Electromagnetic Shielding Effectiveness Calculation for Cascaded Wire-Mesh Screens with Glass Substrate

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Abstract ─ In this paper, a model is presented to calculate the electromagnetic shielding effectiveness of two cascaded wire-mesh sheets with glass substrate. The model is based on transmission line theory for calculating the equivalent sheet impedance of each wire-mesh screen. The total shielding effectiveness for the sheets is obtained based on transmission matrix method. The wire-mesh screen is numerically simulated as a unit cell with periodic boundary conditions in order to verify the analytical results. It is shown that the shielding effectiveness is decreased by increasing the operating frequency. Also, it is shown that the total shielding effectiveness of the double wire-mesh layers is satisfactory high compared with single sheet shielding. The proposed structure is highly attractive for different shielding applications due to its lower cost, reduced weight and optical transparency compared to metallic sheets. The model results are compared with measurements. Good agreement between the analytical model and the measurements results is obtained.

Index Terms ─ Electromagnetic shielding, transmission line theory, wire-mesh screens.

I. INTRODUCTION

The increased usage and wide spreading of electronic equipment in communications, broadcasting and other purposes have led to a lot of Electromagnetic Interference (EMI) problems [1-12]. The cause of the EMI can be due to telecommunications towers, radar stations with high radiated power and wireless systems which emit electromagnetic waves [10-11]. One of the main concerns which should be considered for protection from EMI is the threat of Intentional Electromagnetic Interference (IEMI) [12-13]. IEMI is the intentional usage of high electromagnetic energy to cause damage to the electronic systems and is considered a big threat to critical infrastructure [14]. Another concern for people who need to work at a certain frequency band is likely to experience severe electromagnetic interference from external sources which is difficult to suppress it [15]. Also, people who are living in the vicinity of telecommunication mobile stations are exposed to high electromagnetic power which can cause dangerous health problems [6-9]. To ensure that electronics devices operate well in the presence of external electromagnetic interference, shielding is required especially for such areas with devices which are highly sensitive to external interference such as military systems, radar stations, and hospital medical electronic devices [16-17]. Electromagnetic shielding can be defined as a barrier to decrease or eliminate the transmission of the electromagnetic wave between two areas [18].

Practically, there are a lot of efforts which have been taken for different shielding techniques, starting from improving the sensitivity of the receiving electronic devices and enhancing the antenna systems till suppressing interference by use of a variety of filters and different shielding materials while all of the above could not get an ideal result because of the technical limitations or high cost [19-20]. A low-cost with high shielding effectiveness technique is required. One such type of good enough shield with the low-cost is the wire-mesh screens [1-4, 21-26]. Due to their physical flexibility and less weight compared to metal sheets, they are appropriate for shielding of large structures [26]. Another advantage of the wire-mesh screen windows over metal coated windows is its optical transparency [27-30]. However, they suffer from lower Shielding Effectiveness (SE) compared with metallic sheets. The objective of the present work is to discuss the shielding effectiveness of a double-sided coated glass window where both sides of the glass window are coated with wire-mesh sheets. It is shown that the proposed structure is highly attractive for different shielding applications due to its high electromagnetic shielding, lower cost, reduced weight and optical transparency compared to metallic sheets.

This article presents the shielding effectiveness calculation method for single wire-mesh screen based on transmission line theory as discussed in [22]. In Section III, the shielding effectiveness for two cascaded wire-mesh screens with a glass substrate is obtained. Finally, measurements are conducted in order to verify the

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analytical analysis.

II. ANALYTICAL AND NUMERICAL ANALYSIS OF SINGLE WIRE-MESH SCREEN

Electromagnetic shielding refers to decrease or suppress electromagnetic wave propagation from one interface to another one. Electromagnetic shielding effectiveness is defined as the ratio of the received power before and after shielding. It can be expressed as [23]:

$$SE\ (dB) = 10log_{10}\left(\frac{P_0}{P_s}\right), \quad (1)$$

where P_0 is the received power without shielding, and P_s is the power measured after shielding the area. The same concept is applied to the electric and magnetic fields shielding.

