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Evaluations of Shielding Effectiveness in the Broadband Frequency Region up to 18 GHz by Using Flanged Coaxial Transmission Lines

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We have designed a jig that employed the flanged, coaxial transmission line through a 3D finite-element-method (FEM) simulation to measure the broadband electromagnetic (EM) shielding effectiveness (SE) in the frequency range from 0.5 GHz to 18 GHz. The flanged, coaxial transmission line comprises the ground (outer diameter: 7.00 mm) and the signal line (inner diameter: 3.04 mm). Representative specimens were prepared with metallic materials (Al, Ni, Cu sheets, & Ni mesh) and non-metallic materials (graphene oxide and magnetic polymer composite) to evaluate the SE. We analyzed the EM properties, the reflection, absorption, and total EM SE, of the fabricated specimens. Further, the SE results acquired from the flanged, coaxial transmission line which compared with those of a rectangular waveguide by measuring the S parameters. The SE measured using the flanged, coaxial transmission line correlates well with those of the rectangular waveguides (WR-90, WR-62).

Keywords: Shielding effect, Flanged coaxial transmission line, Rectangular waveguide, Broadband, ASTM D4935

I. Introduction

With the vast proliferation of electronic components, electric vehicles, military radar systems, electromagnetic interference (EMI), radiation, and pollution significantly increased, influencing electronic devices' performance and harmful for humans [1–5]. Therefore, it is essential to design a measurement system for a reliable EMI shielding effectiveness (SE) to improve the efficiency and lifetime of electronic devices in a broadband frequency region. In general, the SE can be measured in the microwave frequency range using coaxial transmission lines (CTL) and rectangular waveguides. The CTL method (ASTM D4935) with Transverse Electro-Magnetic (TEM) wave mode has been widely used for EMI SE up to 1.5 GHz [5]. Further, to measure the SE beyond 1.5 GHz, such as S-band (2-4 GHz), C-band (4-8 GHz), X-band (8-12 GHz), and Ku-band (12-18 GHz), etc., the rectangular waveguides with Transverse Electric (TE) wave mode have been employed with the different dimension of the waveguide at the specific frequency region. It indicates that the specimens should be prepared with varying sizes as the waveguide's different dimensions with the measuring frequency region [6, 7]. Recently, few research groups have attempted to extend the measurement frequency range up to 8 GHz and 13.5 GHz based on the ASTM D4935 method [8,9]. However, wide frequency range EMI SE measurements of materials are essential to study the materials' applicability for broadband frequency applications. Therefore, we designed a flanged coaxial transmission line (FCTL) for the broadband frequency range of 0.5 to 18 GHz using 3D finite element method (FEM) simulations and fabricated the home-made FCTL.

To evaluate the broadband SE values by using the FCTL, we measured the SE using various samples with metal sheets, dielectric and magnetic composite, and metal mesh. To confirm the accuracy of these SE values,

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the measured SE results by using FCTL were compared with those of the conventional rectangular waveguides.

II. Design of the flanged coaxial transmission line

We have designed the FCTL to measure EMI SE in the broadband frequency range from 0.5 GHz to 18 GHz. The EM wave propagation on the FCTL with TEM mode is based on transmission line theory [10], and TEM is the dominant propagation mode. The non-TEM higher energy mode in the CTL could be excited beyond the cut-off frequency. The cut-off frequency can be determined by the outer diameter of the CTL and the diameter of the signal line. The highest frequency that only the principal TEM mode propagates in the line is calculated by the following Eq. (1) [10–13].

$$f_T = \frac{c}{\pi(D_1 + D_2)} \tag{1}$$

where c is the speed of light, D_1, D_2 are the outer and inner diameters of the transmission line. Besides, the CTL should satisfy 50 Ω-characteristic impedance for matching with the vector network analyzer. The characteristic impedance of the CTL can be determined from the dimension of the outer-ground and inner-signal coaxial transmission line [6]. Based on the CTL's outer diameter, the cut-off frequency variation is shown in Fig. 1. The ground of CTL with an outer diameter of 7.00 mm can be safely used in the frequency range up to 18 GHz. The diameter of the signal line was determined to be 3.04 mm for 50 Ω-characteristic impedance matching.

