A Square Coaxial Transmission Line with a Thin-Wire Inner Conductor to Measure the Absorbing Performance of Electromagnetic Absorbers

Tae-Weon Kang[1] · Christos Christopoulos[2] · John Paul[2]

Abstract

A low-frequency coaxial reflectometer(LCR) with a thin-wire inner conductor is designed and constructed to measure nondestructively the absorbing performance of electromagnetic absorbers in the frequency range of 10 MHz to 200 MHz. The LCR consists of a square coaxial transmission line and a network analyzer with a time-domain measurement capability. Inherent characteristics of a square coaxial line with a thin-wire inner conductor which deteriorate the impedance matching of the input port of the LCR are addressed. And the characteristics are improved by employing a multiwire inner conductor. Measured and calculated reflection losses of a flat ferrite tile absorber are presented.

Key words : Low-Frequency Coaxial Reflectometer(LCR), Electromagnetic Absorber, Absorbing Performance, Reflection Loss.

Ⅰ. Introduction

Semianechoic chambers are a good alternative test facility to open area test sites(OATS) for carrying out radiated emission(RE) measurements because they are not affected by external electromagnetic noises or weather conditions. Electromagnetic absorbers are used to line inner walls and ceiling of the chambers to simulate an OATS. To maximize the working space of the chamber, flat or grid ferrite tile absorbers have been proposed[1]. Broadband hybrid absorbers have been developed by combining a ferrite type electromagnetic absorber and a lossy dielectric[2] or by shaping the ferrite absorber in a complicated geometry such as cutting-cone and modified circular cylinder[3].

To predict the performance of the chamber before its actual installation, it is recommended to calculate a figure of merit of the chambers, such as the normalized site attenuation for RE test requirements[4] and the field uniformity for radiated field immunity tests[5]. The absorbing performance of electromagnetic absorbers is a prerequisite parameter for evaluating the performance of the chamber. In particular, to optimize the low-frequency performance of electromagnetic absorbers, it is of importance to measure the absorbing performance of the absorbers.

Techniques for measuring the reflection loss of absorbing materials have been discussed in [6]. These techniques range from time-domain methods[7], and square coaxial line methods[8], to waveguide methods [9]. A new large square coaxial line which requires no metal reflector at the bottom of an absorber under test has been proposed[10].

In this paper, a design of a square coaxial transmission line as a low-frequency coaxial reflectometer(LCR) is presented. It is noted that thin wires serve the inner conductor of the coaxial line. The configuration of the LCR with a thin-wire or multiwire inner conductor is featured by measuring nondestructively the absorbing performance of flat or grid ferrite tile absorbers, or hybrid absorbers. Inherent characteristics of the coaxial line are addressed and a couple of modified LCRs are compared. Calculated and measured reflectivities of a flat ferrite tile absorber are presented.

Ⅱ. The Low-Frequency Coaxial Reflectometer

2-1 Square Coaxial Transmission Lines

An LCR system consists of a square coaxial transmission line and a network analyzer. Note that the network analyzer should have a time domain mea-

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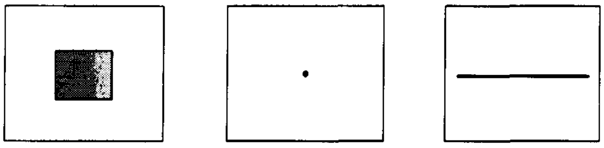
(a) (b) (c)

Fig. 1. Configurations of a rectangular coaxial transmission line. (a) square coaxial, (b) thin-wire coaxial, (c) stripline.

surement capability.

There are three typical configurations of a square coaxial transmission line as shown in Fig. 1[6]. Due to 3:1 ratio of the outer to inner conductor dimensions in Fig. 1(a), the characteristic impedance of the LCR line is approximately 61 Ω. Therefore, there is 20 dB reflection due to the mismatch between the LCR and a 50-Ω instrumentation. This reflection can be effectively suppressed using time-domain gate techniques[6],[8]. To construct a 50 Ω stripline LCR shown in Fig. 1(c), the width of the septum would have to be only a few inches smaller than the outer conductor. Due to gravity, a vertical asymmetry is usually present, because the cross section of the LCR is normally oversized to allow easy handling of the absorber tiles during the test. In [8] and [10], a long square coaxial line presented in Fig. 1(a) was used.