A. Analytical analysis of wire-mesh screen

The simple structure of wire-mesh screens is constructed by parallel metal wires with equal space. For such a case, the shielding effectiveness of the wire mesh is depending on the spacing between the wires and the thickness of the wires as well as the angle of incidence of the wave [20]. To increase the shielding effectiveness for such mesh, we can add additional wires orthogonal to the first set.

The electromagnetic shielding effectiveness of wire-mesh screens is considered where the mesh apertures are of a small size compared to the operating wavelength. It is described by the equivalent sheet-impedance of the wire-mesh screen [22]. Because of the mesh aperture periodicity and the mesh aperture is electrically small compared to the wavelength, a mesh under the incidence of an electromagnetic wave carries a reactive field that is confined to the vicinity of the mesh surface where the reactive field decays away from the screen surface as an exponential factor [20, 30].

The shielding effectiveness of a mesh with square aperture of length a_s and wire radius r_w as shown in Fig. 1 can be described as [22]:

$$SE(\omega,\theta) = -10log_{10}\left[\frac{1}{2}|T_1(\omega,\theta)|^2 + \frac{1}{2}|T_2(\omega,\theta)|^2\right], \quad (2)$$

where $T_1(\omega,\theta)$ and $T_2(\omega,\theta)$ are the transmission coefficients for the polarization of Transverse Electric (TE) and Transverse Magnetic (TM) modes, respectively and given by [20]:

$$T_1(\omega,\theta) = \frac{\left(\frac{2Z_{s1}(\omega)}{Z_0}\right)cos\ \theta}{1+\left(\frac{2Z_{s1}(\omega)}{Z_0}\right)cos\ \theta}, \quad (3)$$

$$T_2(\omega,\theta) = \frac{\left(\frac{2Z_{s2}(\omega)}{Z_0}\right)}{cos\ \theta+\left(\frac{2Z_{s2}(\omega)}{Z_0}\right)}, \quad (4)$$

where θ is the angle of incidence and calculated from the normal of the planar sheet and Z_0 is the free-space impedance. Z_{s1} and Z_{s2} are the eigenvalues of the mesh impedance operator corresponding to the TE and TM modes, respectively [20, 30]:

$$Z_{s1}(\omega) = Z_w\ a_s + j\omega L_s, \quad (5)$$

$$Z_{s2}(\omega) = Z_{s1} - \frac{j\omega L_s}{2}sin^2\theta, \quad (6)$$

where the sheet inductance LS and the wire impedance per unit length Z_w are given by [20, 30]:

$$L_s = \frac{\mu_0}{2\pi}ln\left\{\left(1 - e^{\frac{-2\pi r_w}{a_s}}\right)^{-1}\right\}, \quad (7)$$

$$Z_w = (\pi r_w^2\sigma)^{-1}, \quad (8)$$

where μ_0 is the free space permeability and σ is the wire conductivity.

It is important to note that the above analysis for mesh with square apertures [22]. If the apertures of the mesh are not square as for hexagonal aperture, an equivalent square area can be calculated as discussed in [20].

B. Numerical simulation of wire-mesh screen

The transmission of electromagnetic wave through the wire-mesh screen was numerically simulated by using HFSS (High Frequency Structural Simulator) [31]. HFSS is a commercial computational electromagnetics software package which uses the finite element method to solve the electromagnetic problems including antennas and microwave filters design [31]. The numerical simulation is used to verify the proposed analytical results. The mesh screen is approximated in the simulation analysis as an infinite periodic structure [20, 32]. Typically, the wire mesh screen is constructed of periodic small square apertures. In case of an incident plane wave, the structure can be approximated by a single unit cell with periodic boundary conditions [33]. The fields on both sides of the screen are identical with a phase shift that depends on the angle of incidence of the planar wave [21].

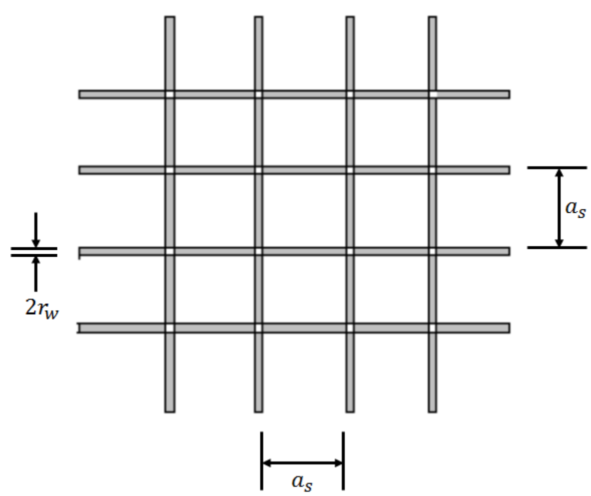


Fig. 1. Wire-mesh screen with square apertures [22].

