Design and Analysis of a TEM Mode Rectangular Coaxial Waveguide for Mobile 5G Millimeter Wave Antenna Module Applications

Eunyoung Park · Sangkil Kim*

Abstract

In this paper, design and analysis of a transverse electromagnetic (TEM) mode rectangular coaxial waveguide for a mobile 5G millimeter wave (mmWave) antenna module are presented. General structures of 5G radio frequency (RF) module for mobile sub-6 GHz and mmWave applications are also discussed in this paper. Thorough analysis of transmission line and waveguide structures at mmWave frequency band is essential and fundamental information to design highly integrated RF front-end modules. Theoretical design equations of the waveguide, such as impedance, loss, and radiation are presented, and the equations are verified by a full wave 3D FEM electromagnetic simulator. Impedance value of the rectangular waveguide structure was calculated using the conformal mapping method. Theoretical operation frequency bandwidth and design guide are also presented. The characteristics and analysis of the rectangular coaxial waveguide structure presented in this paper is easily scalable to other frequency bands. The proposed design equations are also applicable to various planar layer-by-layer integrated circuit (IC) or module manufacturing process.

Key Words: Millimeter-Wave, mmWave Module, RF Front-End, TEM Mode, Waveguide, 5G Communication System.

I. INTRODUCTION

In April 2019, a commercial sub-6 GHz band mobile 5G communication network service was launched in South Korea for the first time. The 5G communication features an ultra-fast data rate up to several Gbps and ultra-low latency of several ms. Various unprecedented user experiences and technologies, such as augmented reality (AR), smart factory/hospital, cloud computing, and self-driving cars, are available due to the 5G communication network [1, 2]. The next technical challenge is to implement millimeter wave (mmWave) 5G technology operating at 28 GHz or 39 GHz. This technology is able to improve

data rates dramatically by fully utilizing its broad bandwidth of 800–1,000 MHz. The wavelength at the mmWave 5G frequency band is less than 10 mm, which is a comparable size to radio frequency front-end (RFFE) module chips. For this reason, the antennas for mmWave 5G communication could be implemented in the package (antenna-in-package [AiP]) [3]. The distance between the radio frequency integrated circuit (RFIC) and the antenna could be minimized, and the mmWave signals could be tightly confined within the waveguide structures.

The 5G mmWave module was designed using system-in-package (SiP) technology [4, 5]. Many functional chips and

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passive components, such as power management integrated circuit (PMIC), RFIC, antenna, and SMDs, were integrated in a single package laminate, and the module was connected through a flexible RF cable. The RF cable is a critical component, as DC power, analog/digital control, and intermediate frequency (IF) signals are carried by it. Therefore, it is essential for the 5G mmWave module to design and analyze the RF cable thoroughly. This paper discusses the design requirements of the RF cable and presents a proper waveguide structure with thorough theoretical analysis.

II. 5G MMWAVE MODULE FOR MOBILE DEVICES

A high-frequency module is a key component of the RFFE chain. Usually, low noise amplifiers (LNAs), power amplifiers (PAs), filters, duplexers, and antenna switches are integrated into a single chip using the SiP technology. It is an essential part of mobile wireless communication systems because it is able to integrate many IC chips made through various processes (CMOS, GaAs, or SiGe) into a single module chip. The general structure of an RF module for 5G applications is shown in Fig. 1.

The most widely used commercial sub-6 GHz band RF modules for 4G-LTE and 5G communication consist of Rx/Tx amplifiers (LNAs and PAs), an antenna tuning system, and multiplexers (Fig. 1). The antennas are not integrated within the module because they are much larger than the module chip at the sub-6 GHz frequency band (3.6 GHz). However, the operating frequency bands for 5G mmWave RFFE module are 28 GHz and 39 GHz, and their half-wavelength ($\lambda_g/2$) is less than 5 mm in the free space. It is feasible to integrate antennas and RFICs in a single package (module chip) due to an antenna size comparable to the RFICs.

