Low Loss THz Waveguides and Its Potentials towards 6G Communication: A Brief Chronicle Review

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***Abstract*—Advancement in technology has opened the doors for the terahertz (THz) frequency range to be applied in different fields for various applications. The future communication technology, especially 6G, will also intend to utilize the THz frequency band due to its large bandwidth that has the capabilities to achieve a high data rate. Great losses are presented in the early research into terahertz transmission medium. It is critical to design an appropriate waveguide that can integrate the THz waves into the system efficiently with minimum loss and provides the ease of transmission of data and overcomes the free space loss issues. Communication, sensing, and other application parameters are highly affected by transmission losses; therefore, low transmission loss and dispersion loss waveguide designs are required for proper utilization. In this paper, the review on reduction in the transmission loss in different types of waveguides operating at the Terahertz frequency range is studied. The design and the experimental setup for several classes of THz waveguides for minimizing transmission loss are also discussed. The review study shows that these waveguides can be a promising transmission medium for future 6G communication.**

***Index Terms*—Spectroscopy, transmission loss, terahertz, waveguide, 6G**

I. Introduction

The region between the microwave and the infrared radiation in the electromagnetic spectrum is terahertz (THz) radiation. This range of frequency shares the properties of microwaves as well as infrared radiations. THz radiation travels in the line of sight (LOS), similar to microwave and infrared radiation. THz radiation can pass through cardboard and plastic, ceramics, paper, and a wide range of non-conducting materials. However, the depth of penetration is lower as compared to microwaves. These radiations have poor penetration through the clouds and fogs and can not penetrate through the water and metals [1, 2].

With the advancement in equipment and devices, the THz frequency range is being used in various new applications and it has been proven that the gap has a potential for future applications in every field. This range of frequency is being used to detect and recognize foreign bodies, insects, metals, and other materials in powder milk processing with 100% accuracy [3]. Due to its non-ionizing characteristics and transparency in plastic, glass, and packing, it can easily justify the quality of packed food [4]. The THz range is also used to detect and real-time track any moving object with and without a line of sight (LOS) at great accuracy [5] material adulteration, quality food, material characterization, and ultra-compact RFID tags are also taken in this frequency range [6, 7]. Thickness and depth of car paints [8], different sensors [6], imaging for detection of breast cancer [9], the leaky-wave and sub-THz antenna [10, 11], compact size THz waveguide filters [12], rapid detection and sensing of viruses as COVID-19 [13] are utilizing this range of frequencies. Hence capturing a large chunk of applications in every field.

Recently, electromagnetic waves of the optical and the terahertz frequency range have been implemented in a variety of applications. As technology is being advanced, the number of users as well as the number of devices are increasing exponentially. So, the requirement for a high data rate is also increasing. The current available data rate is good for present technologies such as video calling, and online gaming but future applications such as Mixed Reality (MR), Autonomous Vehicles (AV), and so on, require much more data. In this context. 6G and beyond technology will also use the THz frequency range for high-speed communication in the range of terabits per second, which will no doubt bring revolution in technology as well in the human lifestyle. The expected frequency spectrum allocated for the 6G communication is shown in Fig. 1 [14, 15].

The optical and microwave waveguides have been exploited in the electromagnetic spectrum as imaging and sensing probes. The key component of the quantum cascade laser is the waveguide that guides the

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electromagnetic waves in the sub-wavelength range; beyond the diffraction limit and offers tight confinement of the waves in the waveguide structure beyond the Rayleigh range. Similarly, the waveguides can provide the same benefits at the THz spectrum. The increase of research activities in the terahertz frequency range for various applications has produced a layer of interest for the development of the THz component, such as sources, detectors, and low-loss guides. The THz systems are being used for different applications ranging from simple power delivery to enhancing the sensitivity in THz spectroscopy and improving the resolution of the THz imaging.

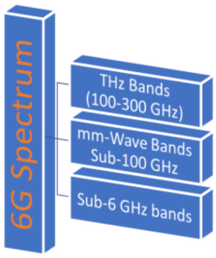


Fig. 1. 6G Expected spectrum allocation.

Conventional waveguides, rectangular or cylindrical, were limited to the frequency of 200 GHz; as the frequency goes high, they offer high attenuation, low power handling capability, dispersive nature, and so on. The attenuation level measured at these frequencies was about 10 dB to 20 dB per meter [16]. This limitation led the researchers to research various transmission methods [17, 18].

In this study, the Characterization and measurement of THz waves are discussed in Section II. Section III briefly discusses the different low-loss waveguides proposed for THz propagation, which is further categorized on the basis of materials, and each one is discussed in detail in further sections. Metallic waveguides with categories are discussed in Section IV, dielectric waveguides in Section V, and hybrid waveguides are discussed in Section VI. Each category is discussed with types, pros, and cons. Section VII briefly discusses the analysis and the discussion of all mentioned THz waveguides. Finally, the conclusion is given in Section VIII.

II. Generation of THz Waves and Measurement Realization

The characterization of THz waveguides is simply the study of dispersion, absorption, and the loss properties of the waveguide as the function of wavelength or frequency. The generation of the THz pulses is done with non-linear crystals and photoconductive antennas. A number of components, such as mirrors, lenses, polarizers, and so on, are utilized to focus and manipulate the optical path of the THz pulses generated by the source. Dielectric lenses are usually used to overcome the coupling issue by focusing the THz beam to achieve a smaller spot size at the waveguide interface.

There are a number of techniques of THz spectroscopy; Frequency domain, time domain, and interferometric spectroscopy by which the waveguide can be characterized. The frequency domain (FD) requires continuous-wave lasers, while the time domain (TD) spectroscopy needs a femtosecond (fs) pulse laser. The TD-THz spectroscopy is usually common in which the time-resolved electric field of THz is measured and compared with the reference beam. The pulse generated is divided into two beams, as shown in Fig. 2.

One optical beam is passed through the waveguide or sample, and the other is delayed with the help of different components. Once the data is received in the time domain, the fast Fourier transform (FFT) is applied to visualize it in the frequency domain [19]. Fig. 3 shows the time domain pulse and its frequency response.

It can be seen in the FFT plot that at 1 THz, the relative amplitude is at maximum or value nearest to 1. Further, as the frequency increases, the amplitude decreases accordingly. In application, researchers [20–22] have followed various configurations of THz spectroscopy by changing optical paths using different components.

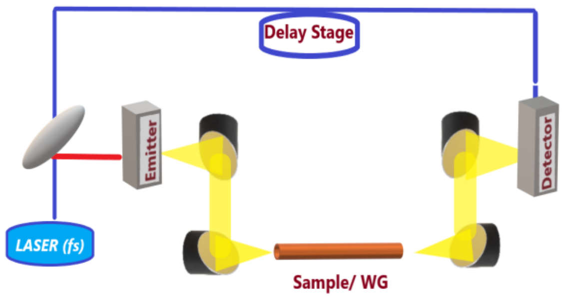


Fig. 2. THz Spectroscopy setup for sample or waveguide characterization.

