Recent Developments of Shielding Effectiveness for Electronics and Information Devices

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Abstract **–** With the increase wireless communications, many wireless devices and equipment have been invented for special applications, resulting in mutual interference that might destroy the systems or distort signal in-transmission. One of the effective methods to reduce or eliminate interference is to devise a shielding to block the unwanted interference in between the approaching systems, circuits, devices, etc. Thus, shielding and estimation of its effectiveness are very important in order to protect the information devices from potential interference and to improve the performance of information equipment. In this survey, we present the recent developments of the shielding and shielding effectiveness techniques and methods, and give a design for an electromagnetic shielding structure.

Index Terms **–** electromagnetic shielding, shielding effectiveness, shielding methods, shielding technique.

I. INTRODUCTION

With the increment of electronic devices and information equipment, uncertain interference might give a destroy or reduce the performance of electronic systems, chips, broads and devices, which can be classified into electromagnetic pulses, lighting, natural or artificial strong electromagnetic interference [1-10]. In recent years, much interference from wireless systems like 4G and 5G will also affect other electromagnetic devices. Fortunately, these systems don't give out strong interference, which is easy to filter out. With the development of high power microwave equipment, strong electromagnetic pulse or interference poses a huge threat to the general operation of electronic equipment [11]. Thus, electromagnetic protection and electromagnetic shielding are vital to reduce the loss caused by these threats.

To give protection from the potential interference, many shielding techniques and shielding methods have been presented, including metal meshes [11], metal plates [12], frequency selective surface (FSS) [13], metal shells [14], and meta-materials [1, 15]. Motivated by these techniques, the shielding methods moves to low cost or high performance for protecting the information devices. Although these techniques or methods are useful for providing desired shielding to protect information devices from electromagnetic radiation that causes harm to hardware systems, components or printed circuit boards, some of them are not effective for practical engineering applications. Thus, the shielding effectiveness of these techniques and methods is required for engineers to select a suitable solution for practical engineering applications.

Recently, more attention has been paid to shielding effectiveness to discuss how to choose a metal mesh or different shielding structures for realization of engineering applications [16-18]. Many shielding effectiveness methods are presented, like the impedance calculation using average field theory [18]. However, the analysis models are not accurate enough for the different size of the meshes to analyze the shielding effectiveness [19-20]. The equivalent transmission line method [19-20] was used for giving an analysis of the double-layer metal meshes, but it failed to get a solution for a wide band of frequency in its engineering to be accurate. In addition, low simulation speed and large computation consumption made these methods difficult to get quick results for different structures and sizes of shielding [16]. Many effective computation methods were then investigated for complex structures with multi-layers and applications in wide frequency bands.

Additionally, many new structures for shielding applications were also presented, like the frequency selective surface (FSS) [13, 21], LC coil [22], diode grids [23], magnetic shielding techniques [24-25]. Also, the related analysis methods are given for various applications to discuss the shielding effectiveness. To get

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the results, many analysis methods are also discussed by considering the structure parameters using the finite-difference time-domain method (FDTD) [26-27] and finite element method [28-29]. Additionally, the time-frequency domain shielding effectiveness analysis of the shielding structures and the magnetic shielding measurement with low frequency are also carried out to improve the performance of the shielding.

In this review, the recent developments of the shielding methods and shielding effectiveness analysis techniques will be presented and investigated to illustrate the performance of the shielding.

II. SHIELDING TECHNIQUES AND METHODS

A. Metal meshes

As we know, shielding is to prevent undesired interference from the environment, in order to protect the information devices. Thus, a great number of techniques and methods have been put forward to provide a safety measure to guarantee that the devices avoid microwave radiation attacks [21-25]. Furthermore, an electromagnetic wave has a different skin effect when it is transmitted from air to substrate. If it incidents into the metal, it will be blocked and it is difficult to penetrate the metals that will provide a good shielding. Thus, metal or metal shells [14] are used to construct a shielding structure. However, these structures are heavy and will waste metal materials, which also increases the cost for the design of a shielding structure. In order to reduce the cost and inherent performance of the metal shells in practical engineering, metal meshes are proposed with different analysis methods [10], shown in Fig. 1.

Using related techniques and methods, a variety of metal meshes with single or multi-layers have been presented and their shielding effectiveness have been investigated using different methods.

B. Frequency selective surfaces (FSSs)

Recently, another effective shielding has been proposed with a periodic array structure to provide a behavior of spatial filtering, which is known as frequency selective surface (FSS) [13, 21]. As we all know, FSS can be designed to have a band-stop characteristic to filter or block unwanted frequency bands with a stable angle characteristics. Thus, FSS has been used for shielding to protect the sensitive electronics components enabling them avoid electromagnetic interference (EMI) or radio frequency interference (RFI) in consumer or industrial electronic systems, as well as military and emergency systems.

