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Investigating the Impact of Waveguide Curvature on the Characteristics of D-Band 6G Communication Systems

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ABSTRACT

With an increase in users and devices, fast data rates are turning increasingly desirable in wired and wireless transmission. Moving towards higher frequency bands, especially in the multi-GHz region, is one potential solution to fulfil the user demands for a high data rate. Recently, it was demonstrated that using a waveguide technique and the higher order guide modes in the already established twisted pair cable, a data rate of terabits per second could be attained. The air-dielectric space inside the cable can be used to transmit the terahertz waves wirelessly. However, the idea is novel and there are quite challenges in the realization of this idea practically such as the bending effect and high attenuation due to the narrow gap. The copper wires and metallic foils inside the cable create an air space similar to the circular waveguide. Therefore, to investigate the feasibility of this cable for next-generation D band communication, a circular waveguide of similar dimensions is simulated, and the effect of bending on the propagation characteristics is studied. It is found that even a small bend in the waveguide structure has a significant effect on the performance of the waveguide. If this cable is properly excited, can be the revolutionary beginning of the high-speed internet and 6G.

1. Introduction

In recent years, the growing demand for high-speed wireless and wired communications has significantly increased the demand for more and more bandwidth in communication systems. This demand is a never-ending process and exponentially increases with the increase in the number of devices. However, the frequency bands below 6 GHz that are currently being utilized in a variety of applications, including mobile radio, AM, FM broadcast, WLAN, RADAR, and navigation, are almost full [1].

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A number of solutions have been proposed by different researchers to overcome this spectrum scarcity, especially under 6 GHz [2]. One of the proposed solutions is using Ultra-wide Band (UWB) Technology [3] that allows different unlicensed users to access the available bandwidth using low power however, this is limited to the short range and has some security concerns [4]. Cognitive Radio (CR) [5,6] and dynamic spectrum access is another solution that allows multiple users to access the same frequency band without significant interference. A few other assumptions and solutions are also proposed to overcome spectrum scarcity, but these are not permanent and long-term solutions. One promising solution is to move toward higher frequencies such as mm-wave and terahertz bands. No doubt higher frequencies have more available spectrum and promising capabilities but also have higher propagation losses, especially in wireless communication.

Recently, the THz range has become a fascinating and quickly growing area of communication research, drawing the interest of scientists and researchers from various fields. THz waves are electromagnetic waves with frequencies between the microwave and infrared regions of the electromagnetic spectrum, ranging from 0.1 to 10 THz. Due to the substantial amount of unutilized bandwidth present in this frequency range, high-speed wireless communication could benefit greatly from these benefits. THz waves, which can carry more data per second and have higher frequencies than microwaves, also present the possibility of ultrafast data transfer rates. THz waves have potential uses in security screening, imaging, and medical diagnosis in addition to communication applications [7].

In terms of wired communication systems, currently available copper-based technologies such as ADSL, VDSL, G-fast, etc. are based on the transverse electric magnetic (TEM) mode to transmit the information. They require two conductors to signal transmission and offer the advantage of not having a lower cut-off frequency, allowing transmission of all frequencies. However, increasing the frequency range or moving towards higher frequency bands such as mm-wave and THz, the attenuation in this TEM mode increases drastically, and it is not practical to utilize these copper-based TEM modes for long-distance propagation. Therefore, the TEM mode is limited by the higher frequency range in the twisted pairs already installed in the infrastructure.

Recently in 2018, a novel idea is proposed by John Cioffi to utilize these existing twisted pair copper bundles to transmit extremely high frequencies such as the THz band. He proposed the terabit DSL (TDSL) concept which uses the higher order modes such as transverse electric (TE) and transverse magnetic (TE) modes to transmit the THz waves wirelessly through these already installed twisted pair cables [8]. However, the guidance mechanism of the THz radiation through the wire waveguide is weak and if bends are introduced, the surface waves tend to separate from the wire [9]. According to Cioffi *et al.,* [8], if these twisted pair cables are excited properly and higher order modes are propagated wirelessly then a data rate in terabit per second can be achieved that can fulfill the future needs.

A frequency spectrum known as D-band spans 110 GHz to 180 GHz. It is a region of the high-frequency spectrum that is referred to as the millimeter-wave spectrum. D-band offers several potential applications in communications in the future, particularly when 6G technology is developed [10]. The D-band is well appropriate for high-speed data transmission due to its wide bandwidth, and high carrier frequencies can support wireless networks with large capacity. In addition, the D-band has the potential for high-resolution imaging and sensing uses, such as for security screening or imaging in the medical field. The significant attenuation of electromagnetic waves in this frequency band, however, causes major challenges in efficient long-distance communication. Research and development work is still being done to investigate the D-band's potential for the future despite these challenges.