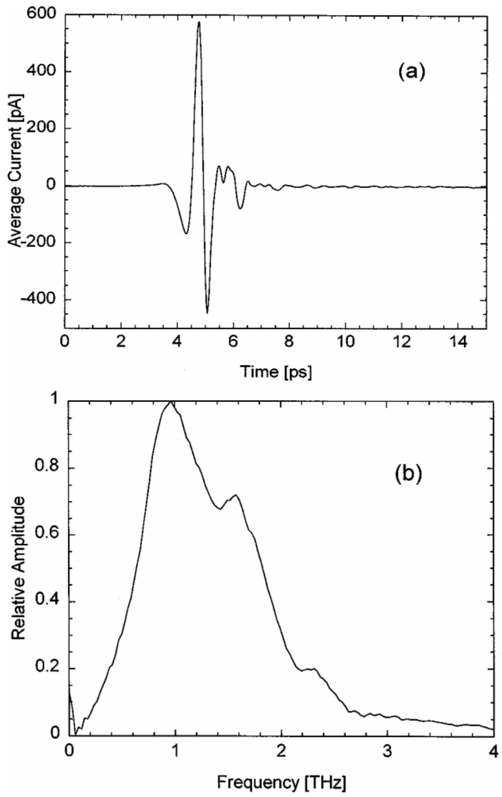


Fig. 3. Pulse: (a) time domain waveform and (b) FFT response.

III. Low Loss THz Waveguide

After the advancement of technology and nano-scale fabrication, THz has almost captured the market of various applications, changed the concept, and opened the doors for new applications, novel designs, and technologies. The propagation of THz radiation through the medium is still quite challenging for the researcher as such a high-frequency range experiences very high attenuation through the medium especially in the air and water. At these frequencies, wavelengths approach the size of the air molecules so, the molecular absorption parameter is also taken under consideration when propagation of THz waves is employed.

Material selection for designing the waveguides at the terahertz frequency range is one of the major barriers to enhancing their applications in many fields. Metals such as copper, silver, and gold are very suitable for microwave frequencies, as they offer very high ohmic loss in the THz frequency range. Whereas polymers, and glass, which are very favorable for the light and infrared frequencies, have undesirable frequency-dependent absorption losses [23]. Another major hurdle that has limited the THz range in the application of communication systems and spectroscopy systems is the group velocity dispersion leading to the different components received at different times and making the pulse distorted. Metals near the cut-off frequencies of their guided mode; transverse electric (TE), transverse magnetic (TM), or hybrid electric (HE) mode face strong dispersion whereas in TEM mode as it has no cut-off frequency, there is no dispersion. In the case of dielectric or polymer waveguides, they mainly suffer from waveguide dispersion.

A variety of waveguides are proposed by different researchers with different types, shapes, and materials that are designed for low loss and low dispersion at the THz frequency range, as shown in Fig. 4. A detailed review of each class of waveguides designed for the THz range is discussed and compared separately in this paper.

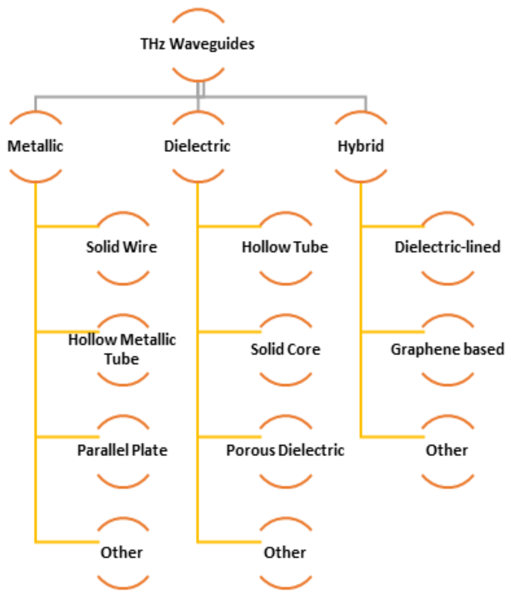


Fig. 4. Classification of THz waveguide.

IV. Loss reduction in Metallic Waveguides

Metallic waveguides are less dissipative at the THz frequency range as compared to the even higher frequency range, such as the visible range. So, they can still be used for terahertz transmission. These waveguides can be considered as the scaled-down variant of the conventional large-size waveguides. Metallic waveguides can be further categorized according to shape and design, such as solid wire, hollow circular, helical, parallel plate, and slot-based waveguides. Each of these types is discussed in this research separately.

A. Solid Core Waveguide

Metallic wire waveguides are promising candidates for efficient THz propagation due to their several advantages such as simple structure, low loss, and dispersion [24]. The solid wire (bare) is also referred to as Sommerfeld wire, named after the successful solution of maxwell equations in the single wire by Sommerfeld, and the waves that flow are called Sommerfeld waves. These waves are loosely confined to the surface of the wire. A bare metal wire was investigated by Wang *et al.* in 2004, and it was seen that the wire has a very small surface area interfacing the field; thus, a very low ohmic loss is experienced [25]. They used stainless steel of 0.9 mm diameter and found an attenuation constant of 0.03 cm^{-1} and almost zero-dispersion from 0.25 THz to 0.75 THz frequency range [25]. They also constructed the THz spectroscope by using the wire waveguide, flasks, and distilled mirrors, as shown in Fig. 5.

Solid wires of different radii were investigated to analyze the attenuation, power handling, and capability by Wiltse [26]. Markov *et al.*, in 2014, reviewed the theoretical and experimental progress in designing the wire-based waveguides for the THz frequency range. They summarized the guidance properties of two-wire and three-wire waveguides coated by the polyethylene dielectric, as shown in Fig. 6. They concluded that the guidance mechanism in these wires can change with the changing of operating frequency [27, 28].

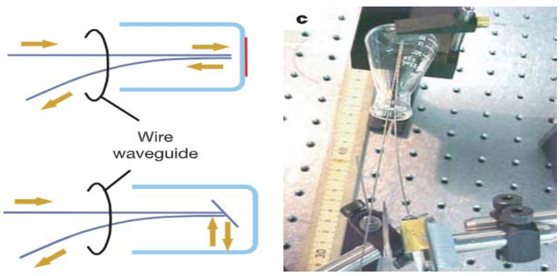


Fig. 5. THz spectroscopy based on wire waveguide [25].

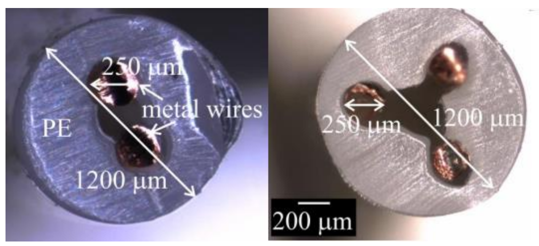


Fig. 6. Two and three-wire with polyethylene dielectric coating from [28].

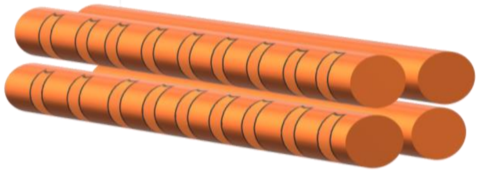


Fig. 7. Metal wire waveguide for THz range.

The AC and DC conductivity model was analyzed on different wires by Chu *et al*. in 2017. A relationship between surface plasmonic and their supporting structure was achieved [29]. They theoretically studied the relation between frequency and attenuation with variation in wire radius. Recently in 2022, a geometry of four wires was used to support polarization division multiplexed (PDM) at the THz range with low loss and low dispersion [30]. The four-wire waveguide geometry, as shown in Fig. 7, supports low loss and low dispersion propagation of THz radiation. By engraving the wire, it is possible to manipulate independently two PDM terahertz signals.

