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Propagation Characteristics in a Circular Waveguide for Feasibility Study of Terabit DSL

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Abstract: Due to the demand for higher data rates and greater download speeds by users and increasing number of deployed devices providing content-rich data, new cost-effective technologies which utilizes the concept of waveguides over copper that can enable the realization of terabit DSL need to be explored to meet the required demands. This paper presents the propagation characteristics of circular waveguide which include reflection/transmission coefficient, attenuation coefficient and surface current. The design and simulation process have been carried out using CST Microwave Studios at the frequency of 100GHz to 300GHz. The circular waveguide is varied for various radius and length to observe for the respective propagation characteristics. Based on the result, it is shown that the reflection coefficient decreases with the increase in radius and length and it is below -50dB. Besides, with the increase in frequency, the transmission coefficient shows that the waveguide is able to achieve 100% transmission (0dB) at 200GHz with the increase in radius and length. Moreover, the attenuation coefficient of the waveguide is low which is about 0.0022dB/mm and maximum surface current intensity of 81.5556A/m. The results obtained can be considered the first step on understanding the propagation characteristics of waveguide at terahertz frequency range towards the realization of Terabit DSL.

Keywords: Propagation characteristics, terahertz frequency, circular waveguide, S-parameter, Terabit DSL

1. Introduction

Digital subscriber line (DSL) technology transmits broadband data over telephone lines and it is the most popular form of broadband access in the world [1]. The latest DSL technology is implementing G.mgfast which can operate up to 848MHz and can achieving data rates of 5 to 10Gbps [2]. However, with the current copper access on G.mgfast, the consumer's demand for higher data rates is still increasing. Aside from the typical mobile communication, newer uses of high-speed wireless links also require very high data rates such as board to board communications inside a computer [3], downloading high definition movies from a kiosk [4] and transferring a large amount of data between mobile terminals and storage device wirelessly.

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In order to achieve higher data rates, terahertz frequency range that has greater available bandwidth is needed to be explored. Terabit DSL technology which utilizes higher frequency spectrum together with the new concept with waveguide over copper is now being studied [5]. Waveguide over copper access operates at millimeter frequency which is about 30 GHz to 1 THz that can provide higher data rates. According to the study reported in [6], a metallic sheath two-wire waveguide has been shown to support terahertz beams by carrying a 200GHz signal and at the same time able to achieve aggregate data rates up to terabits at short range. Besides, in [7] shows that a 3cm short circular dielectric waveguide is able to achieve data rates up to 30Gbit/s at 335GHz and can operate between 260GHz to 400GHz.

However, the transmission at high frequency have a higher attenuation and in return there might be a higher loss in the process of transmission. As stated in [8], the attenuation due to the two-wire waveguide is found to be 1.97dB/m at 20GHz and the attenuation is increasing with the increase of frequency. Moreover, study reported in [7] shows that an average measure of attenuation coefficient of around 0.05dB/cm is achieved within the frequency range of 260GHz to 400GHz of a circular dielectric waveguide.

Previous studies show, circular waveguides have always been chosen for the feasibility study of terabit DSL. However, the feasibility study on the propagation characteristics of linear-polarized signal in circular waveguide at terahertz frequency has not been explored by other researchers. Therefore, in this paper, circular waveguide will be chosen to study the propagation characteristics which include reflection/transmission, attenuation coefficient and surface current intensity. The circular waveguide design structure has been explained in section 2. The analysis and discussion of the results are presented in section 3 and conclusion of the study is presented in section 4.

2. Circular Waveguide Design Structure

The cut-off frequency of a waveguide is the minimum frequency for which a mode will propagate inside a waveguide. The cutoff frequency of a circular waveguide can be calculated through equation (1);

$$f_c = \frac{1.8412c}{2\pi a} \tag{1}$$

Where, a is the radius of the waveguide, while c is represented as the speed of light. The cutoff frequency is calculated so that the designed waveguide can operate at the terahertz frequency between 100GHz to 300GHz. Besides, CST Microwave Studio software is used to perform the design and simulation of the waveguide. The time domain solver is used and the simulated frequency is between 100GHz to 300GHz. Fig. 1 below shows the designed circular waveguide structure where 5 different dimensions of radius and length are varied between 1 to 2.8 mm and 1 to 20 mm respectively. The material of the circular waveguide is constructed using Perfect Electric Conductor (PEC). Table 1 shows the comparison of simulated cutoff frequency with the calculated cutoff frequency. It can be found out that the simulated cutoff frequency is almost the same as the calculated cutoff frequency.

