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Investigation of Two-Wire Power Line for Efficient Propagation of THz Waves for Future 6G Communication Systems

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Abstract: The hunger for high speed data transmission and wide bandwidth has led to exploration of the terahertz (THz) frequency bands. Designing an efficient waveguide that propagates the THz waves with minimum loss at such high frequencies is quite challenging. In this paper, commercially available two solid core wires are investigated for the efficient propagation of THz waves using higher order modes. The THz radiation propagates wirelessly through the dielectric space between two wires. The effect of different airgaps between the two wires is also analyzed to analyze its various propagation phenomenon. The simulation analysis is performed through CST Microwave Studio, and it is found that commercially available solid core two wire can be applied for efficient and reliable propagation of THz radiation for future generations to meet the needs of users and high-speed applications.

Keywords: THz, Waveguide, Solid Core Wires, 6G

1. Introduction

With an increasing number of devices, new technologies, and users, the demand for high data rates in wired and wireless communication networks is increasing day by day and it is not going to stop. Currently, available technologies such as 4G, 5G, G-fast, etc. can provide good data rates which can support the current applications and needs. However, the near future and future technologies such as autonomous vehicles (AV), mixed reality, smart cities, holographical

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meetings, and other needs require much higher data rates. Wireless communication networks face significant challenges with the development of smart Internet of Things (IoT) and industry 4.0 applications that require much higher bandwidth and spectral efficiency [1]. The frequency range below 6G is extensively utilized by different applications such as AM, FM broadcasting, mobile radio, RADAR, WLAN, and navigation systems. Thus, the spectrum scarcity problem of the available spectrum is introduced due to the extensive use of bands below 6 GHz, and it creates significant challenges for new technologies and applications to be deployed within the limited frequency range [2]. Several solutions are proposed for this problem such as spectrum aggregation [3], ultra-wideband technology (UWB) technology [4], and Cognitive Radio [5] that facilitates unlicensed users to access the available frequency bandwidth using very low-power transmission. These solutions are not permanent and have limitations such as low range, security threads [6], etc. that restrict them from being practically applicable in certain scenarios.

One implying solution is to progress and explore the frequency beyond 6 GHz, and a large spectrum is available for new applications and technologies of the future. One possible frequency range that is gaining in popularity is the sub-THz and THz region which is still not fully explored. The THz range has recently emerged as an exciting and rapidly expanding area of communication research, attracting the interests of scientists and researchers across a variety of disciplines. THz waves are electromagnetic waves having frequencies in between infrared and microwave ranges of the electromagnetic spectrum, ranging from 0.1–10 THz [7]. Due to the substantial amount of unutilized bandwidth present in this frequency range, high-speed wireless communication could benefit greatly from these benefits. High data transfer rates are also possible using THz waves, which have higher frequencies than microwaves and have a higher amount of information per second. In addition to communication applications, THz waves have potential use in security screening, imaging, and medical diagnosis. However, dealing with extremely high frequency is much more challenging and complex, especially in terms of component size and losses.

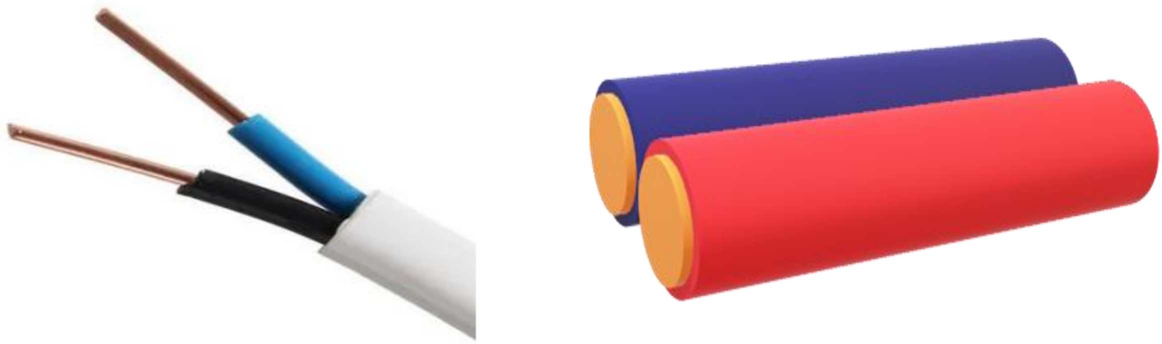
Recently, FCC has opened the THz spectrum licensed-free for testing purposes and this boosted research all over the world to explore the potential capabilities of the THz spectrum [8]. Future generations such as 6G, which is currently in the testing phase, are also utilizing the THz band [9]. No doubt the THz band will bring a revolution in human living, especially in communication with very high data rate, low latency, and more connected devices. Moreover, the THz range can enhance the precision in the imaging and sensing of different objects with fine details, making it useful for security screening, medical imaging, non-destructive imaging, and quality control [10].