Bare metallic wire THz waveguides are popular due to their different advantages such as low loss and low dispersions and ability of radiation manipulation and processing such as [31, 32].

Remarks: Hence the metallic wire waveguide, due to its low dispersion property, can be used for broadband signal transmission. However, coupling loss is due to the polarization mismatch, and different approaches are proposed for this issue [33].

B. *Hollow Metallic Tube*

Metallic circular cross-sectional waveguides for the THz frequency range were first experimentally investigated by McGowan *et al.* in 1999. They used the quasi-optical method to couple THz pulses [34]. They presented that circular metallic waveguides have lower losses compared to coplanar and transmission line cables. This is because THz propagating in the circular wave-guide faces only ohmic losses in the body of the metallic waveguide, while in the case of coplanar and microstrip, they experience three losses while propagating the THz pulses, i.e., Dielectric loss of substrate, ohmic loss due to the metallic strip or conductor and the radiation loss. At 1 THz frequency, McGowan got attenuation constant α= 0.7 cm^{-2} for circular waveguide, α= 14 cm^{-2} for coplanar, and α= 14 cm^{-2} for the microstrips transmission line. However, circular metallic waveguides at THz have strong dispersion near cut-off frequency [34].

He *et al.* in 2021, theoretically as well as experimentally demonstrated the gradually tapered metallic waveguide (GTMW) for efficient transmission and imaging purposes at the frequency range of 300 GHz [35]. The authors claim that the proposed waveguide has much lower transmission losses and small additional losses due to bending. The diameter of the waveguide with bore size ranges from 1.6 mm to 2.6 mm, one with straight and the other with bending condition, and the length was chosen as 1 m. The measured attenuation constant for straight and bent waveguides was obtained at 4.48 dB/m and 7.78 dB/m respectively. In 2022, for the linearly polarized 100 GHz wave propagation and imaging, a hollow elliptical waveguide (HEW) is fabricated and analyzed experimentally. The proposed waveguide has a flexible polarization-maintaining (PM) metallic hollow waveguide with an elliptical core. The elliptical core of a polycarbonate (PC) capillary with a silver film interior is used to produce the HEW. At 100 GHz, a measured loss of 0.92 dB/m and a polarization ratio of 97.2% is obtained [36]. A very narrow circular copper metallic waveguide of radius 1 mm has been studied to analyze its feasibility to be utilized for efficient and low loss propagation of THz waves [37]. Recently, Yan *et al.* [38] and Syahnon *et al.* [39] investigated the circular waveguide for the propagation of THz waves for future communication systems such as TDSL.

Remarks: The waveguides operating at the THz frequency range tightly confine the propagation modes in the structure, and the hollow metallic waveguide experience attenuation only due to ohmic loss by the metallic surface and have very low loss as compared to the microstrip line transmission.

C. *Parallel Plate Waveguides*

The main feature of the parallel plate THz waveguide is that its fundamental mode of propagation is a quasi-TEM mode. Therefore, there is no cut-off frequency for the parallel plate THz waveguides. If the bandwidth is about 3 THz, the gap between the plates should be less than 100 µm. For effective coupling into the air gap between the plates, a tapered parallel plate waveguide was experimentally analyzed [40]. In 2001, Mendis and Grischkowsky used parallel plate metallic waveguides to demonstrate the distortion less propagation at THz pulses supporting the single TEM mode of propagation. They achieved the attenuation constant of about 0.3 cm^{-1} in parallel plate waveguide and almost no dispersion from 0.1 THz to 4 THz frequency range. The main losses in these waveguides are ohmic loss due to finite conductivity and divergence loss due to beam spreading in unguided directions [41].

In 2013, Mueckstein *et al.* investigated the effect of gap size on THz pulse transmissions in the tapered parallel plate waveguide (PPWG) geometry. They found out that due to the mismatch between the free space propagating beam and fundamental TEM mode, there is an excitation of higher-order modes. By optimizing the gap, multimode interference can be mitigated as the gap affects the leakage radiations and group velocity in higher-order modes. The proposed parallel plate waveguide for the THz range can be seen in Fig. 8 [42].

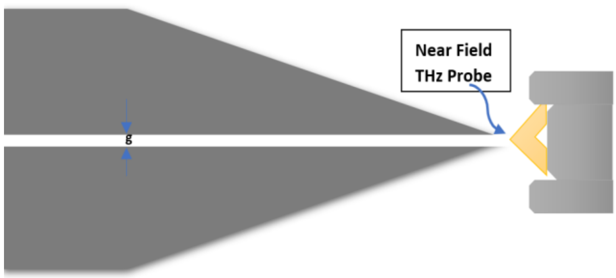


Fig. 8. Parallel plate waveguide for THz range.

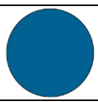
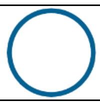
Remarks: Parallel plate waveguides have no cut-off frequency and almost no dispersion because of TEM mode excitation. It is possible when the incoming beam polarization is perpendicular to the parallel plate and TE11 when it is parallel. The separation between the plates should be properly chosen to confine the propagation mode.

D. Other Metallic Waveguides

Besides these THz waveguides, there are a few more types of metallic waveguides, such as metallic helical waveguides theoretically and experimentally analyzed by Vogt *et al*. [43] with different patches for low loss and low dispersion THz waveguide and achieved the attenuation coefficient below 0.1 cm^{-1}. Another type: the metallic slot waveguide, was proposed by Wacher *et al.* in 2007 for the strong field confinement of THz waves in the waveguide. It confines more electromagnetic fields as compared to the metal wire waveguide, but the slit waveguide has more attenuation loss than the metal wires. The attenuation coefficient for this waveguide was found to be less than 0.07 cm^{-1} in the frequency range of 0.1 to 1 THz [44]. Progress in designing an efficient THz waveguide is non-stop as recently proposed ultra-broadband metallic waveguide for THz wave transmission [45].

The pros, cons, and solutions to mitigate or improve the cons of the above-discussed metallic waveguides are given in Table I.

TABLE I: PROS, CONS, AND SOLUTIONS OF DIFFERENT METALLIC WAVEGUIDES

	Solid wire	Hollow tube	Parallel plate
Type			
Pros	Very low dispersion	Low loss, High field confinement	Support TEM mode, No group velocity dispersion
Cons	Coupling issue, low field confinement	High loss due to finite conductivity, High dispersion near the cut-off frequency	Low Propagation mode confinement
Solution	Coating with dielectric, use two/three wires	Dielectric coating	Using tapered PPWG

V. LOSS REDUCTION IN DIELECTRIC WAVEGUIDES

Dielectric waveguides are another major or widely used waveguides for the frequency range of terahertz. Optical fiber is also one of the dielectric waveguides used to guide optical frequencies. Choosing a proper dielectric material greatly affects the performance of the waveguide, such as transmission loss and dispersion. The systematic investigation of dielectric properties such as the dielectric constant and refractive index of different polymers in the terahertz frequency range was done by Jin *et al.* [46]. The hollow-core waveguides have low absorption loss at the THz frequency because THz radiations are mainly concerned with air core, while solid-core waveguides suffer from material absorption. Therefore, waveguide structure and material have great importance to performance. There are a number of classes and types of dielectric waveguides introduced by researchers. The three main types of dielectric waveguide, hollow, solid core, and sporous dielectric waveguide are discussed here.