Fig. 1 - Circular waveguide

Table 1 - Cutoff frequency of circular waveguide

Radius (mm)	Simulated Cutoff Frequency (GHz)	Calculated Cutoff Frequency (GHz)
1.05556	88.7	83.23
1.5	59.2	58.57
2.0	44.2	43.93
2.5	35.5	35.14
2.8	31.6	31.38

Next, the propagation characteristics which include reflection coefficient, transmission coefficient and attenuation will be evaluated in the next section. Fig. 2 illustrates the concept and definition between reflection coefficient, transmission coefficient and attenuation within a waveguide. The waveguide is represented by the block, and the incident ray is the terahertz signal being fed into the waveguide. When the signal is being fed into the waveguide, some of the signal is being reflected which can be represented by the reflection coefficient. Inside the waveguide, some of the signal will be loss due to the absorption of the waveguide which might refer to the attenuation. The absorption will occur due to the conductor loss and dielectric loss. When the signal is passed through the waveguide, the transmitted ray will be received by the receiver or antenna. However, some of the signal will be reflected and not all the signal will be received by the antenna.

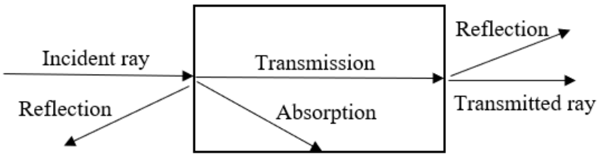


Fig. 2 - Block diagram showing the relationship of reflection, transmission and absorption

3. Results and Discussion

The initial dimension of the simulation started with a radius of 1.5 mm and length of 8.875 mm. Based on the simulation, it is found that the cutoff frequency which is measured at -3dB of the transmission graph is at 59.2 GHz as shown in Fig. 3. To evaluate the surface current intensity between the bandpass and bandstop characteristics of transmission characteristic of waveguide, the surface current of TE_{11} and TM_{01} mode at 30GHz (bandstop) and 300GHz (bandpass) is observed as shown in Fig. 4. (a) -(b) represents the TE_{11} mode while Fig. 4(c)-(d) represents TM_{01}mode. The surface current intensity during the bandstop shows weak intensity, which has current intensity of only 21.1107A/m for TE_{11}mode and 18.4783A/m for TM_{01} mode. During the bandpass, both TE and TM mode shows higher surface current intensity which is 68.9932A/m and 81.5556A/m respectively. It can be observed that during a bandpass, the current intensity is higher due to the signal contained inside the circular waveguide. Note that surface current density is also higher near the input port and as the waves propagate into the waveguide the surface current intensity reduces gradually depending on the attenuation constants.

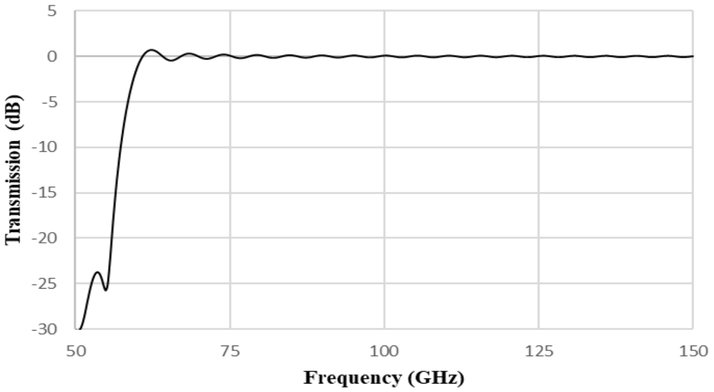


Fig. 3 - Transmission, S21 of circular waveguide with radius = 1.5mm and length = 8.875 mm