The world's first commercially available 5G mmWave module chip for mobile devices also has a structure similar to Fig. 1

[6]. Antenna arrays, antenna feeding networks, mixed analog/digital signals, and RF connectors are integrated in a single package substrate. IC chips and other passive components were mounted on the other side of the antenna array. Mixed analog and digital signals, such as IF band, baseband, and mmWave RF signals, travel through the transmission lines embedded in the module or external connectors/cables. The RF cable is one of the most critical components of the 5G mmWave antenna module, as the RF cable and connector carry IF, digital control, VDD, and baseband signals. Therefore, it is necessary to analyze the structure of the cable thoroughly to design the mmWave antenna module for mobile devices.

III. A TEM MODE WAVEGUIDE FOR MOBILE 5G MMWAVE MODULE APPLICATIONS

The first step of the RF cable design for the mobile 5G mmWave module is to find a proper transmission line (or waveguide) structure. RF cables for 5G mmWave modules should support a broad frequency spectrum from DC to GHz band. VDD and digital/analog control signals range from DC to a few hundred MHz, and IF signals are located at 6–10 GHz. It is desirable to use a low-loss TEM (transverse electromagnetic) mode waveguide structure to minimize signal dispersion and achieve an ultra-wide operation frequency bandwidth (extremely high cutoff frequency). Furthermore, the capability of extending to a multi-signal line structure is also important for signal integrity. A multi-line circular coaxial structure satisfies most of the above conditions, but it is challenging to build a compact connector and stacked line structure. A rectangular coaxial structure is an appropriate structure to meet all the design considerations.

Fig. 2 shows the proposed structure of a rectangular coaxial waveguide. In the case of Fig. 2(a), each side of the waveguide is closed with a continuous metal wall. The structure shown in Fig.

Fig. 1. The structure of a 5G mmWave antenna module for mobile devices.

Fig. 2. (a) Rectangular coaxial waveguide with continuous side walls, (b) practical model with via walls, (c) practical model with via wall, and (d) stacked multi-line rectangular coaxial waveguide.

2(a) is a desirable structure due to complete field confinement, but it is challenging to implement a continuous metal wall on the flexible substrate. The structure using the via wall is more practical, as shown in Fig. 2(b), (c), and (d). The via pitch is a critical design parameter in this case, as it controls field leakage (radiation) from the waveguide structure and coupling between the adjacent waveguides. It is possible to achieve more than a 60-dB isolation level between the waveguides easily when each waveguide supports TEM mode waves. Fig. 2(b) and (c) show that both the left and right sides of the rectangular waveguide are closed through the via wall. It is easy and practical to extend the rectangular cable to the multi-line structure, as shown in Fig. 2(d). By sharing the via-wall or metal surface between the adjacent waveguides, the waveguides can be arranged densely without wasting space, and the electromagnetic fields can be effectively confined in the cross-section of the waveguide.

In this section, important design parameters, such as the waveguide impedance (Z_0), loss (α), cutoff frequency (f_c), and via pitch (p) of the rectangular coaxial waveguide, are discussed.

1. Impedance

The impedance of a TEM mode waveguide is expressed as follows. L and C are the inductance (L/m) and capacitance (F/m) per unit length, respectively, v_p is the phase velocity in the given waveguide structure and material, and ϵ_{eff} is the effective dielectric constant of the dielectric material. The characteristic impedance and phase velocity of a TEM mode waveguide can be expressed as Eqs. (1) and (2).