Current copper-based technologies for wired communication, including ADSL, VDSL, G-fast, etc., rely on the transverse electric magnetic (TEM) mode to transfer information data. They have the advantage of not having a lower cut-off frequency, allowing transmission of all frequencies, and needing two wires to signal transmission. The attenuation in these TEM modes grows significantly as the frequency range or frequency band increases, such as mm-wave and THz, making it impractical to use these copper-based TEM modes for long-distance propagation. As a result, the greater frequency range in the commercially available and installed twisted pairs cables in the buildings and infrastructure limits the use of TEM mode. A novel idea of transmission of THz radiations wirelessly through the conventional copper twisted pair bundle wires was proposed by John Cioffi [11]. The idea was to propagate the THz radiation through the air space and dielectric space in the twisted pair wire bundles for terabit DSL (TDSL). This idea created an opportunity for researchers to explore this phenomenon and share their contributions to achieve the high-speed data rate for 6G. Hype is created, and numerous researchers have proposed to achieve the data rate in terabits per second using higher-order modes through the wires. Various THz waveguides with different materials are proposed in the literature for efficient propagation of THz waves, such as metallic wires and tubes [12], [13], dielectric [14], and hybrid [15] waveguides each having their advantages and limitations. It is shown that metallic structures when interacting with high-frequency waves such as optical and THz, generate the surface waves and can propagate the THz waves along the surface. The theoretical basics of surface wave propagation through a single wire are studied by [16] and for two metallic wires waveguides, theoretical analysis is performed by [17]. Wang in 2014, practically propagated the THz waves through the metallic wires with very low loss and negligible group velocity dispersion and successfully constructed a THz endoscope [18]. The coupling of THz waves efficiently between two wires is conducted in [19] and the comparison of metallic and dielectric waveguide is studied in [20]

For the realization of TDSL, a simulation analysis of twisted pair copper binder is studied by Souza in 2019 [21] and achieved an attenuation constant of 8 dB/m. Propagation of THz waves through metallic one and two wires has been investigated theoretically as well as experimentally by Shrestha in 2020 [22]. J. Dong in 2022, used four parallel bare wire waveguides for low loss propagation of THz waves and introduced the multi-structured brags grating in the metallic wires to achieve the polarization division multiplexing (PDM) [23]. In this study, two coated metallic wires are commercially used in houses and small industrial applications to propagate the THz radiation wirelessly through the surface plasmonic polariton.

2. Waveguide model for two parallel wires

Two-wire power lines are also known as single-phase power lines and are commonly used for residential and commercial electrical distribution systems. They are used to deliver alternating current (AC) electrical power to different electrical appliances such as fans, lights, etc. Both wires are coated with a dielectric material to avoid short circuits as one wire is a live wire and the other is a neutral wire. Two-wire power lines are available in different gauge sizes and materials; however, copper material is widely used and is reliable. Traditionally, TEM mode is used to transmit the current and it needs two conductors, one wire as a return. In this study, two wire power line is analyzed to study their feasibility to be utilized under higher order modes such as TE and TM modes and work as a waveguide. The structure of the commercially available two-wire power line is shown in Fig. 1 (a) and the simulated two-wire power line is shown in Fig. 1 (b).



(a) Commercially cable (b) 3D Model

Fig. 1- Two wires power line as a waveguide.

