2, when varying the center-to-center distance between metal wires (D) of 0.4 mm, 0.6 mm, and 0.8 mm, the electric field distributions in the air gap of these hybrid waveguides are illustrated in Fig. 5.

The simulation results in Fig. 5 (top row) show that the THz fields are entirely confined across the air hole for a short distance between the wires. In contrast, the THz field exists in both an air hole and TOPAS material for a considerable distance between the wires, which inevitably leads to a potential absorption loss.

Since the copper wire surface accommodates the surface plasmons to initiate the THz field, the effects of the copper wire surface on the confined field in the hybrid waveguide were investigated. The radii of the metal wires of 100, 150, and 200 µm with other parameters fixed were used in this study. The configuration and electric field distribution are shown in Fig. 5 (bottom row). The simulation results illustrate that the increased sizes of the metal wires result in a strong field confined in the square air hole. This is because the greater radius of the metal wires gives rise to the greater metal surface, leading to more fields generated and confined. Nevertheless, with larger radii of metal wires, the thinner wall thickness of TOPAS results in low robustness of the hybrid waveguide structure. Hence, the suitable parameters are $D = 600$ µm and $R_m = 150$ µm.

Effect of porous waveguide structure

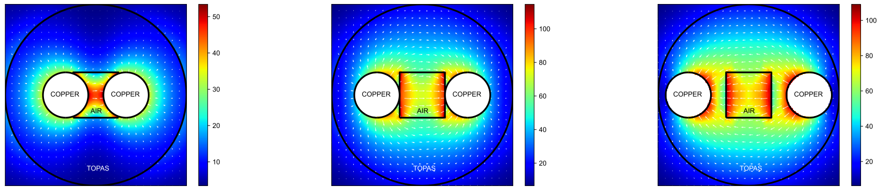
In this section, the effects of the geometrical structure of the proposed hybrid waveguide are investigated in terms of the width of the central air hole and the shape of the air hole. As mentioned in the previous section, the separated distance (D) between the copper wire can affect the THz field confinement in the waveguide. In this section, the separated distances equivalent to the change in the width of the central air hole are studied. The widths of the square air hole were varied in the range of 300 to 500 µm. By varying the widths of a rectangular air hole, the strength of the electric fields confined in a waveguide is found. Nevertheless, in terms of the field confined in an air hole, the higher strength fields are confined at the edges of the rectangular air hole, and the THz field expands out of the rectangular region when the widths of the rectangular air hole increase as shown in Fig. 6 (top row).

In the hybrid waveguide structure, the air hole structure can be changed due to the tolerance of the fabrication process. This leads to the subsequent investigation, which is the effect of the air hole structure on the confined THz field. The 4 corners of the square air hole were modified. The rounded shapes are introduced at the square air hole's 4 corners by varying the rounded corner radii. The radii of the rounded corners of a square air hole were chosen in the range of 30–150 µm. The simulation results in Fig. 6 (bottom row) show that the increasing radii of rounded corners of the air hole decreases the strength of the supported electric field. Note that smaller radii of rounded corners corresponding to sharp edges require a high-precision instrument to fabricate such a waveguide, which may not be available in the commercial 3D printing market. Hence, the optimum parameters for geometrical structure should be as follows: W_a is 300 µm and R_r is 90 µm.

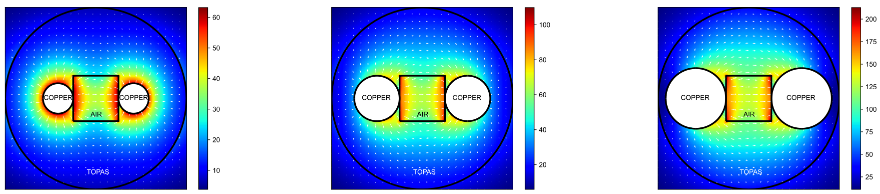
Note that the propagation properties of the proposed hybrid waveguide according to the varied geometrical structure in each configuration were insignificant changes. In addition, at the operating frequency greater than 0.2 THz, the confined THz field is gradually shifted and confined to the surface of the metal wires. This causes the THz wave to propagate more partly in a TOPAS material than in the air, which reduces the propagation velocity due to the material's highly effective refractive index and potentially carries more loss and dispersion.

CONCLUSION

In this work, we present the numerical analysis of the characteristics of the hybrid waveguide, which consists of copper wires surrounded by TOPAS. The copper wires can provide mechanical support to the TOPAS waveguide structure. At the same time, the TOPAS layer can isolate physical impacts from the environment that could affect the propagation properties of

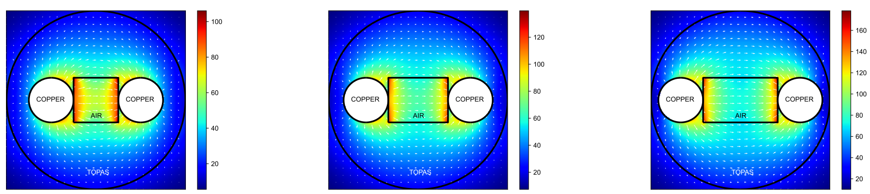


D=0.4 mm D=0.6 mm D=0.8 mm

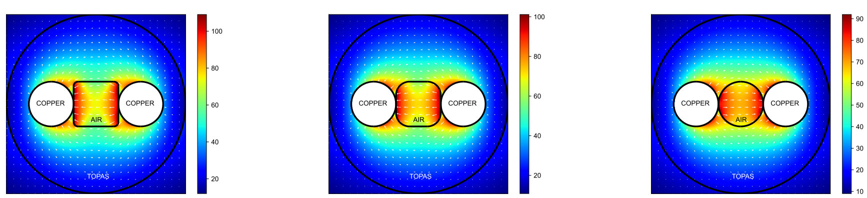


R_m=100 µm R_m=150 µm R_m=200 µm

Fig. 5 The electric field distributions of a fundamental mode confined within a hybrid THz waveguide with (top row) different center-to-center distances (D) and (bottom row) different radii of metal wires (R_m) at an operating frequency of 0.2 THz. The color bar represents a strength magnitude of electric field.



W_a=300 µm W_a=400 µm W_a=500 µm



R_r=30 µm R_r=90 µm R_r=150 µm

Fig. 6 The electric field distribution of a fundamental mode confined within a hybrid waveguide with (top row) different widths of the air hole (W_a) and (bottom row) different radii of rounded shapes at 4 conners of the square air hole (R_r) at an operating frequency of 0.2 THz. The color bar represents a strength magnitude of electric field.

the copper wire in THz wave propagation. Using the hybrid waveguide, the supported fundamental mode within the waveguide corresponds to the supported mode in conventional two-wire and porous waveguides with the air hole lying within the waveguide. The rectangular air hole was chosen to confine the THz wave because it maximizes the linear polarized electric field area compared to the other shapes such as a circular air hole. Considering the condition of the THz wave confinement in the center air hole with high modal energy and low absorption loss, suitable parameters are composed of the radii of copper wires of 150 µm and center-to-center distance equal to 600 µm. The width of the square air hole is 300 µm, and the radii of rounded corners are 90 µm at the operating frequency of 0.2 THz. The simulation results are expected to assist in designing and developing an effective THz hybrid waveguide. In addition, the study may be applied to other THz research fields such as sensors or fabrication of component devices in the THz system.

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