A. Hollow Core

Hollow-core waveguides have low material absorption in the THz range because radiation mainly propagates through the air core. In metallic pipe waveguides, the transmission efficiency is not good and does not have the facility of bending and flexibility, so a flexible hollow dielectric waveguide of polyvinylidene fluoride (PVDF) was introduced by Hidaka *et al.* [47] for the THz spectrum. The transmittance of bent hollow PVDF waveguides is also investigated. The dielectric constant of PVDF is frequency-dependent and becomes negative at frequencies above 0.3 THz, so the material shows reflection like metals. Hidaka *et al.* prepared two waveguides, one with PVDF and the other with Ni-Cu of the same size of 8 mm bore diameter, 120 µm thickness, and 30 cm long. He analyzed the transmission characteristics of both straight waveguides [47].

It was found that PVDF has a three times larger transmission coefficient than metallic pipe of the same size. The attenuation constant of 7.4 dB/m and 23 dB/m was achieved for PVDF and metallic pipe, respectively, which is again three times less for PVDF as shown in Fig. 9. Chen *et al.* studied the comparative study between solid and hollow polymers. Different parameters were studied and simulated and showed that the hollow polymer has better confinement properties and low loss as compared to solid polymer [48].

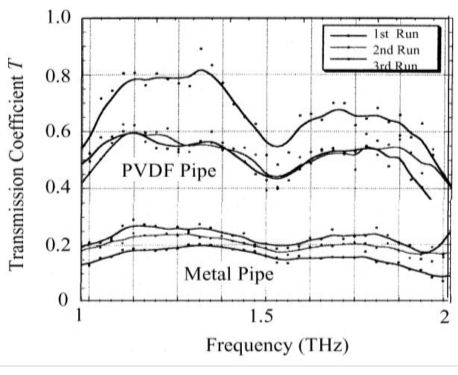
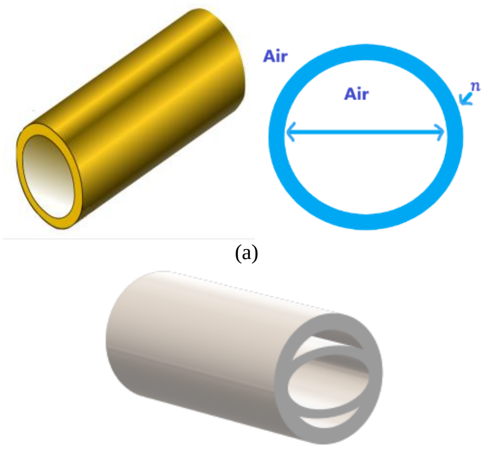


Fig. 9. Transmission coefficient for PVDFF and Metal pipe from [47].

In 2018, Lai *et al.* investigated the transmission characteristics of the THz dielectric waveguide under the extreme conditions layer where the cladding index is near to one or very thin. It was found that bandwidth increases as the cladding index of cladding thickness is reduced. Besides that, by increasing the core diameter, the bandwidth is enhanced. However, practically it is almost impossible to get both simultaneously [49]. The proposed THz pipe waveguide can be seen in Fig. 10 (a). A simple, easily-made 3D printer THz fibre with an elliptical hollow core was proposed in 2019. The photosensitive resin (SomosEvoLVe 128), the most popular material for 3D printers, is used and is shown in Fig. 10 (b). An elliptical tube works as the core leading to the structure and an outside circular tube acts as cladding. The proposed waveguide can be used for sensing in the bending direction because it is highly sensitive to that direction [50].



(a)

(b)

Fig. 10. (a) THz pipe waveguide and (b) elliptical hollow core.

In 2022, an experimental demonstration of an innovative hollow-core antiresonant THz waveguide with high birefringence and low loss. The waveguide is a spherical tube with two pairs of symmetric parallel slabs implanted in it. This waveguide is manufactured with photosensitive resins by using 3D printing technology and investigated using THz-TD spectroscopy. The authors claim to achieve the lowest loss about 0.12 cm^{-1} by using this proposed waveguide [51].

Recently, a circular hollow dielectric waveguide made up of polyethylene (PE) for a potential candidate as a transmission medium in the future communication system such as TDSL. The inner and outer diameters as 0.5 mm and 1 mm respectively and the lowest attenuation constant obtained through simulation analysis is about 0.003 dB/mm [52].

Remarks: Almost all the THz pulse propagates through the hollow tube air. The small interface with the material makes it a low-loss dielectric waveguide and can be used for sensing applications. One drawback is that they are not flexible as they are very thin in dimension.

B. Solid Core

Solid core dielectric waveguides are mostly affected by material absorption as almost all radiation interacts with the dielectric material. Since not much material is available for very low loss in the THz range, it is very important to select the proper shape and material for a solid core waveguide. Sapphire fibers and Ribbon waveguides were one of the initial solid wire waveguides proposed by Jamison *et al.* at Oklahoma State University Research Group. As the name implies, the structure of these waveguides was sapphire having diameters of 325 µm, 250 µm, and 150 µm. These waveguides offer very low absorption loss of less than 6 cm^{-1} at the frequency range of less than 2.5 THz and less than 1 cm^{-1} for the frequency range of 0.1 THz to 3.5 THz for sapphire and plastic ribbon waveguides, respectively [53, 54]. A solid core dielectric waveguide was proposed in 2006 by Chen *et al.* [55], in which a polyethylene waveguide was used, and a loss of less than 0.01 cm^{-1} was achieved at 0.3 THz. They used the waveguide whose dimensions were less than its operating wavelength; hence almost power travels in the air clade, thus reducing the loss dramatically. In 2015, a 3D-printed dielectric helical waveguide was compared with a helical metallic waveguide. It was demonstrated that the dielectric helical waveguide had a very low loss than the metallic one at higher frequencies above 0.7 THz. It was flexible and could be easily printed by 3D printing [56]. With this advantage, in 2019 and 2020, a solid core polypropylene fiber was experimentally demonstrated by Nallappan *et al.* to transfer a very high data rate for 10 meters [57, 58].

In 2021, a polytetrafluoroethylene (PTFE) solid core fiber is proposed by Wang *et al.* for a THz polymer transmission system for the short, secure, and fast communication system. The diameter of the PTFE waveguide was taken as 2 mm and the length varied from 1 m to 10 m simulated results were achieved to obtain low loss and better SINR and BER from the communication system with medium as PTFE waveguide for efficient future communication system design. The lowest. The authors obtained the lowest attenuation constant of less than 6.5 dB/m with dispersion parameters smaller than 1.8 ps/GHz/m between the frequency range of 100 GHz to 1600 GHz [59].

Remarks: Due to its sub-wavelength dimension, the electric field is almost guided in the air surrounding, thus reducing the absorption drastically. Besides this, it has some disadvantages as it is affected by bending and discontinuities, and guided signals are affected by handling the equipment.

C. Porous Dielectric Waveguides

The ratio between the surfaces of air holes to the core is called the porosity of a waveguide. The absorption loss in the core can be reduced by introducing the pores in the core. In 2002, a plastic photonic crystal fiber (PPCF) was demonstrated by Han *et al.* and showed that PPCF can be used for efficient propagation of guided waves in the frequency range of 0.1 THz to 3 THz [60].