One of the designs of the FSSs is presented in Fig. 2, where the cell of the FSS and the circuit extraction of the FSS cell is also given [29]. From the circuit analysis of the FSS, we can see the filter characteristics clearly. Additionally, we found that the FSS can provide an additional degree of freedom to precisely control the frequency response. It can easily select the desired frequency band and reject the unwanted band, which can filter the incident electromagnetic wave via designing the FSS geometry and arrangement of the FSS cells.

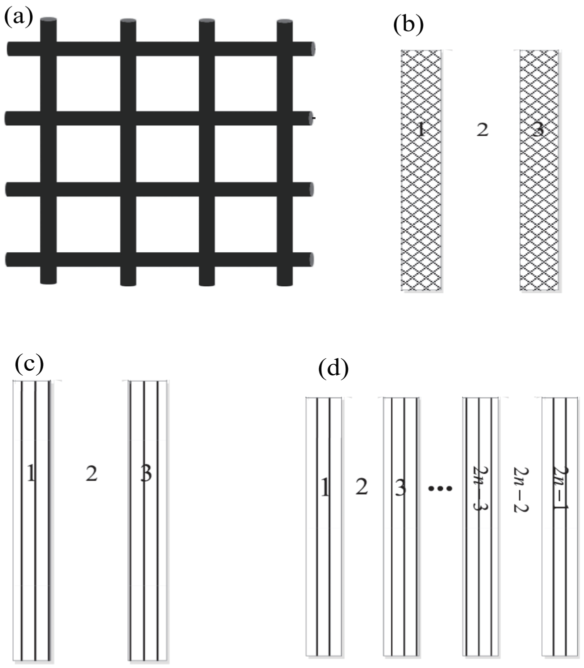


Fig. 1. Geometries of metal meshes [10]. (a) Planar square metal mesh with holes. (b) Double-layered metal plates. (c) Double-layered metal meshes. (d) Multi-layered metal meshes.

C. Braided shielding structures

As we know, cables are useful for information devices not only in low frequency but also in high frequency, and they can work in a wide frequency. Many braided structures have been proposed and investigated for cables [30–32]. Figure 3 shows a typical braided structure. By using these braided shielding structures, most of the low frequency interference can be filtered.

D. Coil shielding structures

The magnetic field can also be cancelled using shielding coils excited by an auxiliary source, and many coil shielding techniques are also presented and investigated via optimizing the phase and magnitude of the current in the coils to suppress the flux density. In addition, the coil couplings can be weakened using metal plates. Figure 4 shows an improved reactive hybrid shielding with an LC coil structure, where aluminum is designed as the ring shape and placed to surround the LC coil [22].

In this improved reactive hybrid shielding structure with an LC coil, an application with the equivalent

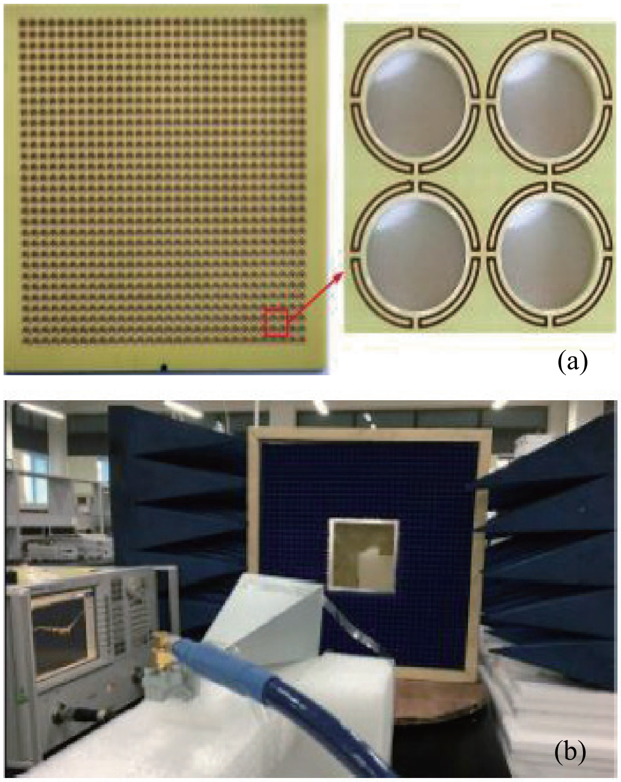


Fig. 2. FSS shielding structure [21]. (a) 3-D FSS cell. (b) Circuit model of the FSS cell. (c) Equivalent circuit of the FSS structure.

circuit for a WPT system with LC shielding coil is also given in Fig. 4. The conventional horizontal aluminum plate (HALP) is equivalent to a vehicle chassis to improve the performance using a vertical aluminum plate (VALP) [22]. In addtition, there are also shielding methods using diode grids, metal plates with slots, shielding for orbital angular momentum waves, materials, and meta-materials.