In order to check the validity of the model, the shielding effectiveness is calculated analytically using the presented model and numerically simulated using HFSS for wire-mesh screen with square aperture of width is $2\ mm$ and radius is $0.05\ mm$. The frequency band is 200-900 MHz which covers multi-bands including lower GSM band. The sheet is made of aluminum material with conductivity is 3.7×10^7 s/m. The excitation is assumed to be plane wave with normal incidence. Figure 2 shows the comparisons between analytical and simulation results with good agreement is obtained. The calculated mean error between the analytical model and simulation results is about 3%.

It can be noted that the shielding effectiveness is quite high at low frequency band while by increasing the operating frequency, the shielding effectiveness decreases. This can be explained as by increasing the frequency, the sheet impedance increases and the shielding effectiveness decreases [24]. From the plane wave theory, when a radio wave propagates from a free space with high intrinsic impedance into a wire-mesh sheet with low impedance, the reflection coefficient is high and the total shielding effectiveness increases while by increasing the frequency, the sheet resistance increases and the total shielding effectiveness decreases [24].

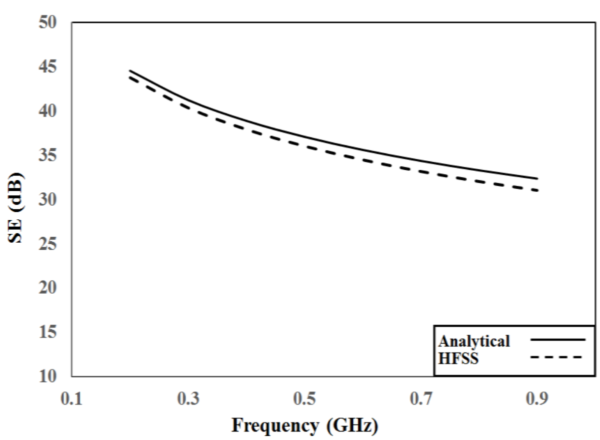


Fig. 2. SE of aluminum wire-mesh screen with square aperture, the aperture is width=2 mm and radius=0.05 mm.

Using the analytical model, shielding effectiveness for a mesh with square aperture is calculated for different angle of incidence and operating frequencies. The mesh aperture dimensions is kept constants with width of 2 mm and wire radius is 0.05 mm. Figure 3 shows the shielding effectiveness as a function of the frequency and incidence angle. It worth noting that the effect of the angle of incidence on the shielding effectiveness is limited to large incidence angles, also it can be shown that higher frequencies leads to lower shielding effectiveness. The same analysis is repeated to calculate the effect of the mesh aperture width a_s and wire radius r_w on the total the shielding effectiveness. The operating frequency is kept constant for 0.5 GHz and normal wave incidence is assumed. Figure 4 shows the shielding effectiveness as a function of the aperture width and wire radius. It can be shown that increasing the aperture width leads to low SE while the opposite is true for wire radius. The best SE can obtained by using an optimization techniques to determine the optimum aperture width and wire radius for desired operating frequency.

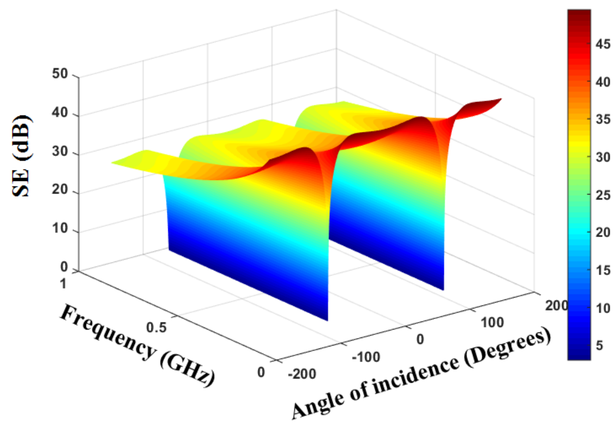


Fig. 3. SE as a function of frequency and angle of incidence for single layer of aluminum wire-mesh screen with square aperture, the aperture is width=2 mm and radius=0.05 mm.