In 2011, THz porous fiber was characterized by using the micromachined photoconductive prob-tip technique, and the obtained loss was under 0.08 cm^{-1} in the frequency range of 0.2 THz to 0.35 THz. The lowest loss achieved at 0.24 THz was 0.003 cm^{-1} [61]. In 2021, the optical properties of hexagonal-shaped air holes in the defect-less porous core were experimentally analyzed for the THz range. In the frequency range of 0.1 THz to 0.33 THz, the loss was about 0.02 cm^{-1} to 0.07 cm^{-1}. A PCF waveguide based on the D-shaped core was proposed for the efficient propagation of THz waves [62]. The authors achieved a loss of about 0.027 dB/cm and for the frequency range from 0.85 THz to 1.25 THz, almost zero flatted dispersion is obtained. Islam *et al.* in 2019 suggested a fiber with a square lattice-shaped core made of suspended Topas as shown in Fig. 11(a). At 1.0 THz operating frequency, they were able to design a porous core fiber with an extremely low effective material loss (EML) of just 0.017 cm^{-1} for 330 µm of core length [63].

An extremely low-loss PCF with a novel and unique core design was presented by Dash *et al*. in 2020. For improved performance, the core's hexagonal configuration of circular air holes was significantly modified. A hexagonal arrangement of circular air holes surrounds the core area acting as cladding. Additionally, TOPAS has been utilized as backdrop material because of its consistent refractive index and is less expensive. The lowest loss achieved by the them is 0.049 dB/cm. [64]. Another defect less porous core fiber was proposed and experimentally analyzed by Lee *et al.* in 2021. The proposed THz waveguide was made from PTFE material and has air holes arranged in a hexagonal manner as shown in Fig. 11(b). The diameter of the waveguide was 3 mm, length 207 mm with a porosity percentage of 40. It was experimentally validated with a calculation that the proposed THz waveguide has a low loss of about 0.02 dB/cm to 0.07 dB/cm over the frequency range of 100 GHz to 330 GHz [65]. Porous core fiber for the THz communication system is actively taking part due to its lower loss as recently suspended square core photonic crystal fiber is proposed for low loss THz waveguide. An attenuation constant of 0.05 dB/cm and dispersion loss of 0.48 ps/THz/cm is achieved [66].

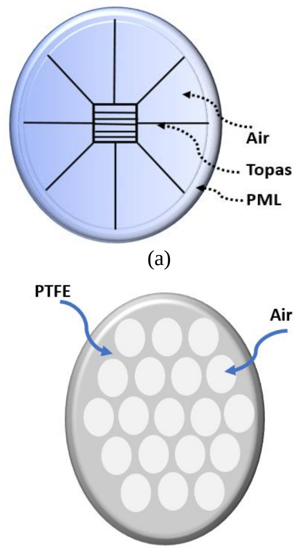


Fig. 11. (a) Square lattice-shaped core waveguide and (b) Hexagonal manner THz porous waveguide.

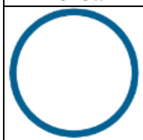
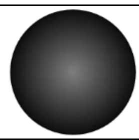
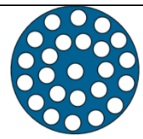
Remarks: Porous waveguides have less frequency-dependent losses and dispersion losses as compared to solid core dielectric waveguides. Nevertheless, high birefringence is introduced with the asymmetrical discontinuities, and the fabrication of these porous waveguides is quite challenging. The major application of these waveguides is biosensors.

D. Other Dielectric Waveguides

Besides these shapes and materials, a number of dielectric waveguides have been proposed by different researchers, but few of them are discussed in this study. A slab dielectric waveguide was introduced in 2013 by Melakabadi *et al.* [67], and they used high resistive silicon because of its high transparency in the THz frequency range. It was found that it has a very low loss and dispersion in the time and frequency domain. Another rectangular flexible and thermally isolated waveguide was introduced and investigated for radio astronomy. The measured average attenuation was 0.034 dB/mm and 0.069 dB/mm at two temperatures, 3000 K and 3400 K, in the frequency range of 240 GHz to 300 GHz [68]. In 2020, a planner dielectric waveguide miniaturized is analyzed for broad-scale applications. The power transmission loss obtained in between 0.55 to 1.05 THz frequency range is 0.32 cm^{-1} to 1 cm^{-1}. A broadband planner dielectric waveguide was experimentally analyzed by Mukherjee *et al.* using TD-THz spectroscopy [69]. The waveguide was made up of highly resistive silicon of 200×50 μm^2 dimensions and the attenuation constant achieved was between 0.32 dB/cm to 1 dB/cm for the frequency range of 0.55 THz to 1.05 THz.

The pros, cons, and the solution to mitigate or improve the cons for the above-discussed dielectric waveguides are given in Table II.

TABLE II: PROS, CONS, AND SOLUTIONS OF DIFFERENT DIELECTRIC WAVEGUIDES

Type	Hollow	Solid Core	Porous
			
Pros	Low absorption	Flexible, Low absorption loss	Better confinement and low loss
Cons	Not Flexible	Affected by bending	Fabrication complexity, discontinuity loss
Solution	Using metamaterial cladding	Using sub-wavelength waveguide	Need Advanced fabrication technology

VI. LOSS REDUCTION IN HYBRID-CLAD WAVEGUIDES

Dielectric materials have relatively high absorption in most dielectric materials while metals have ohmic losses, so the development of waveguiding technology for terahertz waves is quite difficult. One way to mitigate this loss is by designing a waveguide structure where the wave energy is mostly distributed in the air region, and only a small fraction propagates inside the absorbing medium [23]. A hybrid waveguide is another category in the waveguides proposed to reduce the attenuation and dispersion loss in the waveguides, which have a minimum of two different cladding layers. Each layer has its own special property and contributes to mode propagation. In some cases, one layer acts as a support to another layer. Layers can be simple material, meta-material, or any structure. Generally, in hybrid-clad waveguides metal layer is used as a reflecting surface. There are a number of hybrid-clad waveguides proposed for the THz frequency range, such as dielectric-lined waveguides, meta-material, and so on. A few of them are discussed below.

A. Dielectric-Lined THz Waveguides

Among the designs, the dielectric-lined hollow metallic waveguide has the lowest transmission losses [70]. Dielectric-lined hollow waveguides have drawn the attention of researchers for a few decades due to their low loss and low dispersion. The dielectric coating can be done on the outer surface of a tube, the inner surface of a tube, or on both sides. Different approaches have been proposed for loss reduction. In 2004, Harrington *et al*. proposed the first hybrid-clad hollow-core metal-coated waveguide for THz propagation. Hollow-core waveguide with an inner metallic coating behaves as a metallic waveguide if the metal film thickness is greater than the skin depth at THz frequency. The deposited Cu thickness was chosen as 0.5 µm to 0.7 µm, which is greater than the skin depth of 0.05 µm. They choose three bore diameters of 2 mm, 3 mm, and 6.3 mm and taken measurements at three different frequencies 1.6 THz, 1.9 THz, and 2.5 THz. The lowest loss achieved was 3.9 dB/m at 1.9 THz for the bore size of 3 mm [71]. Another hybrid-clad design was proposed by Bowden *et al*. They fabricated a silver/polystyrene (Ag/PS) coated hollow glass waveguide with a PS coating thickness of 8.2 µm and a waveguide bore size of 2.2 mm. The large bore size reduces the attenuation to a great extent and increases the coupling efficiency [72]. On the other hand, a larger bore size allows the excitation of higher-order modes [23]. Ag/PS hollow glass waveguide achieved a much lower attenuation of 0.95 dB/m at 2.5 THz with a bore size of 2.2 mm and 90 cm waveguide length. They found that hollow glass waveguides having thin PS coating support TE mode; if the width of PS coating increases, the HE mode dominates [72]. Experimental and numerical analysis with fabrication technique for low-loss hollow waveguide in 2011 was done by Oleg Mitrofanov *et al.* [73]. They reviewed the research on low loss terahertz waveguides and compared some previously proposed low loss waveguides, as shown in Fig. 12.