III. SHIELDING EFFECTIVENESS ANALYSIS

With the developments of the shielding techniques and the methods used in the shielding and the electromagnetic computation methods, various shielding effectiveness analysis methods have been proposed and investigated for different applications, including the finite-difference time-domain method (FDTD) [26–27], the method of moments [28–29], time domain integral equation method [33], transmission-line model method [34], and time-frequency methods [35].

A. Model analysis method

To obtain the performance of shielding effectiveness, a lot of models have been presented and investigated in detail. Recently, a model was used to get a reasonable approximation to evaluate the shielding effectiveness of a rectangular enclosure filled with conductive plates and the computation results were compared with the finite element method (FEM) [12, 28–29]. The model is given in Fig. 5. The computation results obtained from the model agree well with the FEM simulation, which also help to verify the effectiveness and correctness of the model [12].

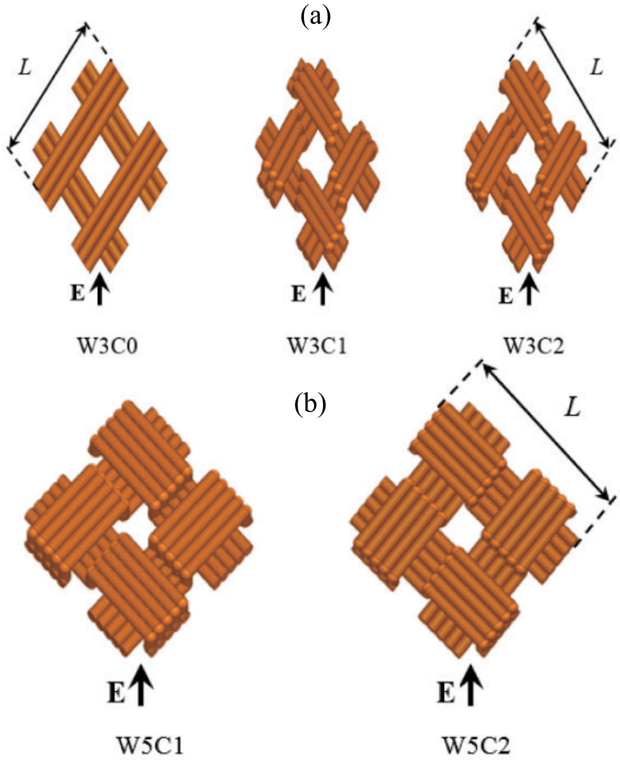


Fig. 3. Braided shielding structure [31]. (a) Geometry of planar braids with three wires per carrier, without (W3C0) and with curvatures (W3C1 and W3C2). (b) Geometry of dense braids with fire wires per carrier and with curvatures (W5C1 and W5C2).

B. Time-domain analysis of the shielding effectiveness

In this subsection, we introduce an improved half-space FDTD method to replace the half-space Green’s function, where generalized transition matrix (GTM) method combined with Fourier transform is used to get the reflection coefficient [35]. In the computations, multi-direction and multi-polarization incident waves are considered for the total-field/scattered-field (TF/SF) given in Fig. 6 in the FDTD. Based on the modified FDTD method, it is applied to a typical half-space composite electromagnetic problem to get the time-domain shielding effectiveness of the shielding enclosure. The results show that the modified method without complex half-space Green’s function has low complexity