For analysis, copper material is considered for wires, and PTFE as a dielectric coating. The radius of the simulated two wires is chosen as 0.5 mm and the length of the wires is kept at 10 mm to save computational time. The thickness of the dielectric coating is 0.1 mm. Two-wire power line analysis is performed through the computer simulation technology (CST) tool using a time domain solver. The frequency range of operation ranges from 300 GHz to 350 GHz which is quite a high frequency for these types of wires if used in TEM mode and offers very high attenuation loss. The purpose of the study is to analyze the feasibility of these power line wires as waveguides for future 6G communications systems. Initially, as normally available two wire power lines with no gap between them are analyzed to study the performance characteristics such as scattering parameters, attenuation constant, surface current power flow, and the electric field distribution in the waveguide. Secondly, the effect of the gap between the power lines on the performance of the waveguide will be studied to analyze the feasibility of using these wires as waveguides for high-frequency applications such as 6G and beyond.

3. Results and Discussion

The proposed two-wire power line as an efficient waveguide is simulated for future communication systems for the frequency range from 300 GHz to 350 GHz. Scattering parameters are the basic parameters when the performance of any high-frequency structure is to be analyzed. The return loss S (1,1) and transmission coefficient S (2,1) for the two-wire waveguide attached along with the PTFE coating are shown in Fig. 2.

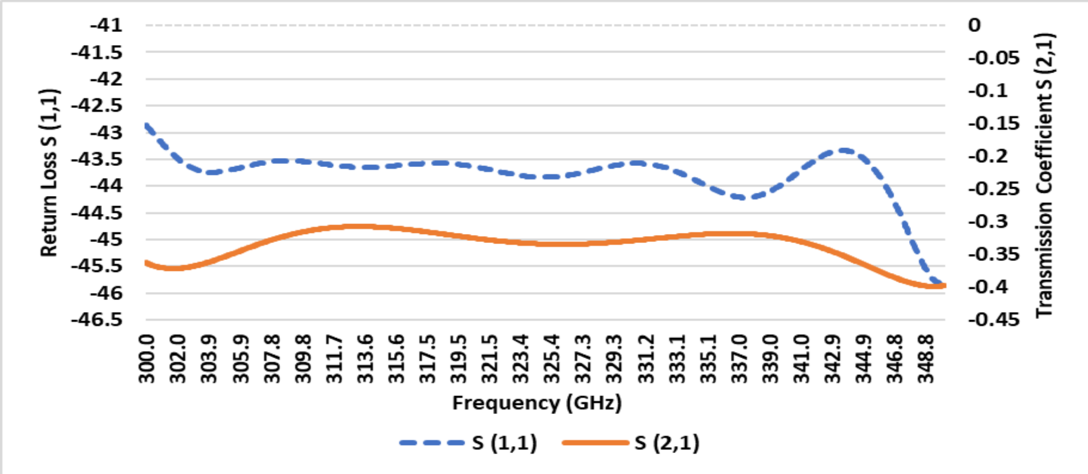


Fig. 2- Return Loss S (1,1) and Transmission Coefficient S (2,1) for two-wire power line

It can be noticed that the transmission coefficient and return obtained for the proposed waveguide are promoting and provide efficient propagation of THz radiations with low loss. The transmission coefficient throughout the band is near 0 dB while the return loss is below -44 dB. Another important parameter that is very important to consider when the communication range is chosen for a longer length and ensures low loss that is the attenuation constant. The attenuation constant defines the loss in the strength of the signal with the distance as the waves propagate through the transmission line. The attenuation constant for the proposed two-wire power line is shown in Fig. 3.