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{1}{v_p C} \quad (\Omega) \quad (1)$$

Fig. 3. Rectangular coaxial waveguide structure section and design variables.

$$v_p = 1/\sqrt{\mu \cdot \epsilon_{eff}} \quad (m/s) \quad (2)$$

As written in (1), C is a dominant parameter of the characteristic impedance value. Fig. 3 shows a cross-section of the rectangular coaxial waveguide. A rectangular signal line is located at the center of the waveguide. The impedance of the waveguide can be calculated by computing the total capacitance (C_t) per unit length, which is obtained through the conformal mapping of the field distribution from a cylindrical to a rectangular geometry [7]. The C_t value includes the corner capacitance values per unit length (C_{f1} and C_{f2}), in addition to the capacitance per unit length of the conventional circular coaxial waveguide [8, 9]. C_{f1} and C_{f2} can be expressed as Eqs. (3) and (4), and the resulting C_t and Z_0 are also shown in Eqs. (5) and (6).

$$C_{f1} = \frac{\epsilon_{eff}}{\pi} \left[\log \left(\frac{w_g^2 + t_g^2}{4t_g^2} \right) + \frac{2t_g}{w_g} \tan^{-1} \left(\frac{w_g}{t_g} \right) \right] \quad (F/m) \quad (3)$$

$$C_{f2} = \frac{\epsilon_{eff}}{\pi} \left[\log \left(\frac{w_g^2 + t_g^2}{4w_g^2} \right) + \frac{2w_g}{t_g} \tan^{-1} \left(\frac{t_g}{w_g} \right) \right] \quad (F/m) \quad (4)$$

$$C_t = 2\epsilon_{eff} \left(\frac{w}{t_g} + \frac{t}{w_g} \right) + 4(C_{f1} + C_{f2}) \quad (F/m) \quad (5)$$

$$Z_0 = \frac{\eta_0}{\sqrt{\epsilon_{eff}} \left[2 \left(\frac{w}{t_g} + \frac{t}{w_g} \right) + \frac{4}{\epsilon_{eff}} (C_{f1} + C_{f2}) \right]} \quad (\Omega) \quad (6)$$

The proposed equations were verified by comparing calculated results to the computation data of the commercial full-wave 3D simulator, HFSS v17.1 (Ansys Inc., Canonsburg, PA, USA). Fig. 4 shows the impedance variation according to the value of the signal line width (w) for each rectangular coaxial waveguide in the vacuum core (Fig. 4(a)) and filled with Teflon (Fig. 4(b)). For the calculation, all the metals were set to copper ($\sigma = 5.96 \times 10^7 \Omega/m$), and the electrical properties of Teflon were defined as $\epsilon_r = 2.0$ and $\tan \delta = 0.001$. The simulated and formulated results agree well. A designed practical 50 Ω rectangular coaxial waveguide has $w_g = 68 \mu m$, $w = 120 \mu m$, $t_g = 42 \mu m$, and $t = 16 \mu m$.

2. Cutoff Frequency

A coaxial waveguide consisting of two conductors, by their nature, supports a TEM mode. The operating frequency band

Fig. 4. Impedance change of rectangular coaxial waveguide filled by (a) vacuum and (b) Teflon.

width of a TEM mode waveguide can be defined from DC to the frequency at which any high-order wave propagation mode is excited. The first high-order mode of a square coaxial waveguide is TE_{01} or TE_{10} . The cutoff frequency (f_c) of the rectangular coaxial waveguide's TE_{10} mode can be expressed by the transcendental equation, and it can be calculated by Eqs. (7)–(9) [10]. For the TE_{01} mode, the design parameters should be modified as $t_g \rightarrow w_g$, $w \rightarrow t$, $w_g \rightarrow t_g$, and $t \rightarrow w$.

$$\cot\left(\frac{2\pi t_g f_c}{v_p}\right) - \tan\left(\frac{t\pi f_c}{v_p}\right) = \frac{B}{Y_{C1}} \quad (7)$$

$$\frac{B}{Y_{C1}} = \frac{2f_c}{v_p} (w + 2w_g) \left[-\ln(4u) + \frac{1}{3}u^2 + \frac{1}{2}(1 - u^2)^4 \left(\frac{f_c(w + 2w_g)}{v_p} \right)^2 \right] \quad (8)$$

$$u = \frac{2w_g}{w + 2w_g} \quad (9)$$

Because (7) and (8) are transcendental equations, it is difficult to obtain an analytical solution. In this paper, a graphical method was chosen to obtain solutions to the transcendental equa-

Fig. 5. Graphical analysis of high-order mode of a rectangular coaxial waveguide.

tions, as shown in Fig. 5. The values of the variables used were a 50-Ω waveguide designed in section A. The first high-order mode cutoff frequency of the 50-Ω rectangular coaxial waveguide was about 334 GHz. Therefore, the operating frequency bandwidth of the designed waveguide was DC to 334 GHz, which was much higher than the operation frequency of the 5G mmWave module.