Figure 2(a) demonstrates the structure of the FCTL. The flanges of two CTLs combined at the end of each transmission line and the specimen placed at the center. In this structure, each signal transmission line should be fixed by support with a low dielectric material. Teflon is one of the suitable materials for signal transmission due to its low dielectric and appropriate mechanical properties to avoid impedance mismatching. The outer diameter of the toroidal-shaped support is 7.00 mm, which is the same as the inner diameter of the CTL's outer ground. The support's inner diameter was set to satisfy impedance matching, as shown in Fig. 2(b). Figure 3 shows the transmission characteristics of the home-made FCTL without a specimen. The transmission characteristics were simulated by HFSS (ANSYS ver. 2019 R3.7), and the curve exhibit a similar trend with the measured values. However, the measured curve exhibits many peaks compared to the simulated curve, which might be due to mismatching conditions. Still, the transmission signal's attenuation revealed less than 0.1 dB, as displayed in Fig 3.

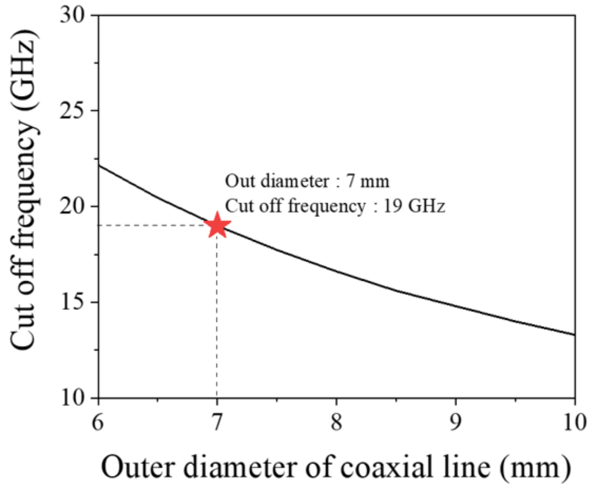

Fig. 1. (Color online) A cut-off frequency of the principal TEM mode of the coaxial transmission line.

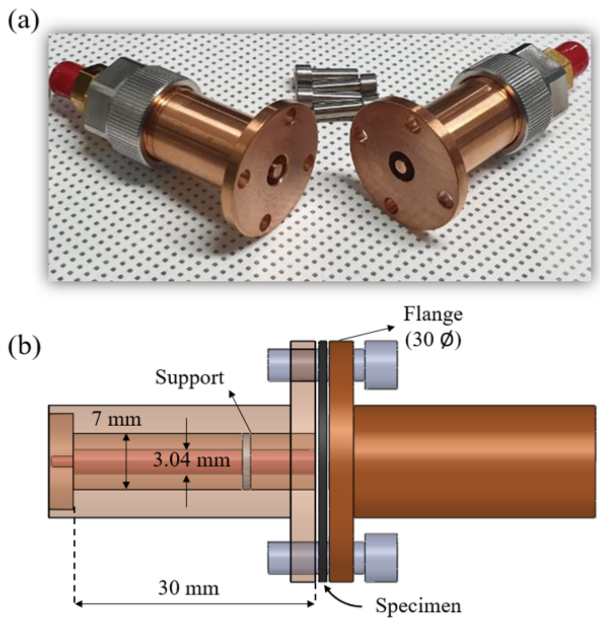

Fig. 2. (Color online) (a) Digital photograph of the fabricated flanged coaxial transmission line. (b) Schematic of the flanged coaxial transmission line and a testing specimen.

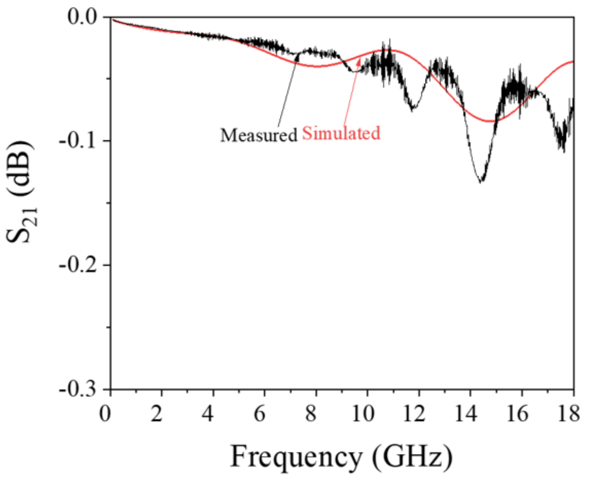

Fig. 3. (Color online) Comparison of transmission characteristics of the flanged coaxial transmission line.

To confirm the transmission signal of TE mod and SE effect of FCTL, electric field propagation inside the FCTL are obtained by EM simulations at 10 GHz for empty (none of the specimen) cases, reference specimen, and load specimen as shown in Fig. 4. The evaluated material has a conductivity of 10^4 S/m and thickness of 100 μm. The electric field for the reference specimen was the same as that of the empty case. When a highly conductive load specimen was loaded, the input EM wave almost did not penetrate to the specimen, and then the intensity of the output EM wave is remarkably reduced. It implies that the FCTL is well designed for measuring SE.