In this paper, a coaxial line with a thin-wire inner conductor illustrated in Fig. 1(b) has been designed and constructed. Details of the coaxial line are shown in Fig. 2. The line consists of a square copper outer conductor with dimension $2b$=0.6 m and a thin strand copper wire with radius r_1=0.625 mm. Therefore, the line accommodates thirty six 10 cm×10 cm-ferrite tile absorbers. The outer conductor is tapered near the input port. The absorber under test is placed against the back wall, i.e., a short plate. The characteristic impedance of the 1-m long uniform section of the line is[11]

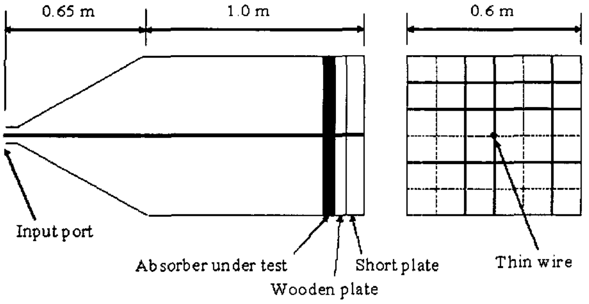

Fig. 2. The original LCR with a thin-wire inner conductor.

$$Z_0 \approx 59.95 \ln\left(1.08\frac{b}{r_1}\right). \tag{1}$$

In (1), the characteristic impedance of the line is close to the intrinsic impedance of free-space. Matching the LCR's impedance to a 50-Ω instrumentation requires the use of matching networks or calibration techniques[6],[8]. Although the IEEE Recommended Practice[6] proposes the method to use a sophisticated matching network at the input port of the LCR, the method does not resolve an inherent problem of the thin-wire coaxial line. The measured characteristic impedance of the coaxial line was found to be 340~390 Ω over the frequency range of 5 MHz to 250 MHz.

2-2 The Measurement Method

To measure S_{11} of the coaxial line, the test port 1 of an HP 8752A network analyzer with the time domain measurement capability is connected to the coaxial line. Note the characteristic impedance of the network analyzer is 50 Ω. The measured S_{11} data are stored as a file using a data acquisition program and the data can be used later to obtain the reflection loss of electromagnetic absorbers under test.

The reflection loss of an absorber under test can be measured as follows. After calibration of a network analyzer, the end of a test cable at which the calibration was performed is connected to the input port of the LCR. A suitable adaptor might be used between the test cable and the input port, which requires to activate 'the port extension function' of a network analyzer. As the first step a short plate is connected to the end of the uniform section of the LCR. The frequency response of a gated time-domain reflected wave is referred to as $|S_{11}(\omega)|_{\text{with a short plate}}$. Next, an absorber under test and the short plate are installed at the end of the uniform section of the LCR. The resultant frequency response of a gated time-domain reflected wave is referred to as $|S_{11}(\omega)|_{\text{with absorbers}}$. The reflection loss or reflectivity $|R|$ of the absorber is then given by

$$|R| = \frac{|S_{11}(\omega)|_{\text{with absorbers}}}{|S_{11}(\omega)|_{\text{with a short plate}}} \tag{2}$$

or

$$|R|_{\text{dB}} = |S_{11}(\omega)|_{\text{dB, with absorbers}} - |S_{11}(\omega)|_{\text{dB, with a short plate}} \tag{3}$$

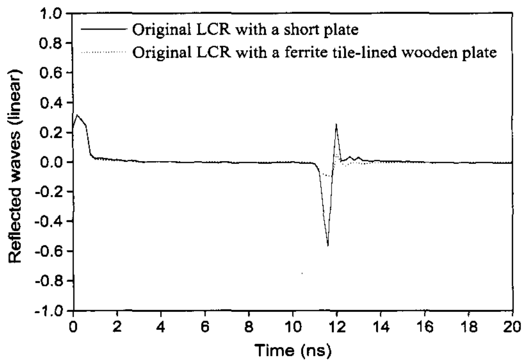

Fig. 3. Measured reflected waves of the original LCR.

The frequency range of interest was 10 MHz to 200 MHz and the range was equally spaced by 201 or 401 points of data. Reflected waves in the time domain were observed. The function of this time-domain measurement enables us to take a desired portion of the reflected waves.

2-3 Measured Results of the Original LCR

Fig. 3 shows measured reflected waves of the original LCR shown in Fig. 2. Note no time-domain gate was applied to obtain the waveforms in Fig. 3. It can be observed that there is a considerably high reflection near the input port. In addition, the reflection at 11.6 ns is due to a short plate terminated at the back wall against of the input port. The reflected wave due to the short plate shown in Fig. 3 has a quite long tail, while an ideal short circuit has no tail. The reflection loss of the ferrite tile measured by the original LCR, which will be presented later, has positive values in decibel up to 74 MHz, which is non-physical. Therefore, the original LCR has to be modified to obtain a meaningful measurement result.