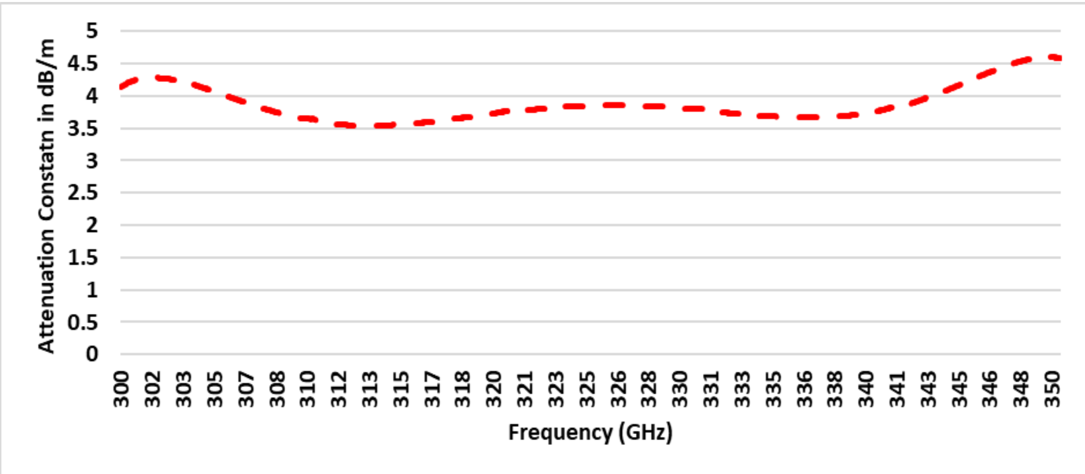
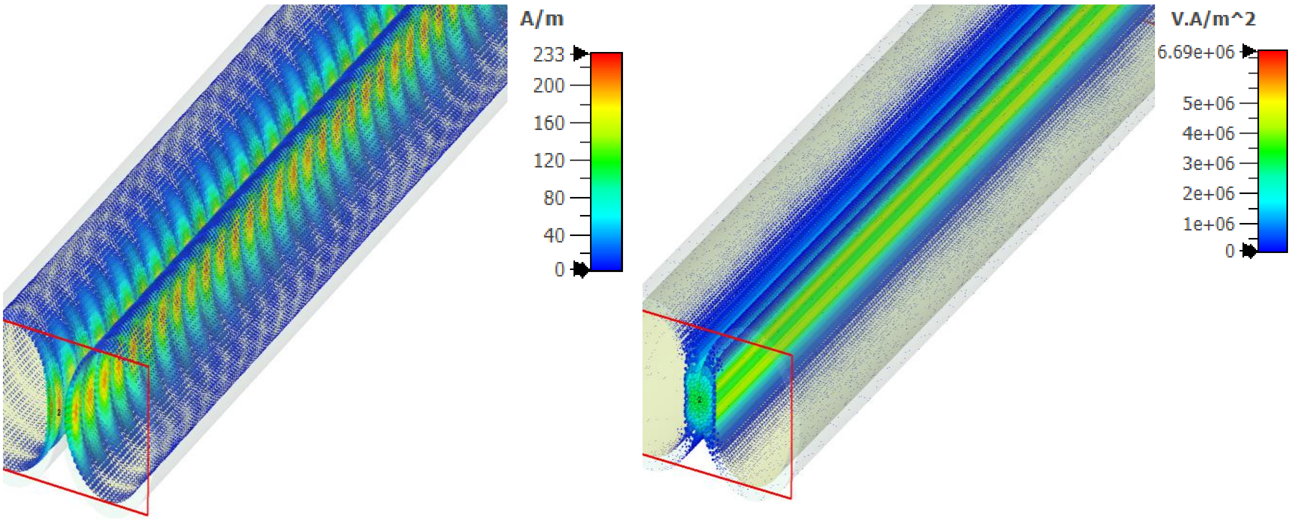


Fig. 3- Attenuation Constant in dB/m for two-wire power line

The attenuation constant obtained for the proposed two wire power lines is quite promising and is low, and throughout the band, it is almost below 5 dB/m. The surface current and the power flow for the two-wire waveguide are shown in Fig. 4. The two wires and PTFE coating are kept transparent to see the current intensity and the flow of power through the two-wire waveguide dielectric gap.



(a) Surface current density (b) Power flow

Fig. 4- 3D simulation Analysis for Current Density and Power Flow

It can two-wire in the surface current Fig. that maximum current flows of 233 ampere per meter (A/m) through the dielectric gap between two conductors, due to the surface plasmonic, while on the other side of the wire, there is the minimum current density. Power flow in the proposed THz waveguide from one port to another can be seen in power flow Fig., it can be noticed that the maximum power flow of 6.69×10^{6} volt. ampere per meter (V.A/m) is through the dielectric gap between metallic wires and there is no significant leakage or disturbance in the flow of power. Thus, showing the promising and efficient propagation of THz waves through the two-wire power line for future generation communication systems.