III. Measurement of shielding effectiveness

To evaluate the transmission and reflection characteristics of the specimen, the FCTL was connected to the Vector Network Analyzer (VNA, N5222B, Keysight Co.) through APC7 adapters, in which the specimen is placed between centers of each flange, as shown in Fig. 2(b). The SE of the specimens were obtained by using the measured s-parameters. The SE can be described as the power ratio of the input and transmitted EM wave. To evaluate the SE two types of specimen (load and reference) should be prepared. One is the disk-shaped load specimen with the same diameter (30.0 mm) of the flange. The other one is the reference specimens,

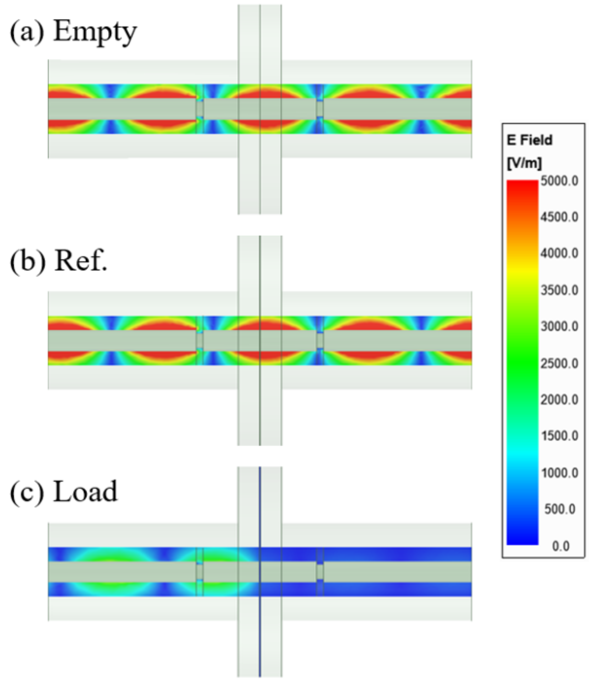

Fig. 4. (Color online) Electric field distributions at 10 GHz inside the flanged coaxial transmission line for the cases of empty (a), reference specimen (b), and load specimen(c). The conductivity of the specimen is 1000 S/m and 100 μm-thick.

which are composed of a toroidal-shaped specimen and disk-shaped specimen. The dimension of the toroidal specimen is the outer diameter of 30 mm and the inner diameter of 7 mm. The disk-shaped specimen has a diameter of 3.04 mm, the same as a cylindrical rod-shaped signal line, as shown in Fig. 5. The SE can be measured using load and reference specimens, which can be evaluated by the following eq. (2).

$$SE = 20log_{10}|S_{21,Ref}/S_{21,Load}| \tag{2}$$

To evaluate the SE, we prepared the metallic specimens (30 μm-thick Cu sheet, Ni sheet, and 15 μm-thick Al sheet, and 12 μm-thick Ni mesh) and non-metallic specimens (150 μm-thick graphene oxide sheet, 365 μm-thick magnetic composites, respectively. To confirm the reliability of SE values, each specimen was also measured by using rectangular waveguides in comparison with those of the FCTL. The rectangular waveguides were employed WR-90 (8.2 – 12.4 GHz), WR-62 (12.4 – 18 GHz). The measured SE values of copper, aluminum, and nickel sheets using the FCTL exhibited around 100 –

Table 1. Comparison of SE by the rectangular waveguide and by flanged coaxial transmission line at 10 GHz and 15 GHz.

	Frequency (GHz)	Shielding effectiveness (dB)	
		Flanged Coaxial transmission line (0.5 – 18 GHz)	Rectangular waveguide (8.2 – 12.4 GHz, 12.4 – 18 GHz)
Graphene sheet (150 μm)	10	7.3	9.0
	15	8.0	9.2
Magnetic composite (365 μm)	10	29.7	29.0
	15	30.3	29.4
Ni mesh (12 μm)	10	50.7	55.1
	15	48.6	51.6

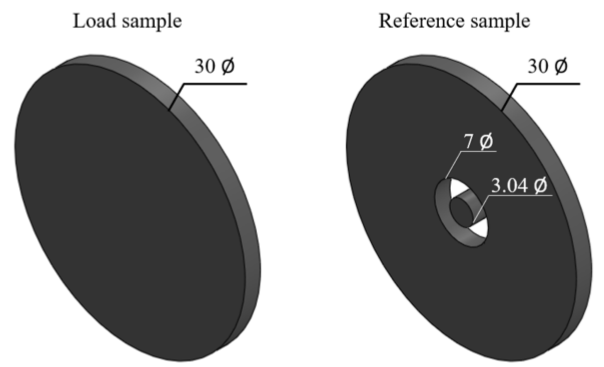

Fig. 5. (Color online) The dimension of load and reference specimen.