Ⅲ. The Modified LCR

A couple of modified LCRs and their measured characteristics are described. For the purpose of intercomparison, the performance of the LCRs will be presented in terms of a time-domain waveform. An intuitive approach for reducing the reflection at the input port is to use an impedance transformer[6]. However, from the experimental results, the use of the impedance transformer does not improve the characteristics of the original LCR. This is attributed to a continuous variation of the ratio of the outer to inner conductor along the tapered section of the original LCR. To keep the ratio constant, a multiwire inner conductor is proposed.

3-1 The LCR with a Multiwire Center Conductor

Background The square coaxial line normally has a constant ratio of the outer to inner conductors along the line of the tapered and uniform sections. The ratio was chosen to 3:1 so that the characteristic impedance of the line is as close as possible to the 50-Ω instrumentation, that is, approximately 60 Ω[6],[8] or 63 Ω[10],[12]. Note the analytical characteristic impedance of the coaxial line of inner and outer square conductors of sides 2*a* and 2*b* is $Z_c=59.952\cdot\ln(b/a)=65.864$ Ω[13] or $Z_c=376.62/[8a/(b-a)+2.232]=60.433$ Ω[14] where $b/a=3$.

The square coaxial line with a thin-wire inner conductor considered in this paper has a constant ratio b/r_1 along its uniform section. However, the ratio varies continuously in the tapered section of the line as shown in Fig. 2. Subsequently, the characteristic impedance of the tapered section also varies. The analytical characteristic impedance of a coaxial line of an outer *N*-regular polygon concentric with an inner circle is given by[13]

$$Z_c=59.952\ln\left[\frac{N}{3\pi}\frac{b}{r_1}\tan\left(\frac{\pi}{N}\right)\left\{1+\sqrt{1+\frac{3\pi}{N\tan(\pi/N)}}\right\}\right] \tag{4}$$

where r_1 is the radius of the inner circular conductor and b is the distance from the center of the inner conductor to a point nearest to the *N*-regular outer conductor. For $N=4$, (4) can be simplified as

$$Z_c=11.027+59.952\ln\left(\frac{b}{r_1}\right) \tag{5}$$

It is emphasized in (5) that the characteristic impedance depends on the ratio of b to r_1. Along the tapered section of the LCR designed in this paper, the radius of the inner conductor is constant $r_1=0.625$ mm whereas the dimension of the outer conductor b increases linearly from b_0 at the input port to b_1 at the uniform section by an equation

$$b=b_0+\frac{b_1-b_0}{l_t}x$$

where b_0 and b_1 are the dimensions of the outer conductor at the input port and at the end position of the transition section, respectively and l_t is the length of the transition section of the LCR. The value x indicates the distance from the input port to the position at which

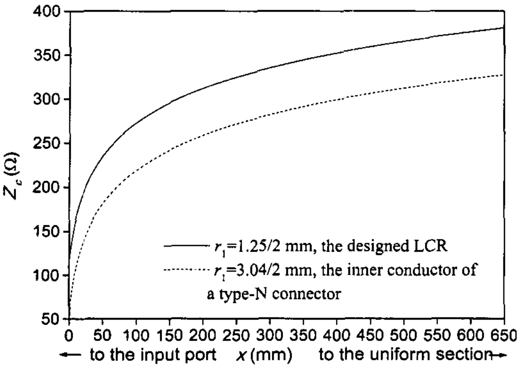

Fig. 4. Variation of the characteristic impedance in the tapered section of the original LCR.

the impedance is calculated and x varies 0 to 650 mm.

Fig. 4 shows variation of the characteristic impedance in the tapered section of the LCR. For the original LCR, the characteristic impedance ranges from 114 Ω to 381 Ω. If the diameter of the inner conductor at the input port is 3.04 mm, the outer diameter of 7-mm coaxial system, the impedance varies from 61 Ω to 328 Ω in a logarithm of b/r_1.

With multiwire inner conductors As already mentioned, the ratio b/r_1 should be constant for proper characteristics of an LCR. We modified the original LCR by introducing a multiwire inner conductor as shown in Fig. 5. To mechanically hold the multiwire inner conductor, a 60 cm×60 cm-cardboard was inserted at the start position of the uniform section. It should be emphasized that the modified LCR with a multiwire inner conductor does hold the same configuration of square inner and outer conductors shown in Fig. 1(a). One sides of the eight or four wires were tied into a bundle so that the sides are soldered to the inner conductor of the input port. The other sides of the wires ran through the hole of the short plate or ferrite tile-lined wooden plate and fastened to the short plate by auxiliary copper sticks. An LCR with a four-wire inner conductor was also tested to consider the influence of a number of thin wires for the inner conductor to reflection of the coaxial line.