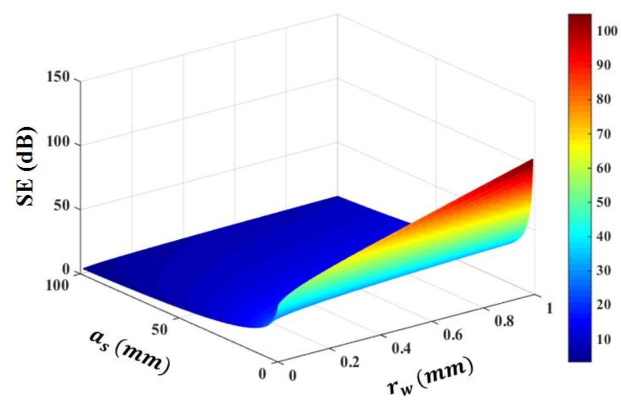


Fig. 4. SE as a function of mesh aperture length and wire radius for single layer of aluminum wire-mesh screen with square aperture, the operating frequency is 0.5 GHz with normal wave incidence.

III. SHEILDING EFFECTIVNESS OF DOUBLE-SIDED COATED GLASS WINDOW

In this section, the total shielding effectiveness of the double-sided coated glass window is obtained. The coating sheets can be of same material as to increase the total SE. Also, the sheets can be of different materials for wide frequency band shielding or it can be used for different shielding applications, as one layer can be used for electromagnetic shielding of radio wave of specific band, e.g., GSM band, and the other one can be used for magnetic shielding by using the second sheet with high permeability material [34-35] in which, the structure shielding will server for different types of applications.

Ciddor and Whitbourn [36] presented an equivalent film model for single wire-mesh sheet based on transmission line lumped circuit and gave a transfer matrix M_{mesh} for wire-mesh with a normalized equivalent admittance Y_{mesh} [36]:

$$M_{mesh} = \begin{bmatrix} 1 & 0 \\ Y_{mesh} & 1 \end{bmatrix}, \tag{9}$$

where the normalized admittance Y_{mesh} is the reciprocal of the sheet impedance Z_{mesh} of transparent conductive wire-mesh screen,

$$Y_{mesh} = \frac{1}{Z_{mesh}}, \tag{10}$$

the normalized impedance Z_{mesh} can be given by (5) and (6).

The transfer matrixes of glass window substrate M_{win} can be obtained using a transfer matrix theory of optical thin films [36]:

$$M_{win} = \begin{bmatrix} \cos\varphi & iY_{win}\, sin\varphi \\ \left(\frac{i}{Y_{win}}\right) sin\varphi & cos\varphi \end{bmatrix}, \tag{11}$$

where φ is the optical path difference and Y_{win} is the optical admittance of the film [36]:

$$\varphi = \frac{2\pi n t_{win}}{\lambda}, \tag{12}$$

where n is the complex refractive index of the film and t_{win} is the film thickness. The optical admittance Y_{win} is obtained by [36]:

$$Y_{win} = nY_0, \tag{13}$$

where Y_0 is the free space admittance.

For double mesh coting with glass substrate as shown in Fig. 5, the transfer matrix for each wire screen is calculated using (9). According to transmission matrix method, the transfer matrix M_{total} of the structure can be calculated by:

$$M_{total} = M_{mesh1}\, M_{win}\, M_{mesh2} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}. \tag{14}$$

The total transmittance coefficient T_{total} of the structure is obtained from the transfer matrix M_{total} [24]:

$$T_{total} = \frac{2}{A+B/Z_0+C\,Z_0+D}, \tag{15}$$

and the total shielding effectiveness can be obtained by [24]:

$$SE_{total}(dB) = -20log_{10}(T_{total}). \tag{16}$$

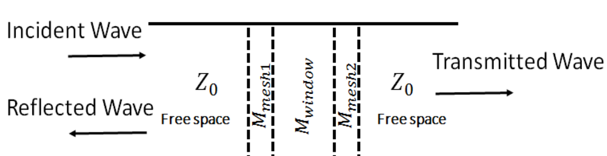


Fig. 5. Cascaded wire-mesh screens layout.