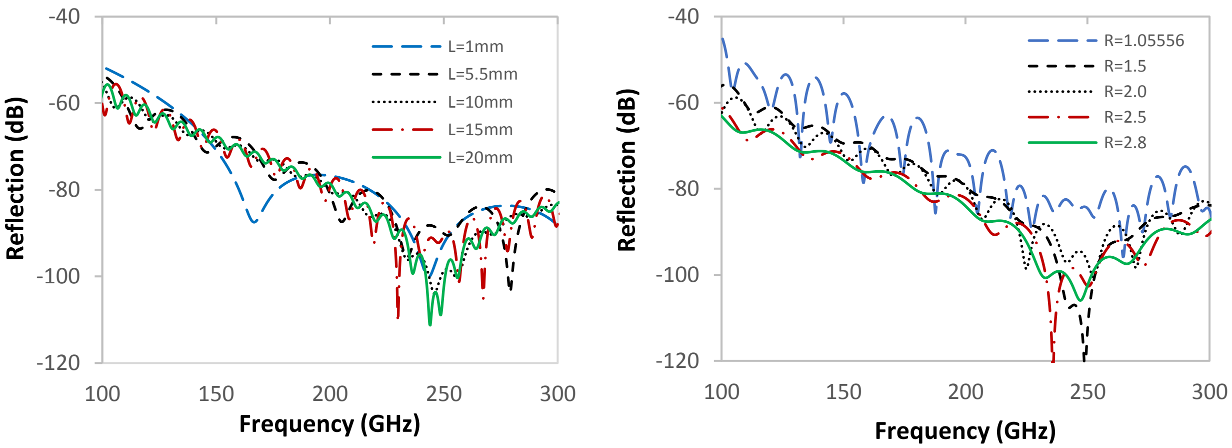
(a) 30GHz **(b) 300GHz**

(c) 30GHz **(d) 300GHz**

Fig. 4 - Surface current intensity (a) bandstop of TE; (b) bandpass of TE ;(c) bandstop of TM and; (d) bandpass of TM

3.1 Reflection Coefficient

Fig. 5(a) shows the reflection coefficient of a waveguide with a radius fixed at 1.5mm, and the length varies from 1 mm to 20mm. Furthermore, Fig. 5(b) shows the reflection coefficient of a waveguide with a length fixed at 8.875 mm and the radius varies from 1.05mm to 2.8mm. Both the responses show the same trend where the reflection coefficient decreases with the increase of frequency, which is below -40dB. However, it can be observed that after 250 GHz, there is a slight increase in the reflection coefficient. Fluctuation is increase with the increase in length and decrease in radius. Fig. 6 shows the relationship of reflection, with radius and length at 100 GHz, 200 GHz and 300 GHz respectively. Based on the result, it can be observed that the reflection coefficient of 100 GHz is in the range of -40 dB to -65 dB, -70 dB to -85 dB for 200 GHz and -80 dB to -95 dB for 300 GHz. The range of the reflection coefficient is relatively low because the waveguide has a cut off frequency much lower than 100 GHz.



(a) **(b)**

Fig. 5 - Reflection coefficient, S_{11} graph (a) effect of length; (b) effect of radius

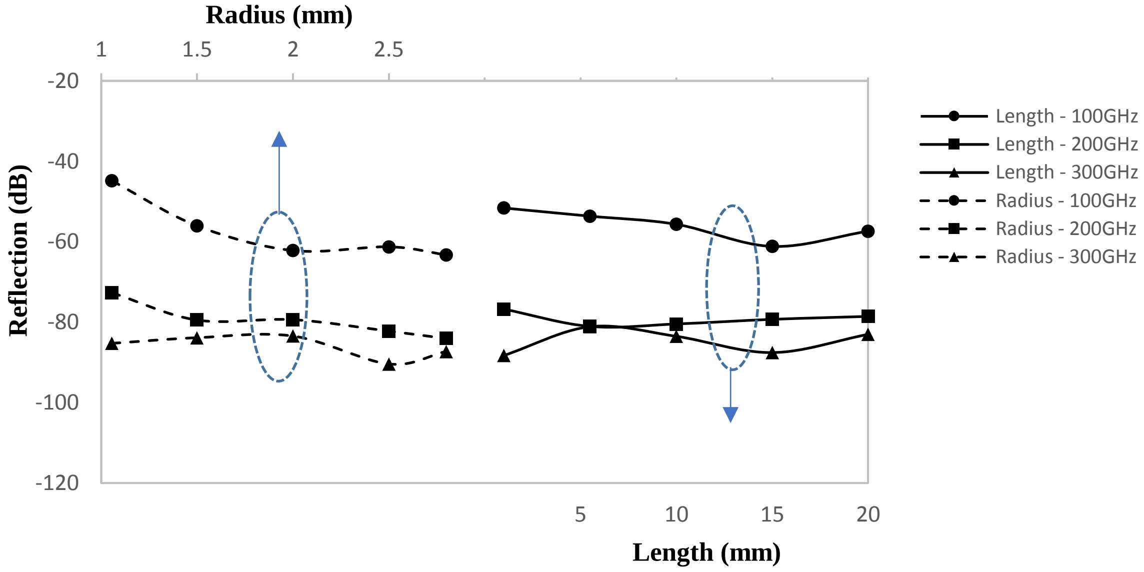
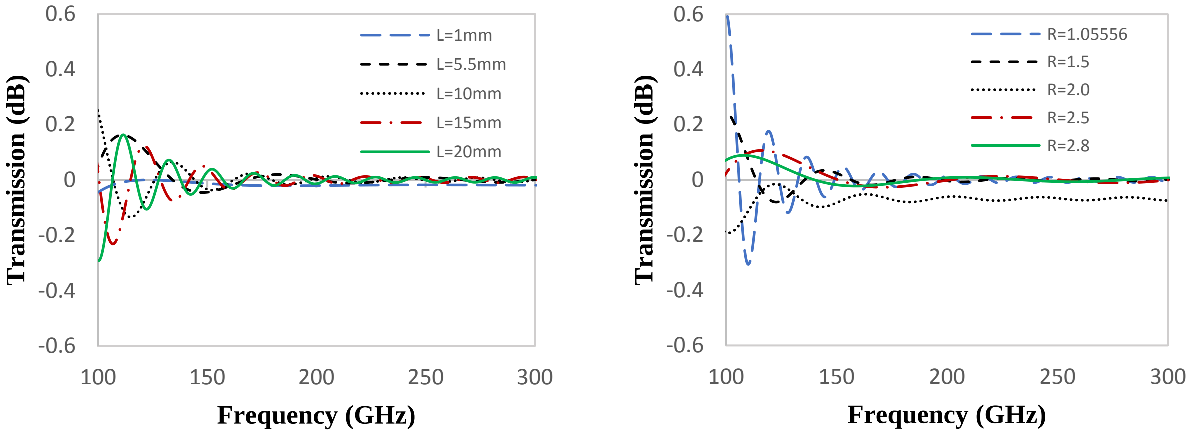