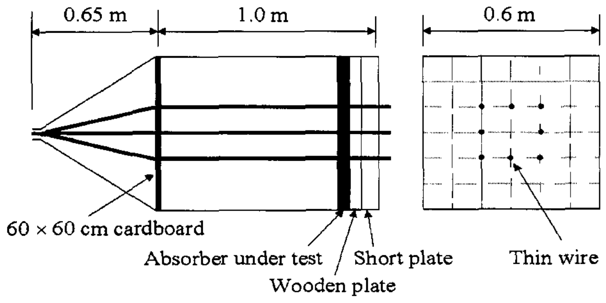

Fig. 5. Modified LCR with a multiwire inner conductor.

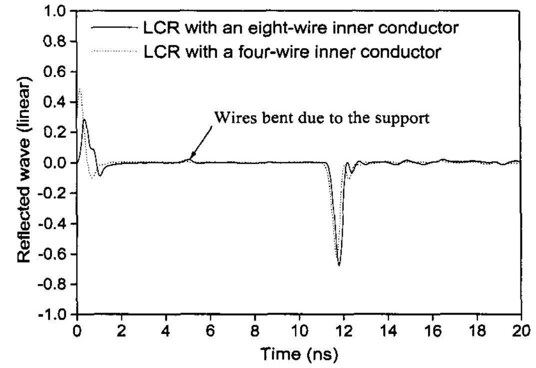

Fig. 6. Reflection characteristics of the LCRs with multiwire inner conductors. The LCRs were terminated with a short plate.

Fig. 6 illustrates reflection characteristics of the LCR with multiwire inner conductors. Each wire comprising the inner conductor has 0.5-mm diameter. From the figure, the larger the number of wires used to form the inner conductor is, the smaller is the reflection at the input port. It is noted that the reflection at a short plate for the LCR with eight-wire inner conductor lowers to −0.68 in linear scale, and the tail of the waveform has been improved comparing to that of the original LCR. Small reflections after the position of the short plate come from wires bent locally.

3-2 The LCR with an Eight-Wire Inner Conductor and an Extended Coaxial Cable

In Fig. 6, for the LCR with an eight-wire inner conductor, a relatively large peak near the input port was appeared and its linear magnitude was 0.29. This first reflection noticeably aggravates overall performance of an LCR. To reduce the first reflection, a coaxial cable was pushed into the input port. For a mechanically tight fixing of the cable at the input port of the LCR, an rf cable with 75 Ω was used. The threaded outer conductor of the cable was firmly fixed between the flange of the type-N panel connector and the input port of the coaxial line. The inner conductor of the cable was soldered to the multiwire inner conductor of the square coaxial line. Note that the soldered part of the multiconductor still has somewhat discontinuity and this causes quite high reflection as shown in Fig. 6. To improve this, one should make a center conductor to ensure the multiconductor to have

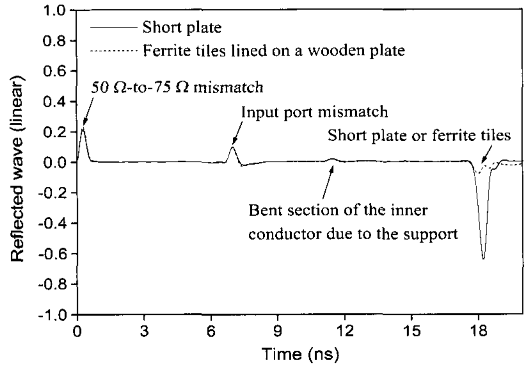

Fig. 7. Reflected waves of the LCR with an extended coaxial cable and the eight-wire inner conductor.

smooth variation especially at the soldered position.

Fig. 7 shows the reflected waves of the LCR with an extended coaxial cable and the eight-wire inner conductor. The largest reflection ahead of the position of a short plate is 0.21, that is, −13.6 dB. Details on each reflection are described in Fig. 7. The impedance mismatch of a short-ended square coaxial line presented in [8] is mainly due to 50 Ω/63 Ω mismatch and measured reflection of the line is −20 dB. In [10], a coaxial line without a short reflector was developed to measure transmitted wave as well as reflected wave. They inserted 13-Ω series resistor to reduce multiple reflection between the test port and test sample.