3. Loss

The total loss (α_t) of a TEM mode rectangular coaxial waveguide can be divided into three parts as, shown in (10): radiation (leakage) loss (α_l), dielectric loss (α_d), and conductor loss (α_c).

$$\alpha_t = \alpha_l + \alpha_c + \alpha_d \cong \alpha_c + \alpha_d \quad (10)$$

There is negligible radiation loss when the waveguide is closed with continuous metal walls or a fine-pitched via array. Each loss can be calculated as shown in (11) and (12) [11].

$$\alpha_d = \frac{k_0^2 \tan \delta}{2k_z} = \frac{k_0 \tan \delta}{2\sqrt{\epsilon_r}} \quad (11)$$

$$\alpha_c = \frac{47.09R_s}{\eta Z_0} \left(1 + \frac{t + 2t_g}{w} \right) \frac{w}{[0.2794(t + 2t_g) + 0.7206w]^2} \quad \text{for } (t + 2t_g)/w < 2.5$$

$$\alpha_c = \frac{59.37R_s}{\eta Z_0} \left(1 + \frac{t + 2t_g}{w} \right) \frac{1}{t + 2t_g} \quad \text{for } 2.5 \leq (t + 2t_g)/w \leq 4$$

$$\alpha_c = \frac{47.09R_s}{\eta Z_0} \left(1 + \frac{t + 2t_g}{w} \right) \frac{1}{t + 2t_g} \quad \text{for } (t + 2t_g)/w < 4 \quad (12)$$

R_s is the sheet resistance of the metal ($R_s = 1/(\delta_s \sigma)$), η is the intrinsic impedance ($\eta = \sqrt{\mu/\epsilon}$) of the medium, Z_0 is the characteristic impedance of the transmission line ($Z_0 = \sqrt{L/C}$). Fig. 6 shows the calculated and simulated attenuation constants of a rectangular coaxial waveguide made of copper and

Fig. 6. Loss of rectangular coaxial waveguide composed of Teflon: (a) dielectric loss, (b) conductor loss, and (c) total loss.

Teflon. The simulated and calculated results are well matched.

4. Via Pitch

Continuous sidewalls can be considered as via arrays with zero pitch length but it is challenging to implement solid metal walls in the flexible RF or module substrate. The periodically arranged via wall shown in Fig. 2(b) and (c) is a more practical structure than the continuous metal wall. The critical design parameters are the diameter (d) and pitch (p) of the vias. The

electromagnetic bandgap (EBG) should be considered because the via wall is a periodic structure [12, 13]. From (13), the first visible bandgap occurs when $n = 1$.

$$\beta_z = n\pi \quad (13)$$

$$p = \frac{\pi}{\beta_z} = \frac{\lambda_g}{2} \quad (14)$$

It is clear that the via pitch should be shorter than the half-wavelength, as shown in (14). The smallest via pitch is defined by mechanical durability and feasibility. It is desirable to set the minimum via-to-via distance of the fabrication process, but excessive via density decreases the mechanical durability of the designed rectangular coaxial waveguide. As a rule of thumb, the maximum via pitch should be less than a quarter wavelength of the guided wave, and the minimum via pitch is $\lambda_g/20$ when the design and fabrication margins are considered. It should be noted that the maximum via pitch is a hard bound because the bandgap effect should be prevented. The minimum via pitch is a soft bound that varies depending on the manufacturing capability and process. Fig. 7 graphically presents the via design guide when the via pitch (p) and diameter (d) are given. The via diameter and pitch are normalized by the guided wavelength. The upper half plane is a reasonable design area, as the via diameter cannot be larger than the via pitch.