This novel idea of transmitting the THz waves wirelessly through the air and dielectric space inside the twist paper cable bundles that are expected to provide the data rates in terabits per second (Tbps) has created hype in researchers and a lot of research is being conducted for the realization of this concept [11,12]. Propagation of THz waves through metallic wires is not new, back in 2004, THz wave propagation through a single metallic wire with low attenuation and low dispersion has been experimentally shown by Wang and Daniel [13] and Markov *et al.,* [14] through an experiment analyzed the TEM mode guidance using THz propagation on two and three metallic wire waveguides. TEM mode offers the benefit of having no cut-off frequency, however twisted pair wires have very significant attenuation at such a high-frequency range. Efficient coupling and propagation of Sommerfeld waves at 100 and 300 GHz are analyzed theoretically as well as experimentally [15].

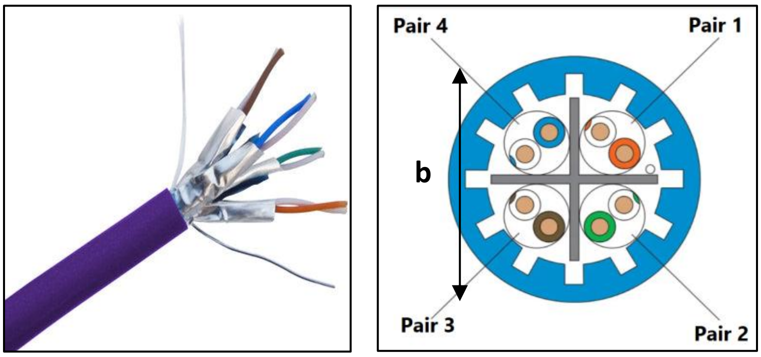
Pahlevaninezhad and Thomas [16] theoretically calculated the coupling of THz waves from the dipole into the two-wire waveguide. A novel active wire waveguiding is practically tested and compared with the PCA for efficient coupling of THz waves into the wires [17]. In 2019, Souza *et al.,* [18] simulated the copper binder cable containing multiple twisted pair cables and estimated the data rate achieved through the first 16 modes and it was estimated that a data rate of 3 Tbps can be achieved through the copper binders containing 8 twisted pairs for the distance of 10 meters. Propagating of THz waves through the two metallic wires enclosed in a metallic sheath to estimate the maximum data rate was experimentally tested by Shrestha *et al.,* [19] in 2020 and he estimated the maximum data rate of 10 Tbps over 3 meters. The upper bound of the un-shielded single twisted pair copper cable is tested by Dinc *et al.,* [20] A metallic waveguide is simulated for the frequency range of 100 to 300 GHz future communication [21]. In 2022 Dinc *et al.,* [20] four parallel copper wires with Bragg grating are experimentally tested to propagate the THz waves and manipulated the two independent polarization division multiplexing. Propagation of THz waves through the two-wire power line is also analyzed for high-speed applications [22].

Propagation of THz waves through the already installed copper cables wirelessly utilizing the waveguide approach is still in the infant stage, a lot of research progress is needed and there is much space for experimental analysis. However, in this study, the feasibility of propagation of the THz waves through such a narrow space and the bending effect on propagation is studied for the realization of the TDSL.

2. Waveguide Model in Twisted Pair Cable

Twisted pair cables are frequently used for underground installations of DSL (Digital Subscriber Line) connections. Copper wire pairs are twisted together to create these cables, which minimize crosstalk and electromagnetic interference. CAT6a cable is of tremendous interest due to its potential application in high-speed communication systems. Understanding the properties of this propagation is crucial for creating new communication technologies because the air gap between the twisted wires in the cable provides a special environment for THz wave propagation. This study intends to spot fresh light on the utilization of the CAT6e cable as a medium for high-speed data transfer in communication systems by investigating the behavior of THz wave propagation through the cable.

In this work, the terahertz wave propagation through the CAT6e cable's airgap and dielectric is investigated. The copper twisted pairs inside the cable are arranged in a circular manner rounding the dielectric and airgap inside the CAT6a cable, thus forming a shape resembling the circular tube as shown in Figure 1. A typical CAT6a cable has a diameter of about 6 mm indicated as ‘b’ and the air gap, or space between the twisted wires, is around 2 mm indicated as ‘d’ in Figures 1 and 2. Due to the twists, irregular shape, quantity of wires, and bends in this cable, which is very different from standard waveguide, waveguide approach or higher order mode propagation (TE and TM) has not yet been thoroughly tested.