The total shielding effectiveness of two aluminum sheets with glass substrate is calculated analytically using the presented model and numerically simulated using HFSS. The sheets are constructed of square wire-mesh with aperture width is 2 mm and wire radius is 0.05 mm. The frequency band is 200-900 MHz. The glass substrate relative permittivity is 5.2 and thickness is 6 mm. Figure 6 shows the comparisons between analytical results and HFSS simulation with a good agreement is obtained. It can be noted that the shielding effectiveness of the structure is increased by about 50% with introducing additional coating layer of wire-mesh. The calculated mean error between the model and simulation results is about 4.1%.

The same HFSS setup is used while one of the sheets is kept aluminum and the other one is replaced with iron material of conductivity is 1.01×10^7 s/m using the same dimensions. Figure 7 shows SE as a function of frequency based on HFSS simulation for two scenarios. In the first scenario, the two sheets are made of aluminum while the other scenario, one of the sheets is kept aluminum and the other sheet is replaced with iron sheet. It can be shown that changing the wire mesh material with different conductors has less effect on the total SE of the structure.

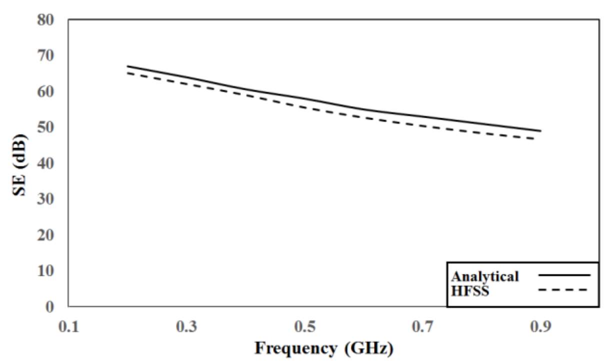


Fig. 6. SE of double coating wire-mesh screens with square aperture, the aperture is width=2 mm and radius=0.05 mm. The two sheets are made of aluminum.

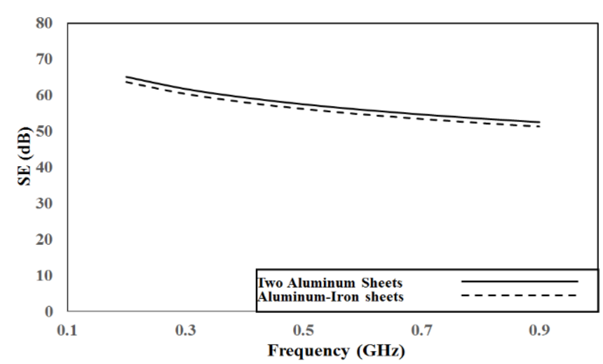


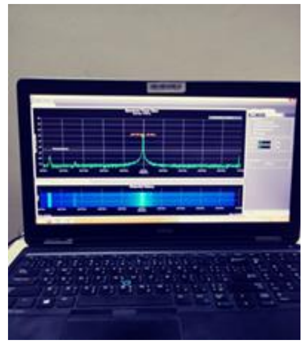
Fig. 7. SE of two coating wire-mesh screens with different materials based on HFSS simulation.

IV. MEASUREMENTS

In this section, sample results are presented to verify the accuracy of the proposed model for two scenarios, single and double-sided coated glass window.

The experimental setup consists of Handheld RF Signal Generator (RFEGEN 1.12) with dipole antenna with gain of 2.2 dBi which is used as a transmitter while the receiver is RF Viewer wireless USB dongle and data is collected using computer software package RF spectrum analyzer (TOUCHSTONE PRO) as shown in Fig. 8. The transmitting and receiving antennas are kept vertically polarized as shown in Fig. 8. In the first scenario, single aluminum wire-mesh screen is fixed in the front face of shielded box with dimensions 50 cm × 50 cm × 30 cm and the transmitter is fixed on wood table at 1 m away from the receiver as shown in Fig. 8. The mesh aperture width is 2 mm and wire radius is 0.05 mm. The operating frequency band is 200-900 MHz which covers multi-bands including lower GSM band. The received power is measured where no sheets are installed in the front face of the box while the other faces as fully shielded then the measured data is collected after shielding with single layer of aluminum wire-mesh sheet. The shielding effectiveness is calculated as the ratio between the received power with and without shielding. Figure 9 shows a comparison between the shielding effectiveness which is calculated from the measured data and the one which is calculated by using the analytical model. Good agreement between the measured and analytical results is obtained. The slight differences can be explained due to errors in the manual positioning of the receiving antenna, differences due to the boundary conditions of the actual setup and slight interference from external sources. The mean calculated error between the model and measured results is about 5.9%.