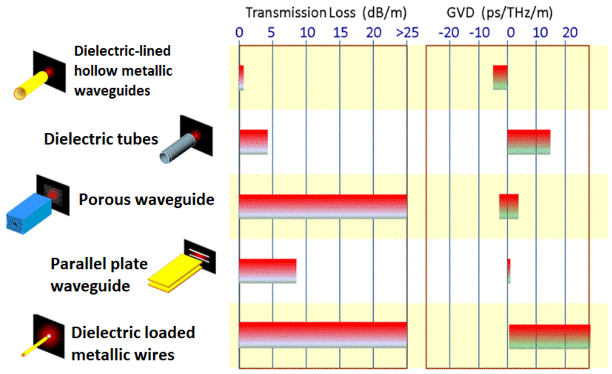


Fig. 12. Transmission loss estimation of different waveguides from [73].

It can be seen that the waveguide having the lowest loss for the THz transmission is the dielectric-lined hollow metallic waveguide. Skorobogatiya *et al.* introduced Bragg waveguides [74]. They are multilayer band-gap waveguides in which the periodic cylindrical structure surrounds the air core. They theoretically demonstrated the hollow core with multiple layers of PVDF and Polycarbonate (PC) polymer for the THz frequency range. The diameter of the hollow core Bragg fiber was selected as 1 mm after optimization, and 31 layers of PVD/PC reflectors were used, as shown in Fig. 13.

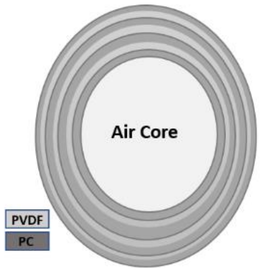


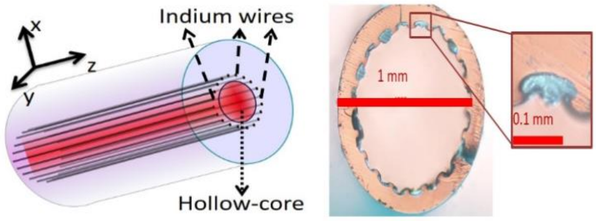
Fig. 13. Bragg THz Waveguide.

Theoretically, the lowest attenuation loss achieved was less than 0.5 dB/m for the frequency range from 1 to 3 THz [74]. In 2013, Munir *et al.* demonstrated the dielectric line method with PS coating into the inner surface of the metallic waveguide walls to reduce the transmission loss of hollow circular waveguide at THz spectrum, especially for TE01. They investigated the effect of waveguide diameter radius and the thickness of PS coating on transmission loss. They showed that increasing the diameter of the waveguide can reduce transmission loss. However, the operating bandwidth becomes narrower, and dielectric thickness should be properly selected. Increasing dielectric width beyond the limit can also increase the loss [75].

Another dielectric-lined metallic hollow waveguide (DMHW) design was theoretically proposed by Sun *et al.* [76] to reduce the losses in the THz waveguide. They analyzed the multilayer structure to reduce the bend and transmission losses in the DMHW. Multilayer gold waveguide having the stack of Silicon doped polypropylene and polypropylene and compared the Au waveguide with single and multiple Au/PP waveguides as shown in Fig. 14. The efficiency of the multilayer DMHW mainly relies on selecting proper geometrical parameters and dielectric material. It was found that low-index dielectric materials have higher losses than high-index dielectric layers.

Fig. 14. Dielectric lined waveguides for THz range.

In 2016, Li *et al.* introduced a new class of dielectric waveguides, the single-mode hollow-core THz waveguide with the metamaterial cladding that had sub-wavelength diameter metal wires embedded into the dielectric as shown in Fig. 15. They proposed, studied, fabricated, and experimentally characterized the THz metamaterial waveguide and found that the proposed metamaterial waveguide with the same dimension as in the dielectric coated metal waveguide has 2.3 times wider bandwidth and achieved the minimum loss of 0.28 dB/cm [77].



(a) (b)

Fig. 15. Hollow waveguide with metamaterial cladding (a) sketch of a waveguide and (b) fabricated waveguide with the cross-sectional view from [77].

In 2020, another design for metamaterial cladding was introduced by Sultana *et al*. An anti-resonant waveguide with optimized metallic wire inclusion was proposed for the low-loss terahertz spectrum. They compared the waveguide with and without the wire inclusion and explained the confinement of modes with the metal wires and found that the proposed metamaterial waveguide has a six-time lower loss as compared to the only anti-resonant fibers [78]. Another low loss and low dispersion hybrid THz waveguide was analyzed experimentally by Li *et al.* [79]. They fabricated a waveguide integrated on a single chip that contains silicon photonic crystals which are sandwiched in between the parallel gold plates. It was found experimentally that this proposed waveguide confines the THz radiation completely in the air channel. The lowest attenuation constant achieved was below 0.05 dB/mm with the dispersion parameters values from –8.4 ps/GHz/mm to 0.9 ps/GHz/mm for the frequency range of 0.36 THz to 0.411 THz.

In 2022, Thackston *et al.* experimentally measured the characteristics of a dielectric lined waveguide fabricated by General Atomics (GA) for very low loss and low-cost THz waveguide. The inner, outer, and length of the waveguide were 31.5 mm, 44.45 mm, and 1.07 m. The interior of the waveguide was anodized with alumina to act as a dielectric coating of 82 µm thick. The lowest attenuation constant achieved was 0.02 dB/m [80]

Remarks: These waveguides have the lowest transmission loss as compared to the other metallic waveguides. The attenuation constant is considerably lowered with the additional layer, allowing hybrid mode propagation. The thickness of the dielectric decides the propagation mode, either TE01 or HE01. However, this coating introduces interference peaks, and operation bandwidth is limited. So, it is essential to design optimized coating thickness. Another drawback of inner coating is that it adds absorption losses. It can be resolved by using meta-material cladding as bending.

B. Graphene-Based THz Waveguides

Graphene is a new two-dimensional material made up of carbon atoms arranged in a honeycomb structure. If graphene is dropped, it can transmit very low-loss plasmons in frequencies smaller than optical photon frequency. It is shown in the studies that graphene-based plasmonic devices are better than gold and silver in terms of performance, and graphene can confine the electric field of plasmonic mode several times better than metals [81].

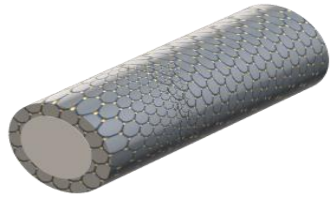


Fig. 16. Graphene-based cladding THz waveguide.

In 2014, Qing Tang described the characteristics of perfect electric conductor (PEC) - graphene and graphene-graphene waveguides for the THz regime. The propagation characteristics of the waveguide can be controlled by the magnetic and electric bias fields. It was found that graphene-based waveguides have lower attenuation than conductor waveguides [82]. Derakhshi *et al.* [81], in 2016, presented a long-range graphene-based waveguide for the THz range. The proposed structure has two anisotropic clads surrounding the core, as shown in Fig. 16.