(a) (b)

Fig. 1. CAT6a twisted pair cable (a) Side view (b) Cross-sectional view

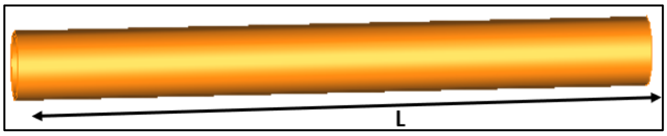
Thus, to analyze the propagation of THz waves through such narrow space, a circular waveguide of similar dimensions approaching the airspace and dielectric space inside the cable is simulated in a computer simulation technology (CST) tool using a time domain solver. With the TEM mode of propagation, the CAT6a cable's performance has been verified up to the 600 MHz frequency range and it can support a maximum of 10 Gbps up to 100 [23]. The concept of this study is to investigate the propagation of the THz waves through the airspace wirelessly and see the effect of bending in the proposed waveguide. As a higher-order approach mode is utilized instead of the conventional TEM mode, the electromagnetic field inside the waveguide supports different modes of propagation and has a cut-off frequency below which it does not support the propagation of EM waves. The cut-off frequency of a circular waveguide for both TE_{mn} and TM_{mn} mode can be calculated by Eq. (1) and Eq. (2) [24].

$$f_c = \frac{p'mn.c}{2\pi a\sqrt{\mu\varepsilon}} \tag{1}$$

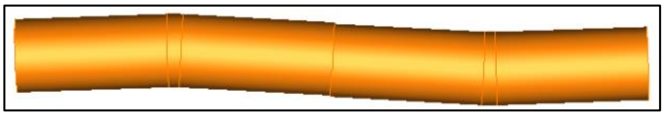
$$f_c = \frac{pmn.c}{2\pi a\sqrt{\mu\varepsilon}} \tag{2}$$

Where a denotes the radius of the waveguide, $p'mn$ and pmn n^{th}-zero of the m^{th}-order Bessel function and Bessel function derivative, respectively. c is the speed of light. Various bends are introduced in the narrow circular waveguide to analyze the bending effect in such a narrow space as shown in Figure 2. The length (L) of the waveguide is kept at 30 mm to save simulation time, while the diameter (d) is chosen as 2 mm while the waveguide thickness (t) is kept at 100 um which is greater than the skin depth of the conductor. These presumptions are made to simplify the analysis and provide an understanding of the sub-THz wave propagation characteristics through the twisted copper bundles and acknowledge that real-world conditions might introduce additional complexities. For the frequency range of 110 GHz to 180 GHz, the proposed waveguide's propagation characteristics are investigated.

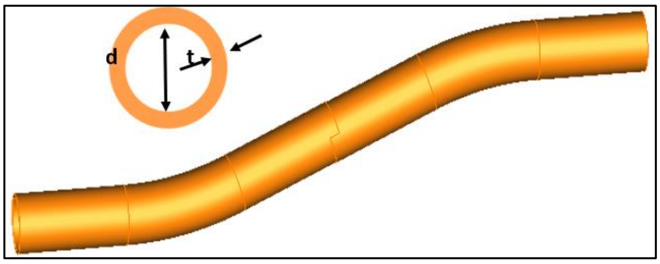
Different propagation characteristics of the waveguide are simulated and analyzed in this study. S-parameters are obtained for different bent angles that define the behavior of a high-frequency network or device in terms of reflected and transmitted signals. The amount of power lost per unit length of the waveguide because of several causes, such as conductor losses and dielectric losses, is referred to as the attenuation constant in a circular waveguide. It is defined in the dBs. The flow of electromagnetic energy along the surface of the waveguide walls is referred to as the surface current in a circular waveguide. It relates to the electromagnetic fields inside the waveguide and is often represented as a distribution of current density on the waveguide's walls. It is essential to minimize surface currents in waveguide designs as they can produce higher conductor losses.



(a)



(b)



(c)

Fig. 2. Narrow circular waveguide with different bent angles (a) 0° (b) 10° (c) 20°

3. Results and Discussion of the Waveguide

The feasibility of utilizing the CAT6a cable for the propagation of the THz wave through the air and dielectric gap inside the cable through the next generation 6G frequency band; 110 GHz to 180 GHz as discussed in the above sections is simulated. The detailed analysis and simulation results are discussed. This study mainly focuses on the effect of minor bending of the waveguide on the propagation characteristics in the proposed bandwidth. The scattering parameters that are most important to analyze the behavior of the system are analyzed for the different bend angles. Figures 3 and 4 show the reflection loss S(11) and transmission coefficients S(21) for different bent angles.