The effect of the gap between the wires on the performance characteristics of a two-wire power line waveguide is studied in detail in a further section.

3.1 Parametrical Study

The two wire power lines that are being considered as a waveguide for efficient propagation of THz waves through the dielectric gap and surface of wires are not always stuck together. Some suppliers prepare the wire bundles without sticking two wires, these wires are independent and are sometimes loose having airgap between them. Here in this section, the effect of the air gap between the two wires is studied and analyzed. In this analysis, three different gaps are taken under consideration: no gap, 200 µm gap, and 400 µm gap. The effect of these different gaps on the performance of a two-line power line can be easily analyzed by extracting the s-parameters. The transmission coefficient S (2,1) is more important when efficient power delivery is required and for all three gaps over a frequency band, transmission coefficients are shown in Fig. 5.

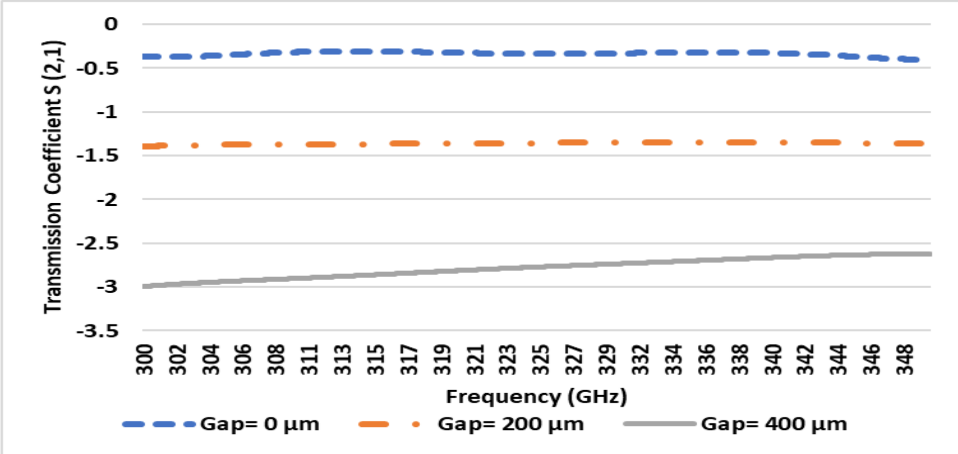


Fig. 5- Effect of Gap on the Transmission Coefficient S (2,1)

It can be noticed in the transmission coefficient for the different gaps in the two wire power line that as the gap is increasing, the transmission coefficient is getting worst. For no gap, the propagation of THz waves is efficient with very low loss as in Fig., it is near zero. For, the gap of 200 µm and 400 µm, losses are increasing. The effect of different gaps on the attenuation constant for the proposed waveguide is shown in Fig. 6.