By varying the core thickness and clad dielectric, the propagation length and the confinement of the plasmons can be controlled. It is found that there is a trade-off between these two parameters. Also, by changing the chemical potential of graphene, these two parameters can be adjusted. Thus, these waveguides can be used to design electro-optical switches and logic gates [81]. Square graphene waveguides with small, normalized mode area and long propagation length [83] and plasmonic decoder based on graphene for the THz applications [84] are also introduced. Recently in 2021, Teng *et al.* analyzed the graphene-based dielectric-loaded waveguides theoretically. Model losses, effective mode index, and model properties of fundamental mode were investigated. It was found that the effective index method for analyzing the dielectric-loaded graphene waveguide is highly valid, and it can be used in applications such as tunable integrated photonic devices [85]. Sun *et al.* has presented an entirely novel hybrid graphene plasmonic waveguide for future THz field programmable arrays. The primary component of the waveguide is a simple gap-slot area. Under the right conditions, this waveguide's transmission distance is an order of magnitude greater than that of a conventional waveguide while maintaining the benefit of high-energy confinement [86].

Remarks: Graphene-based waveguides for THz is an emerging technology, and a lot of research gap is to be filled. Recent studies show that graphene-based devices have better performance characteristics as compared to silver or gold. Chemical and electric variations can change their parameters. Due to these facilities, as well as low loss propagation, graphene has been focused on by many researchers for THz waveguides.

C. Other Hybrid Waveguides

Besides these, a number of hybrid waveguides are proposed for terahertz spectrum applications. In 2018, a quantum-cascaded laser source based on a double metal waveguide was reported by Kim *et al.*, as shown in Fig. 17(a). Terahertz modes in the active region of the device were highly confined, and along the entire length of the waveguide, the extraction of terahertz radiations was effective [87].

A year later, another design was proposed and fabricated for the quantum cascaded laser with double metal waveguides. For the reduction of the losses, an Ag-based dual metal waveguide (DMW) was used, and it was shown that Ag-based DMW reduces the losses by about 2-4 cm^{-1} compared with the Au-based DMW. The design was based on the three and four quantum well GaAs/Al0.15Ga0.85As active module, as shown in Fig. 17(b) [88].

The pros, cons, and the solution to mitigate or improve the cons of the above-discussed hybrid-clad waveguides are given in Table III.

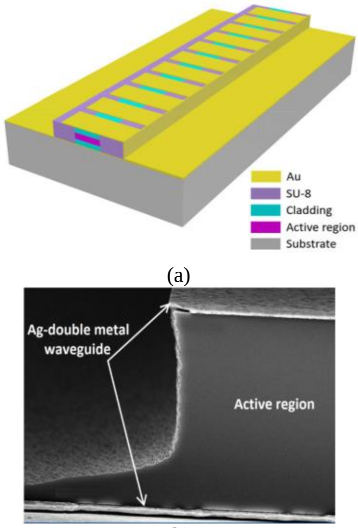
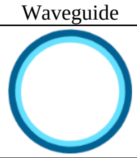


Fig. 17. (a) Schematic of THz QLC with double metal [87] (b) SEM image of THZ QLC with Ag-Ag double metal from [88].

TABLE III: PROS, CONS, AND SOLUTIONS OF DIFFERENT HYBRID-CLAD WAVEGUIDES

Type	Dielectric-lined Waveguide	Graphene-based clad waveguide
		
Pros	Low loss, Hybrid mode	Controllable propagation characteristics, Low loss and dispersion
Cons	Interference limits the bandwidth	Mass production is very expensive and complex
Solution	Optimized coating	Need more technological advancement

VII. ANALYSIS AND DISCUSSION

THz waveguides proposed for low loss are divided into three major categories according to their material: metallic, dielectric, and hybrid. They are further classified according to the structure and configuration as explained in the previous sections.

Among the metallic waveguides, solid bare metallic wires have a low loss because the wire acts as a rail for the TM-01 guided mode; thus, ohmic losses are reduced scientifically. These wires have low dispersions and low loss in the THz region because the mode is expanded around the wire in the air and not bounded. The hollow metallic waveguide has propagation modes TE or TM confined in the metallic walls (structure), thus having very high loss due to finite conductivity with metals at the THz frequency range. Parallel plate waveguides have the advantage of TEM mode, they have no cut-off frequency, so they offer dispersion-free propagation. Their propagation mode is confined between the plates in one direction, so they have low losses as compared to circular or rectangular metallic waveguides. The bare wire and parallel plate have undistorted wave propagation at the THz range. The dielectric coating can be done to solve the confinement issue in the metallics waveguide.

In the dielectric waveguides, the main loss is due to the material absorption, so it is important to use the proper material to transmit THz pulses. In the hollow core dielectric waveguides, this absorption is almost zero because mostly the radiation propagates through the air, making them suitable for sensing applications. The disadvantage of these waveguides is that their size is larger, so they cannot be used in integrated THz devices, and due to their large core size, they exhibit multimode. By reducing the core size, the single mode can be achieved, but attenuation loss will be increased. So, there is a trade-off between the mode and the attenuation. A properly optimized core size must be chosen. Solid core dielectric fiber faces high absorption as all the THz radiation propagates through the dielectric material. The loss in these waveguides mainly depends on the material, so one way to mitigate the losses is to use the proper low-loss dielectric material such as Cyclin Olefin Copolymer (COC). Another solution to reduce this loss is to reduce the dimensions of a waveguide to the sub-wavelength waveguide allowing the mode to propagate through the air. The third category of dielectric THz waveguides, porous waveguides, have air pores, and they offer very low absorption loss as there is less interface of THz radiation with the dielectric material. Also, a porous waveguide offers low bending loss and better radiation confinement. As compared to the solid-core fibers, porous dielectric waveguides have lower frequency-dependent dispersion and loss. However, birefringence is produced when any discontinuity is introduced in the waveguide.

Hybrid-clad THz waveguides are the waveguides with the lowest losses due to the additional dielectric layer with the metal. The dielectric waveguide thickness determines the mode in the waveguide, either TE_{01} or HE_{01}. However, introducing the dielectric coating adds interference peaks, so it is very important to optimize the thickness of the dielectric coating. Additionally, this dielectric layer also introduces absorption loss. Adding metamaterial to the cladding also adds more advantages, such as improving the field confinement and lower loss. Graphene-based clad waveguides recently attracted researchers due to their unique properties, such as their tunable electric, magnetic, and chemical properties. It has been shown that these waveguides have better performance than gold and silver. Still, a lot of research is needed on these waveguides, especially for mass production and fabrication techniques.

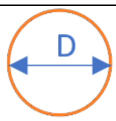
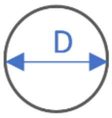
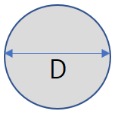
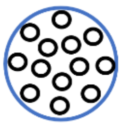
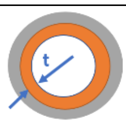
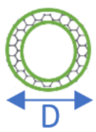
It can be critically analyzed that each type of THz waveguide has advantages and disadvantages of its own. Metallic waveguides offer low loss but are bulky and frequency-dependent, while dielectric waveguides have the advantages of miniaturization and frequency independence but are limited by signal dispersion and low power handling capacity. Hybrid THz waveguides can take advantage of both metallic and dielectric along with low losses. However, they are complex, expensive, and have integration challenges. Graphene THz seems to override other materials due to its tunability and compact design, but it is still under research and faces several challenges to cover. The selection of a waveguide dependents on the specific requirements of the application, taking into consideration factors like propagation loss, bandwidth, constraints on size, and integration capability. The performance and versatility of THz waveguides might be further improved by ongoing work in materials science and nanotechnology.