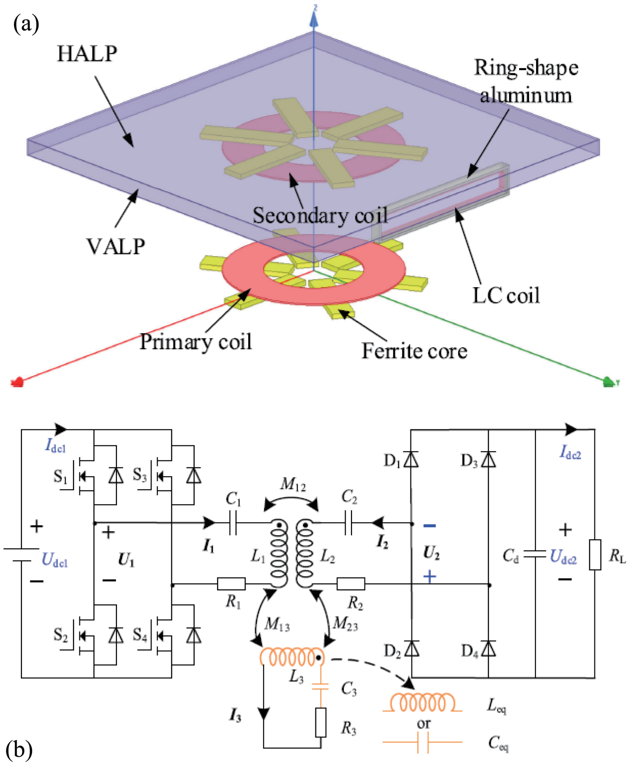
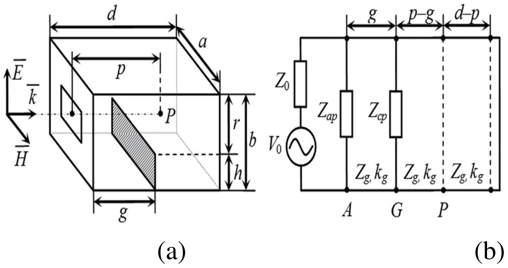


Fig. 4. Improved reactive hybrid shielding structure with an LC coil [22]. (a) Overall view of the improved reactive hybrid shielding with an LC coil structure. (b)Equivalent circuit of a reactive shielding system.



(a) (b)

Fig. 5. Model for shielding effectiveness analysis of a rectangular enclosure filled with conductive plates [12]. (a) Metal rectangular enclosure with metal plates. (b) Equivalent circuit for getting the shielding effectiveness via computations.

compared to the traditional half-space algorithms. In addition, the proposed method can be used for different models, incident conditions, and complex environments.

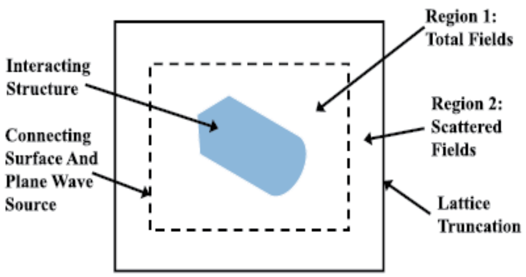


Fig. 6. Zoning of total-field and scattered-field regions [35].

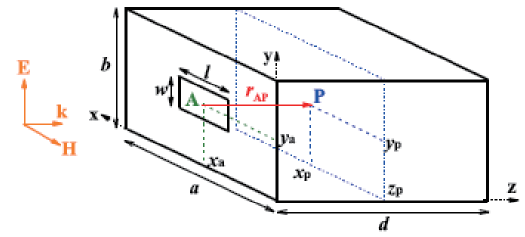


Fig. 7. Schematic of excitation of a rectangular enclosure with an aperture [36].

C. Time-frequency analysis methods

Time-domain analysis always considers electromagnetic pulse (EMP) excitation, which has been used in waveform and spectra [36]. As for shielding against EMP, enclosures with small apertures are conventionally of applicable interest, and the image method limits the application for a large number of dipole images. Recently, for simply estimating time domain shielding effectiveness data of metallic enclosures under EMP excitation and further correlating these data to frequency domain, an analysis between the time and frequency domain for shielding effectiveness is presented and investigated for analyzing the metal enclosures with different apertures, where the analytical formulas for estimating time domain SE data against EMP excitation is also included and derived to analyze the metal enclosures.

The improved method in Fig. 9 is implemented based on the analysis of the transient process at the aperture and an equivalent magnetic current source [36]. Also, only direct emission from the aperture is considered and the equivalent circuit model for frequency domain shielding effectiveness data is used to get the correlation between the time and frequency domain. The simulations are presented to verify the analysis and the simulation agrees well with the analysis.

IV. TIME-DOMAIN SHIELDING EFFECTIVENESS MEASUREMENT

As we know, shielding effectiveness can be measured when a small shielding enclosure is made using frequency-domain techniques under the standard of IEEE 299.1. However, the high level of the shielding effectiveness under a high power microwave or a