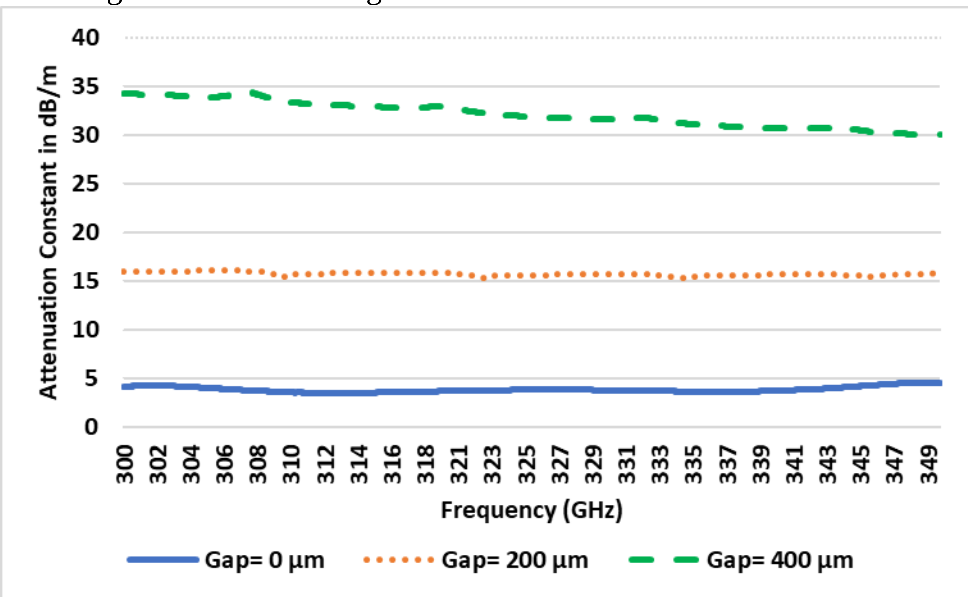


Fig. 6- Effect of Gap on the Attenuation Constant

The attenuation constant plot indicates that with the increase of the gap between the two wire power line acting as a waveguide, the losses are increased. The lowest loss is for the no gap between the coated power wire lines as they are attached. It can be noticed that a rapid increase in the attenuation constant is introduced in the waveguide with the increase in gap even if it reaches about 35 dB/m for a gap of 400 µm. The 3D analysis for the propagation of surface current and power flow and the effect of the different gaps in the performance of two wire waveguides is analyzed. The variation in surface current due to the different gaps can be seen in Fig. 7 with prospective as well as cross-sectional views. The two-wire power line waveguide is kept transparent to visualize the current density effects in detail.

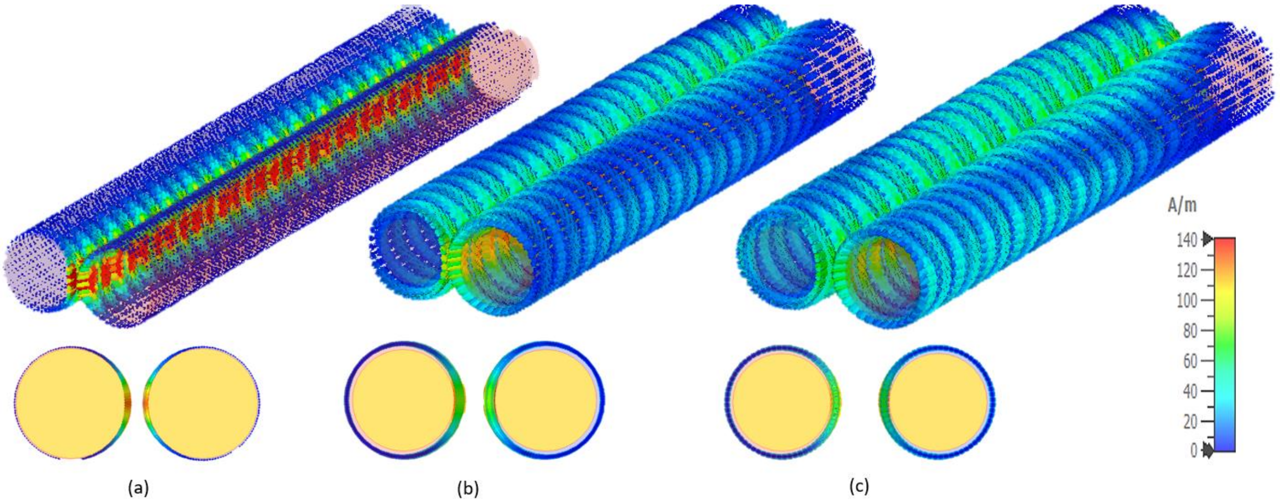


Fig. 7- The effect of the Gap on the Surface Current Density (a) 0 µm gap (b) 200 µm gap (c) 400 µm gap

The dielectric between the two-wire power line waveguide is the key path through which the THz waves are propagating. The above surface current Fig. visualizes the effect of various gap sizes between the wires on the surface current intensity. For the current density of 140 A/m, the areas with maximum current intensity can be noticed in the above Fig. It can be noted that with no gap, the waveguide achieves a maximum current density at the dielectric gap between the wires as indicated by red arrows. Thus, confining and propagating the THz waves through the gap with minimum loss or radiation while introducing the gap, the surface current is being distributed around the wire and low confinement can be seen as a cross-sectional view in Fig. 7 (c). The surface current density for the 200 µm and 400 µm is low in the dielectric gap as compared to the joint power lines. Thus, introducing the gap reduces the surface current density in the gap and distributes around the wires and can be radiated out or leaked.