The same setup is used while by fixing two layers of aluminum wire-mesh sheets on both sides of a commercial glass window with thickness of 6 mm and relative permittivity is 5.2. The structure is installed in the front face of the box while the other faces are kept fully shielded. Figure 10 shows a comparison between measured SE in dB and the calculated one by using the proposed model for cascaded wire-mesh screens. Good agreement between the measured and calculated results is obtained. It should be noted that two mesh layer on both side of the glass window can increase the total SE by about 50% compared with single wire-mesh screen. The total SE of the structure is satisfactory high while the total cost is quite low with good optical transparency compared to metallic sheets. The proposed structure is highly attractive for wide band of shielding applications. The mean calculated error between the model and measured results is about 2.8%.



(a)

(b)

Fig. 8. Measurement setup: (a) TOUCHSTONE PRO RF spectrum analyzer software package. (b) Transmitter (RF Signal Generator) and receiver antenna are installed in shielded box with single aluminum wire-mesh screen in the front face with glass window.

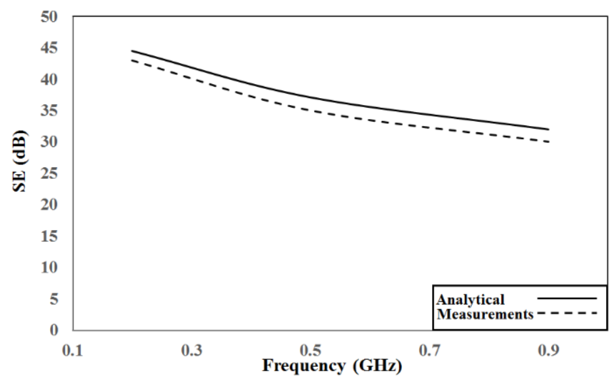


Fig. 9. Shielding effectiveness for single layer wire-mesh screen with aluminum material, $a_s = 2\,mm$ and $r_w = 0.05\,mm$.

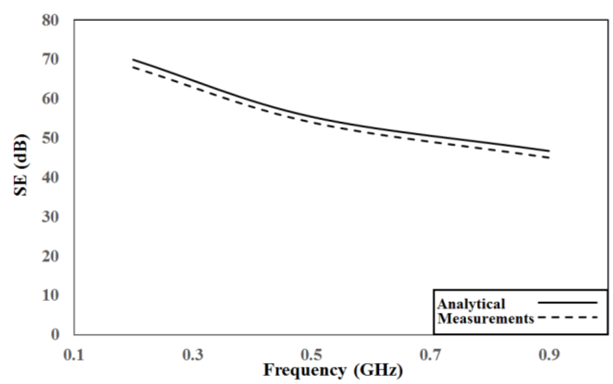


Fig. 10. Shielding effectiveness for double layers of aluminum wire-mesh screens with glass substrate, $a_s = 2\,mm$, $r_w = 0.05\,mm$ and glass thickness = 6 mm.

V. CONCLUSION

An approach is proposed to calculate the shielding effectiveness of wire-mesh screens for single and double wire-mesh layers with glass substrate. The model is based on transmission line theory. It is shown that the wire-mesh screen is providing high shielding effectiveness in low frequency range and by increasing the frequency the shielding effectiveness is decreased. Also, it is shown that the structure shielding effectiveness is satisfactory increased by introducing additional wire mesh layer. The proposed structure is highly attractive for wide band of shielding applications due to its lower cost, reduced weight and optical transparency compared to metallic sheets. The proposed model is verified by comparison with experimental results. Good agreements are obtained from these comparisons.

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