Ⅳ. Measured Reflection Loss of Ferrite Tiles and Discussion

A NiZn ferrite used to manufacture ferrite tiles typically has the following material parameters: the dc relative permeability $\mu_{r0}=1051$, the magnetic relaxation frequency $\omega_m=2\pi\times 7.06$ MHz, the dielectric constant $\varepsilon_r=12$, and the thickness $d_f=6.3$ mm. The ferrite tiles are lined on a 7.1 mm-thick pressed wooden plate to make a test unit of 60 cm×60 cm. Since a ferrite tile has a dimension 10 cm×10 cm, 6×6 ferrite tiles were lined onto the wooden plate.

In Fig. 2 or Fig. 5, the ferrite tile absorber plate placed in the square coaxial line is illustrated. To place the ferrite tile absorber inside the original LCR with a thin-wire inner conductor, we made a hole at the center of the plate. The threaded wire was connected to outside of a short plate using an auxiliary metal pipe and a tiny bolt.

Placement of the absorber-loaded wooden plate inside the LCR with a multiwire inner conductor requires four or eight holes of the plate as shown in Fig. 5. The absorber-loaded wooden plate is inserted inside the LCR. Then a short plate is inserted behind the wooden plate. During this installation, one can not see the inner part of the LCR. Therefore, air space between the short plate and the absorber-loaded wooden plate d_a can be existed, which is undesirable.

The network analyzer is set to be operated in the low-pass impulse mode for time-domain measurements. The gate start and stop are adjusted to take an appropriate portion of the reflected waves. For the LCR with an eight-wire inner conductor, the two parameters are 10.5 ns and 16.5 ns, respectively. Adjusting the gate stop results in the variation of the resonant frequency but causes slight change of the reflection loss level.

Fig. 8 illustrates measured reflection loss of ferrite tile absorbers using the LCRs along with a classical analytic solution. The closest agreement between measured and calculated results can be observed in the case of the LCR with an eight-wire inner conductor and extended coaxial cable. The resonant frequency at 174 MHz shows good agreement between analytic and experimental results. As d_a increases, the resonant frequency also increases and overall reflection loss becomes worse as observed from the analytic solution in Fig. 8. For the analytic solution it was assumed that the axis of the coaxial line is perpendicular to the air space plane and the dielectric constant of the pressed wooden plate is 3.

The level of reflection loss measured by the LCR with an eight-wire inner conductor and an extended

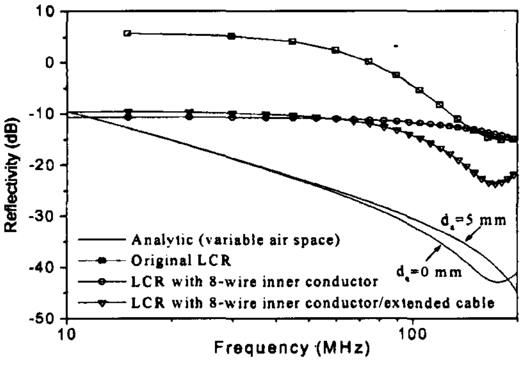

Fig. 8. Measured reflection loss of a ferrite tile absorber using the LCRs along with a classical analytic solution. The parameter d_a indicates an air space between the ferrite tile-lined wooden plate and a short plate during their installation into the LCR.

cable is higher than the analytic one as shown in Fig. 8. There are two reasons for this: First, the reflection of the absorber itself was obscured by nearby reflection mainly due to the input port mismatch. There was some discontinuity along the inner conductor of the LCR because the inner conductor at the input port was soldered to a threaded eight-wire inner conductor. Second, the length of the uniform section is not long enough to discriminate the reflection of the absorber under test from overall response. Therefore, an additional uniform section can be used to extend the length of the section.

V. Conclusion

An LCR with a thin-wire inner conductor was designed and constructed to measure the absorbing performance of electromagnetic absorbers in the frequency range of 10 MHz to 200 MHz. The LCR consists of a square coaxial transmission line and a network analyzer with a time domain measurement capability. Since a thin-wire inner conductor is used for the original LCR, the characteristic impedance of the tapered section varies continuously. This inherent property prevents the LCR with a thin-wire inner conductor from being used for measuring absorbing performance.

Characteristics of the original LCR were improved by introducing a multiwire inner conductor. Absorbing performance of a flat ferrite tile absorber in 10 MHz to 200 MHz range was measured using original and modified LCRs. The LCR with an eight-wire inner conductor and extended coaxial cable shows relatively good performance. The measured and calculated resonant frequencies show good agreement whereas the measured reflection loss level is considerably higher than the calculated level. These can be improved by further modifying the input port of the LCR and by extending the length of the uniform section of the LCR.

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