The waveguides discussed in the above study are almost fabricated and with experimental analysis such as in [25, 28, 41], etc. However, due to the expensive equipment and availability of THz devices, and fabrication facilities in the research institutes of developing and underdeveloped countries, young researchers interested in the THz field are contributing using simulation work, numerical studies, and ideas as in [29, 38, 78], etc. This is also one of the major reasons that limits the practical verification and implementation of THz devices and waveguides. No doubt, the availability of economical THz devices will boost the research in the THz field and innovations.

Table IV shows the summarized properties of different waveguides proposed for the terahertz frequency range. A number of proposed low-loss waveguides for THz are countless, so just for reference, one example of each category discussed above is mentioned in Table.

The above-discussed low-loss and low-dispersion waveguides can be used for future communication networks such as 6G and beyond. As these waveguides can stream the data using the terahertz spectral region, they can meet the never-ending demand for a high-speed data rate (terabits per second).

TABLE IV: SUMMARY OF DIFFERENT WAVEGUIDES PROPOSED FOR THZ RANGE

S. No.	Waveguide		Type	Dimension	Material	Attenuation loss	Dispersion loss
1	Bare Wire [25]		Metallic	D =0.9 mm	Steel	<0.03 cm^{-1}	Almost zero
2	Hollow Metallic Tube [89]		Metallic	D=280 μm	Copper	< 1 cm^{-1}	1 ps to 40 ps
3	Parallel Plate [41]		Metallic	b= 500 μm a= 25 mm	aluminum	0.1 cm^{-1}	0.9 to 150 ps
4	Hollow dielectric pipe [90]		Dielectric	D=9 mm L=3 m	Teflon	<0.02 cm^{-1}	--
5	Solid dielectric fiber [53]		Dielectric	D=150, 250,325 μm	Sapphire	<6 cm^{-1}	0.6 to 13 ps
6	Porous Dielectric [91]		Dielectric	D=560, 600, 760 μm	COC	0.007 cm^{-1}	--
7	Dielectric-lined waveguide [92]		Dielectric lined (Hybrid)	D=200 μm	PE	< 0.64 cm^{-1}	2 to 3 ps
8	Graphene-based clad waveguide [82]		Graphene	--	Graphene	Very low	Very low

The waveguides discussed above show low loss and low dispersion at the THz frequency range, thus opening the door for utilizing them in next-generation communication networks such as 6G. THz spectrum is released now by the Federal Communication Commission (FCC) and will be utilized in 6G. The absorption properties of the terahertz frequency range limit its communication application to a few meters, especially in foggy weather, because water is the best absorptive material at these THz frequencies, so wireless transmission of THz seems impractical or will take high cost as the cell coverage area decrease, and a number of cells with increased of installation cost, lack of labor expertise and congested urban areas can be the problems for 6G implementation. The above-discussed waveguide can be the best candidate and the solution to propagate the THz range for high-speed communication for long distances with low cost, low loss, and low dispersion, especially in the mid-haul and backhaul network.

The 6G network requires a data rate in the terabits per second, which is 100 times greater than 5G. Optical fiber has the tendency to support a huge amount of data required for the 6G, but still, optical fiber systems and their implementation are limited because of their capital cost, labor expertise, congested urban areas, and further complications. Above discussed waveguides can solve this issue, and metallic copper wires, fibers, or hybrids that are already installed in the infrastructure, as shown in Fig. 18, can be utilized to overcome this problem discussed above and have the capability to provide the very high data rate in terabit per second. Thus, issues of implementation of the 6G network can be reduced as these waveguides can be utilized, and there is no necessity to install or implant new fibers to implement the 6G services.

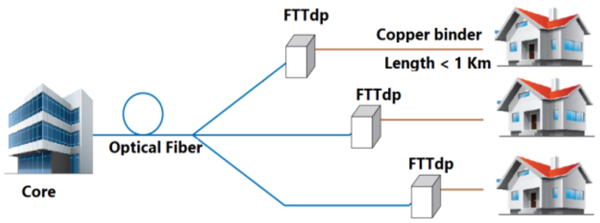


Fig. 18. Fiber to the distribution point (FTTdp) architecture.

There is a lot of research gap in this field to utilize the efficient transmission medium at a very high frequency, especially the THz frequency range, which can be used for different applications. THz will no doubt bring revolution in the near future and will open the room for new applications in medical imaging, detection, quality inspection, high-speed communication, and so on.

Designing an efficient waveguide for the THz transmission is still challenging. The unavailability of THz mixers, modulators, and other high-speed devices also makes it difficult for researchers in the investigation and testing phase. The THz spectroscopy setup is also unavailable in many research institutes, especially in developing and under-developing countries, which also reduces the progress speed in this research area. Technological advancement fabricates compact devices for high-speed range, so researchers worldwide will soon have the facility to fabricate compact devices for the THz range. Researchers worldwide are pushing efforts collectively and collaborating to utilize this unused THz range of spectrum efficiently.

VIII. Conclusion

THz is an unexplored virtual spectrum with numerous fundamental research problems and technical applications. This range is a promising solution to the spectrum scarcity and high-speed data rate, highly sensitive sensing and scanning, 5G, 6G, and beyond. To expand the THz capabilities, efforts are taken to investigate the guided propagation of THz pulses and the feasibility of different waveguides for proper propagation of the THz pulses.

This study discusses a brief review of the different low-loss waveguides proposed for the THz. The performance parameters such as losses and dispersion for different waveguides are discussed with their experimental arrangements. The procedure and types of terahertz spectroscopy characteristics are also briefly defined.

The propagation properties mainly depend on the material as they are reflected by the metals and highly absorbed in water. They propagate in the air freely with minimum loss. Therefore, the selection of material is very important in designing a waveguide that allows the terahertz radiation to be confined and propagated mainly through the air. Losses are also caused by bending and discontinuities, so different techniques are employed to tackle this issue. Metamaterial and Graphene-based waveguides are in the initial phase of development and have the potential to be low-loss waveguides for the THz waveguides. It can be used to transmit the terahertz spectrum efficiently and utilized for future communication technologies such as 6G and beyond. Therefore, it can be a reasonable research direction for the future THz waveguide.

The main aim of reviewing this article is to analyze and compare the existing approaches for guiding THz radiation. The research community will appreciate knowing more about the low-loss THz waveguide's development in this area. This article is motivation especially for young researchers to investigate more and contribute to their progress in this field. No doubt, research is a never-ending process, and researchers continuously work on obtaining the low loss waveguides that can properly be used at the terahertz frequency range for various applications.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Arslan Ahmed is the primary author of this paper, and he has written the entire paper, compiled all necessary information, and presented it in an understandable manner. Fauziahanim Che Seman and See Khee have supervised and suggested relevant research papers and provided guidance on the scope and the focus of the review. Noor Azura and Izhar have provided guidance on the overall structure, organization, and formatting of the paper.

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