Fig. 6 - Reflection over radius and length

3.2 Transmission Coefficient

Fig. 7(a) shows the transmission coefficient of a waveguide with a radius fixed at 1.5 mm, and the length varies from 1 to 20 mm. While Fig. 5(b) shows the transmission coefficient of a waveguide with a length fixed at 8.875 mm and the radius varies from 1.05 mm to 2.8 mm. Both the responses show the same trend of graphs where the transmission coefficient is ±1 dB. However, it can be observed that there are slight fluctuations at frequencies below 200 GHz. The 3dB analysis is performed due to the design structure of the waveguide is more likely behaves as a band pass response [9]. Since the transmission is above -3dB, therefore it can be summarized that the designed waveguide can operate completely at the simulated frequency. Fig. 8 shows the relationship of transmission, radius and length at 100 GHz, 200 GHz and 300 GHz. Based on the result, it can be observed that the transmission coefficient at 100 GHz for length and radius is a bell-shaped graph due to the fluctuations as shown in Fig. 7. Meanwhile, for 200 GHz and 300 GHz, both the transmission coefficient for radius and length is at 0 dB which shows 100 % transmission at these particular frequencies.



(a)

(b)

Fig. 7 - Transmission coefficient, S_{21} (a) effect of length; (b) effect of radius