The power flow in the proposed waveguide for different gap sizes is also analyzed and is illustrated in Fig. 8. The upper portion of the two-wire power line is cut to analyze the power flow rate and direction. Power flow defines the pattern and flow of maximum power within the structure. For the power flow of 2.01x106 V. A/m, it can be noticed that for the no gap, the maximum power is transmitted through the dielectric gap between the two wires, and all the power is concentrated in between the wires as in Fig. 8 (a). With the increment of the gap, the flow of power loses its confinement and concentration in the gap, and it spreads out around the wire as one can easily notice by looking at the cross-sectional view of Fig.8 (a) and (c). The effect of gap sizes of 200 µm and 400 µm are shown in Fig. 8 (b) & (c), and it can be noticed that the maximum power flow for 200 µm and 400 µm at the center of the waveguide is quite lower than the power flow of the wire waveguide without a gap. The power flow is spread over the wire circumference and is not confined to the gap.

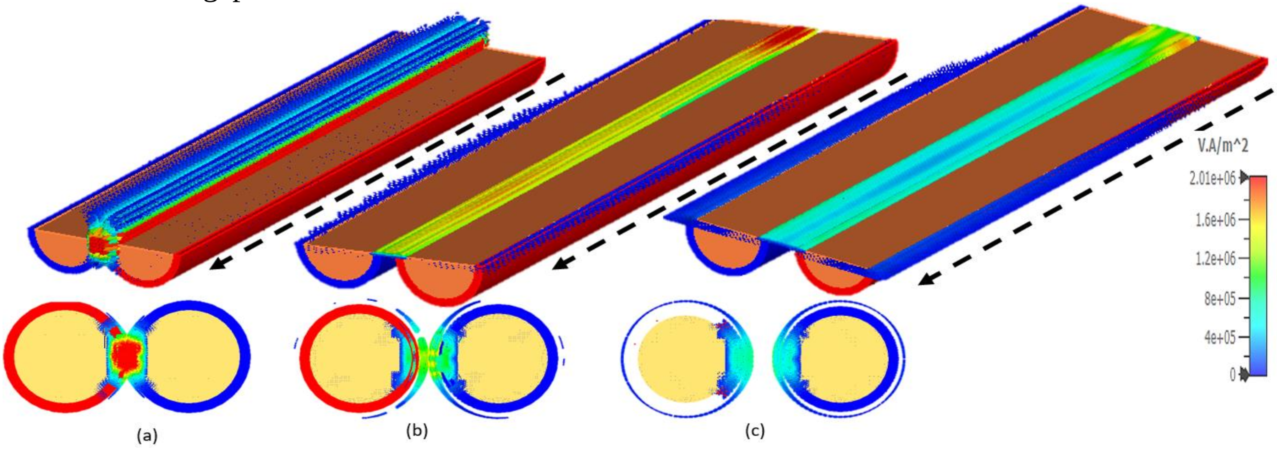


Fig. 8- Effect of Gap on the Power Flow (a) 0 µm gap (b) 200 µm gap (c) 400 µm gap

There, the gap between the two-wire power lines plays a significant role in the propagation of the THz waves. Larger gaps cannot confine the power within the dielectric gap between the wires. Looking at the simulation results for commercially available two-wire power line cable in which there is no gap between the wires can be used to transmit very high frequency in the THz range with low loss and can be a promising candidate for future communication systems such as 6G and beyond. However, there are numerous practical scenarios such as bending and excitation of the two-wire power line waveguide which will introduce further losses should also be considered in practical scenarios.

4. Conclusion

For the efficient propagation of extremely high-frequency THz range for future communication systems such as 6G, and TDSL, a commercially available two-wire power line cable is analyzed to study its feasibility by using high-order modes. From the above study, it can be concluded that two wire power lines can be a promising candidate for the efficient propagation of THz waves. The effect of different gaps between the two wires is also studied and it was found that the increment gap reduces the confinement of waves through the dielectric gap and thus increases the losses. If this two-wire power line cable is properly excited and the gap is optimized, this simple and readymade structure can work as an efficient waveguide for THz propagation with low loss without any expensive and complex fabrication process.

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