It can be seen in the return loss S(11) plot that there is a significant effect of even a small bend of 10° on the reflection loss. The straight waveguide has return loss values below -80 dB and shows a better matching response throughout the proposed D band. However, introducing the bends in the waveguide significantly introduces the losses and reduces the matching. Here in the plot, both minor 10° and 20° bent have a reflection loss above -40 dB which is still quite acceptable however, for major bents the situation is even worse.

The transmission coefficient plot clearly shows the effect of bending on the propagation properties. When there is no bend and the waveguide is in a straight manner, the S(21) is about 0 dB throughout the D-band however, the response of the transmission coefficient is getting poorer with the introduction of the bends. Even for the minor bends, the major effect on the transmission coefficient can be seen in the plot.

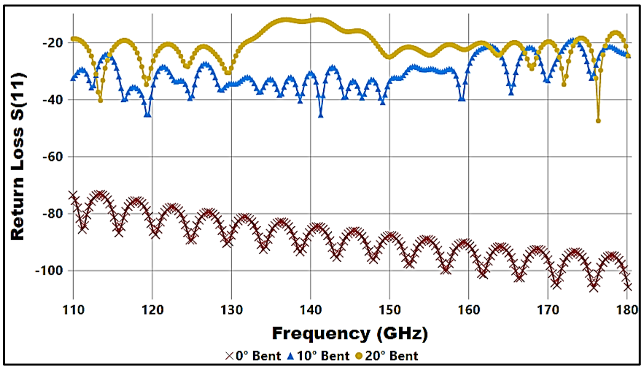


Fig. 3. Return loss for different bent angles

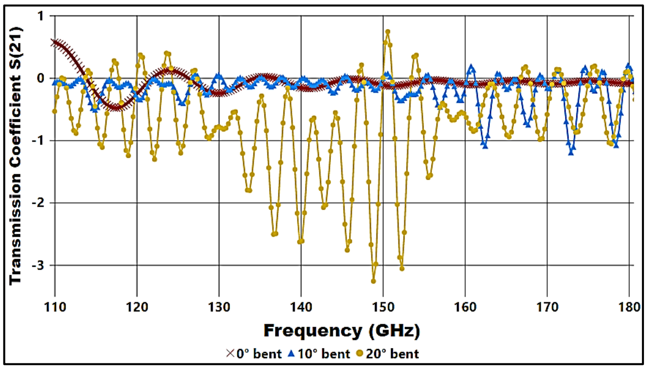


Fig. 4. Transmission coefficient for different bent angles

The attenuation constant is another very important parameter to be considered, especially in long-distance communication. As the concept is to utilize the already installed cables in the infrastructure which has a distance below 1 km from the user-end to the nearest distribution point (FTTdp), therefore, a waveguide with the lowest attenuation constant at such a high-frequency band is required. For the next generation D-band, the attenuation constant plot is simulated for the different bent angles and is shown in Figure 5.

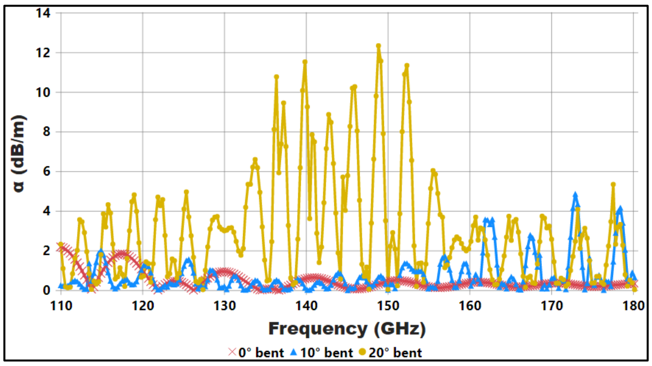
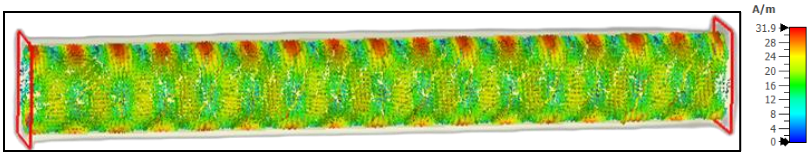