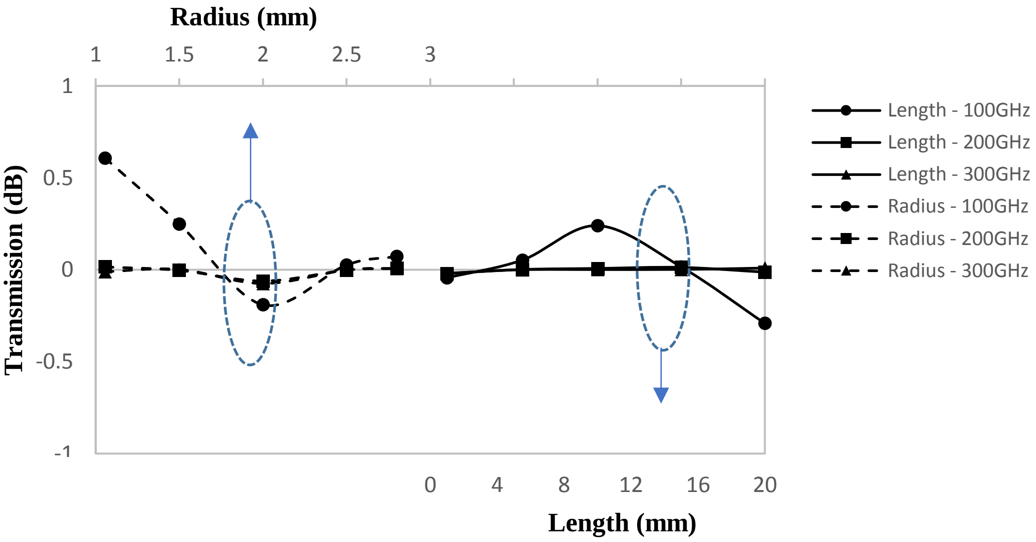
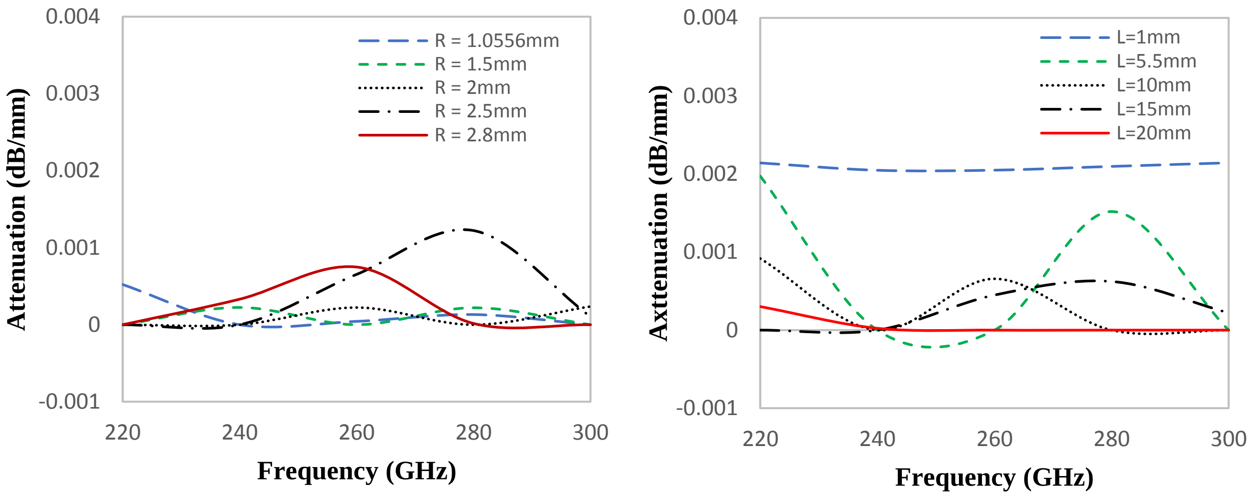


Fig. 8 - Transmission over radius and length

3.3 Attenuation Coefficient

The attenuation coefficient of the waveguide is calculated based on the s-parameters data obtained from the simulated result as in Section 3.1 and 3.2. Fig. 9 (a)-(b) shows the attenuation over frequency at different radius and lengths respectively. It is observed that with the increase in radius, the attenuation is slightly increased with the increase in frequency. This demonstrates that as long as the operating frequency range is above the cut off-frequency, having a smaller radius provides a lower attenuation due to the THz waves being confined into a smaller space. The overall attenuation coefficient for varied radius is below 0.001dB/mm which indicates a low attenuation in the designed waveguide. However, the waveguide radius of 2.5mm has a slightly higher attenuation which is about 0.0012dB/mm at 280GHz. Overall, the attenuation coefficient of the designed waveguide is very low which has a minimum and maximum attenuation of 0.0001dB/mm and 0.0022dB/mm over the frequency range of 100GHz to 300GHz. The low attenuation coefficients in the conventional waveguide are due to the material of the waveguide which is PEC which has a perfectly conducting wall hence the attenuation and loss is low in the waveguide.



(a) **(b)**

Fig. 9 - Attenuation coefficient (a) effect of radius (b) effect of length

4. Conclusion

In conclusion, this paper presents the propagation characteristics of circular waveguides at the frequency range of 100 GHz to 300 GHz. From the result, it can be summarized that with the increase in frequency, the reflection coefficient will decrease and the transmission coefficient will come to maintain at 0dB after 200GHz with the decrease in fluctuations. In addition, the designed circular waveguide has a low attenuation coefficient of 0.0022dB/mm. The results presented in this paper can provide a basic understanding of the propagation characteristics of terahertz signal in the waveguide in order to realize terabit DSL in future communication systems.

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