5. Radiation

Electromagnetic radiation is strictly regulated by law for the public health. According to the FCC regulations for electromagnetic radiation (47 CFR 15.109 Radiated emission limits) [14], mobile devices are classified as Class B, as shown in Table 1. The 5G mmWave module or cable should not exceed 500 $\mu\text{V/m}$ of electric field intensity (E) at a point 3-m away from the device under test (DUT).

Based on the given regulations and the Poynting vector theorem, the maximum allowed power leakage is obtained as follows. Because the distance (r) from the DUT is 3 m, the electromag-

Fig. 7. Graphical analysis for the via wall design.

Table 1. FCC regulation for Class-B devices

Frequency (MHz)	E-field ($\mu\text{V/m}$)
30–88	90
88–216	150
216–960	210
>960	300

netic field having a frequency higher than 10 GHz can be considered the far field at the measurement point. It is reasonable to assume the radiated EM field is a TEM wave. In the spherical coordinates, the relationship between the electric field ($\mathbf{E}$) and the magnetic field ($\mathbf{H}$) intensities satisfies the following conditions.

$$\mathbf{E} = E_\theta \hat{\theta} \quad (15)$$

$$\mathbf{H} = H_\phi \hat{\phi} \quad (16)$$

$$H_\phi = E_\theta / \eta \quad (17)$$

Using Poynting's vector theorem, the total amount of radiated power (P_{rad}) can be obtained as follows [15].

$$\begin{aligned}
 P_{rad} &= \oint_S (\mathbf{E} \times \mathbf{H}) \cdot d\mathbf{s} \\
 &= \oint_S (E_\theta \hat{\theta} \times H_\phi^* \hat{\phi}) \cdot \hat{r} ds \\
 &= \oint_S (E_\theta \hat{\theta} \times H_\phi^* \hat{\phi}) \cdot (r^2 \sin \theta) \hat{r} d\phi d\theta \\
 &= \oint_S \left(E_\theta \cdot \frac{E_\theta^*}{\eta_0} \right) \cdot (\hat{r} \cdot \hat{r}) (r^2 \sin \theta) d\phi d\theta \\
 &= \frac{|E_\theta|^2}{\eta_0} \int_0^\pi \int_0^{2\pi} r^2 \sin \theta \, d\phi d\theta \\
 &= \frac{|E_\theta|^2}{\eta_0} 4\pi r^2 \quad (18)
 \end{aligned}$$

where the intrinsic impedance (η_0) of the free space is 120π , the radiated E-field strength, and the total radiated power are summarized as follows.

$$|E_\theta| = \sqrt{\frac{\eta_0 P_{rad}}{4\pi r^2}} = \frac{\sqrt{30 P_{rad}}}{r} \quad (19)$$

$$P_{rad} = \frac{(r|E_\theta|)^2}{30} \text{ (W)} \quad (20)$$

Therefore, in accordance with FCC regulations, the total radiated power leakage from the designed waveguide structure should not exceed 75 nW to generate an electric field ($|E_\theta|$) less than the FCC requirement of 500 $\mu\text{V/m}$ at a distance of 3 m from the DUT. It should be noted that the FCC's radiation regulation can be verified at a distance of less than 3 m from the DUT by evaluating (21) at any distance.

IV. CONCLUSION

In this paper, the design and analysis of a TEM mode rectan-

gular coaxial waveguide was presented. Detailed design equations for the TEM mode rectangular coaxial waveguide structure, including impedance, loss, bandwidth, vias, and radiation analysis, were also discussed. The design parameters of the 50 Ω TEM mode waveguide were presented and its electrical characteristics were thoroughly studied as a design example. The proposed TEM mode waveguide design and analysis are scalable to other applications such as beyond-5G or sub-THz applications.

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