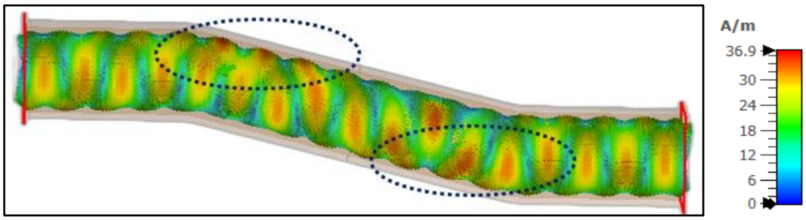
Fig. 5. Attenuation constant for different bent angles

It can be seen that with 0° bent in the waveguide, the attenuation constant is below 1 dB per meter for almost the proposed band. The lowest possible attenuation constant obtained is 0.005 dB/m at 136 GHz and the overall average attenuation constant over the entire D-band is 0.4 dB/m. However, when bends are introduced, there is a major effect, even with a minor bending, a significant rise in attenuation constant can be seen in the plot. Over the entire D-band, the attenuation constant for the 10° bend is 0.75 dB/m and 3.01 dB/m for the 20° bend. The effect of bending the waveguide on the surface current density is simulated and analyzed. The surface current density for different bends at the center frequency of 150 GHz is shown in Figure 6.

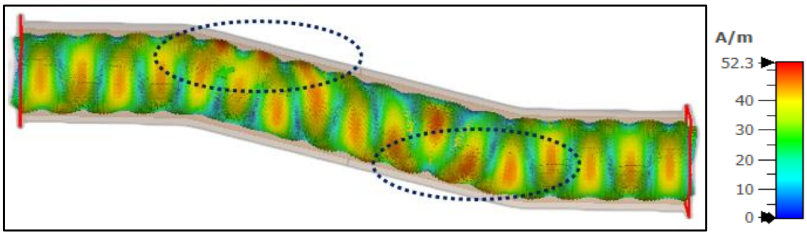
The efficiency of signal transmission is significantly influenced by the surface current density in a waveguide. It can be noticed from the 3D view of the surface current density in the circular waveguides that by introducing the bends, there is a substantial increase in the surface current density. For a straight line, the maximum surface current density obtained is 31.9 A/m and by bending it to 10° and 20°, It increases to 36.9 A/m and 52.3 A/m respectively. This can be understood by the fact that when the waveguide is bent, the wave is compelled to propagate in a different direction, which causes the electric field to be distributed differently along the waveguide's walls. In areas where the electric field is higher, the surface current density therefore increases as can be seen in the circled view. A number of circular hollow metallic waveguides have been proposed by different researchers. Various waveguide types, their attenuation constant, their frequency range of operation, and remarks are given and compared with current work in Table 1.



(a)



(c)



(d)

Fig. 6. Surface current density (a) 0° bent (b) 10° bent (c) 20° bent

Table 1
Benchmarking the proposed waveguide with previous proposed circular waveguide for THz communication systems

Waveguide type	Attenuation constant	Frequency range	Remarks	Year	Reference
Circular hollow waveguide	1.07 dB/m	0 to 1 THz	Designing a low-loss THz waveguide	2013	Munir and Aryan [25]
Copper hollow waveguide	0.4 dB/cm or 40 dB/m	1 THz	Comparison study for low loss at high frequency	2018	Chen *et al.,* [26]
Hollow metallic waveguide	0.0022 dB/mm or 2.2 dB/m	100 GHz to 300 GHz	Metallic circular waveguide design for the realization of TDSL	2022	Dong *et al.,* [27]
Hollow copper circular waveguide	0.4 dB/m	100 GHz to 300 GHz	Narrow circular hollow waveguide to analyze the propagation of THz waves through tiny air space	2022	Ahmad *et al.,* [21]
Bent copper hollow metallic waveguides	Lowest 0.005 dB/m average 0.4 dB/m	110 GHz to 180 GHz	To Analyze the effect of bending on propagation characteristics	-	This Work

4. Conclusions

Twisted pair cables are already installed in the infrastructure and have different twisting rates and bends. In this study, the effect of various bends on the circular waveguide propagation characteristics is studied to analyze the feasibility of utilizing the CAT6a cable for future communication systems and networks. It was found by the simulation analysis that introducing the different bends in the waveguide significantly affects the propagation characteristics such as s-parameters. The attenuation constant also increases with the increase in bend angles. Increasing bent from 0° to 10°, and 20° bent, surface current density is also increased indicating high power dissipation. Therefore, designing or utilizing the waveguides for future communication systems and technologies such as 6G, proper care, and optimization are needed for efficient and low-loss propagation.

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