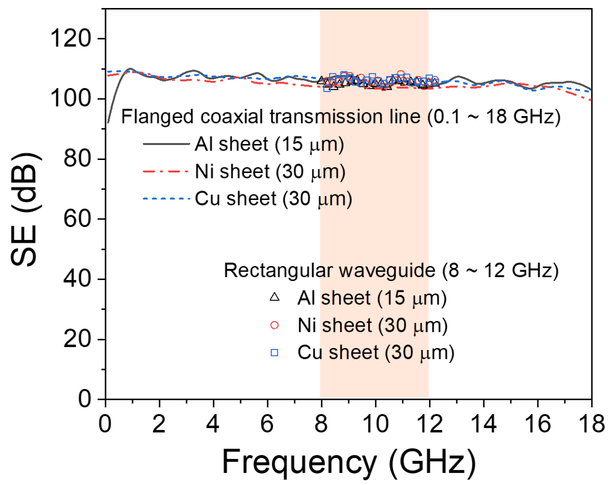

Fig. 6. (Color online) The shielding effectiveness of Al (15 μm), Ni (30 μm), and Cu (30 μm) metallic sheets. Solid lines are SE by the flanged coaxial transmission line, and circles are SE by the rectangular waveguide.

110 dB overall the frequency region. SE values are comparable to those of the rectangular waveguides, which SE values are similar to those of the rectangular waveguides, as shown in Fig. 6.

The measured SE values of graphene oxide sheet, magnetic composite, and Ni mesh by the FCTL were compared with those of the rectangular waveguides, as shown in Fig. 7. The SE values at 10 GHz (WR-90) and 15 GHz (WR-62), which are the central frequency of each rectangular waveguide, are summarized in Table 1. The SE values of Ni mesh at 10 GHz are 50.7 dB and 55.1 dB by the FCTL and the rectangular waveguide, respectively. At 15 GHz, those are 48.6 dB and 51.6 dB. Ni mesh showed the highest SE values among evaluated specimens. The lowest SE values recorded by the graphene oxide sheet are 7.3 dB and 9.0 dB at 10 GHz, 8.0 dB and 9.2 dB at 15 GHz by the FCTL and the rectangular waveguide, respectively. The SE values for magnetic composite exhibited those of the between Ni mesh and the graphene oxide sheet. The values are 29.7 dB and 29.0 dB at 10 GHz, 30.3 dB and 29.4 dB at 15 GHz. Comparison of SE by the rectangular waveguide and FCTL at 10 GHz and 15 GHz is summarized in Table 1. The measured SE values by the FCTL and the rectangular waveguide were well agreed for each specimen.

IV. Conclusions

The FCTL was successfully designed, and the SE evaluated in the broadband frequency range (0.5-18 GHz). The SE measured for various specimens (metallic and non-metallic) using the FCTL. All the measured SE values by FCTL were comparable with those of rectangular waveguides. Therefore, the home-made FCTL can measure the broadband (0.5-18 GHz) SE at a time using one specimen, unlike the waveguide measurements with

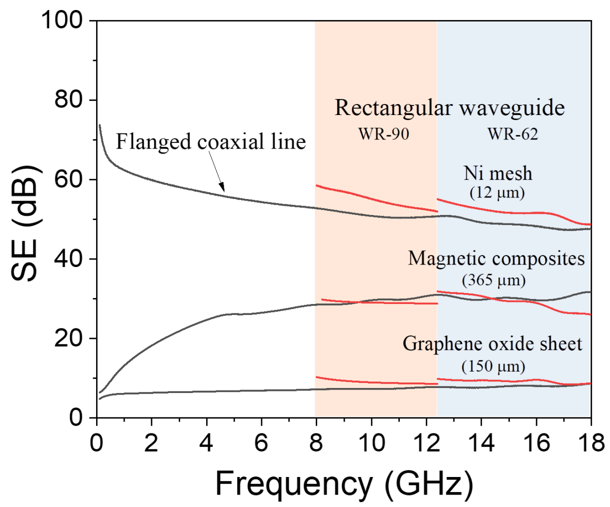

Fig. 7. (Color online) EMI shielding characteristics of the graphene oxide sheet (150 μm), magnetic composites (365 μm) and Ni mesh (12 μm).

various specimens of different dimensions as the discrete frequency regions.

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