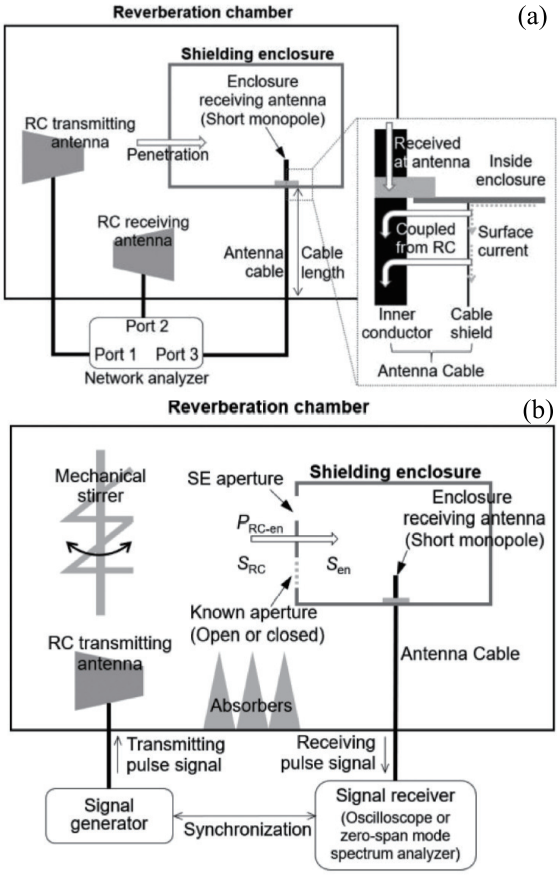


Fig. 8. Popular shielding effectiveness measurement method with frequency and time domain methods [37]. (a) IEEE 299.1 frequency-domain shielding effectiveness measurement method. (b) Time-domain shielding effectiveness measurement method.

directed-energy weapon will reduce the measurement dynamic range of the equipment for shielding effectiveness measurement, which is caused by the cable loss in the signal transmission during the shielding effectiveness measurement [37]. In this section, a time-domain shielding effectiveness measurement method is reviewed in order to achieve high accuracy for a high level shielding effectiveness measurement.

For the frequency-domain shielding effectiveness measurement method, the shielding effectiveness measurement should use a wide dynamic range to get an accurate measurement, where the wide dynamic range is obtained by comparing it to the receiving powers that are obtained before and after replacing a receiving antenna inside an enclosure with a load [37]. In this case, the dynamic range is always reduced by coupling from the cables. In the presence of the shielding effectiveness measurement, continue wave is used to measure the revived power, which will also be coupled into the measurement resulting in dynamic range reduction.

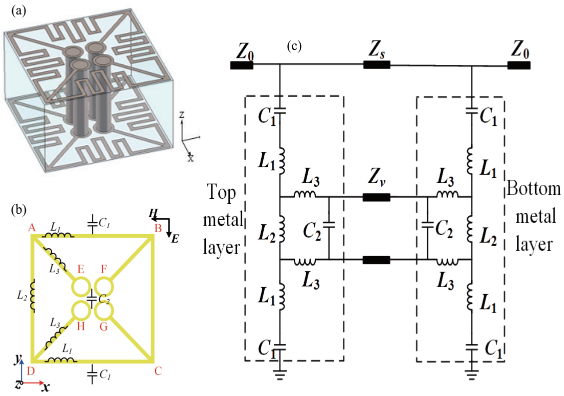


Fig. 9. FSS shielding structure [38]. (a) 3-D FSS cell. (b) Circuit model of the FSS cell. (c) Equivalent circuit of the FSS structure.

For the time-domain shielding effectiveness measurement method, a modulated pulse is used as a transmiting signal in a nested reverberation chamber rather than continue wave signal [37]. When the pulse signal is completely transmitted, the receiving signal is obtained inside the shielding enclosure in the time domain, which is defined as the enclosure response that is used to calculate the shielding effectiveness enclosure. Thus, the measured enclosure response is not affected by the transmitting signal, and hence, the dynamic range for the shielding effectiveness measurement will be unchanged.

V. AN EXAMPLE FOR DEVELOPING FSS SHIELDING STRUCTURE

Since FSS is also useful for shielding effectiveness and most of the FSS only provide a single frequency band with planar structure, we designed a 3-D FSS to mimic the size of the structure [38]. The presented structure is given in Fig. 9 with equivalent circuit of the FSS cell. The designed FSS is printed on a two-layered F4B substrate. To use the FSS cell developed in Fig. 9, a dual-band FSS is presented and given in Fig. 10 (a). The FSS is investigated, fabricated and measured in a chamber. The results shown in Fig. 10 (b) demonstrate that the FSS has good dual-band band-pass performance and the rejected band is wide enough to block the interference from 7GHz to 14GHz. In comparison with the simulations, the band-pass band has been broadened and the bandwidth for the first band-pass is narrowed. There is some difference between the measurement and the simulation, which might be caused by the fabrication and measurement errors. In addition, the FSS can still cover a wide -10dB bandwidth when the incident angle is 40° [38]. Also, in the future, the shielding could be applied in

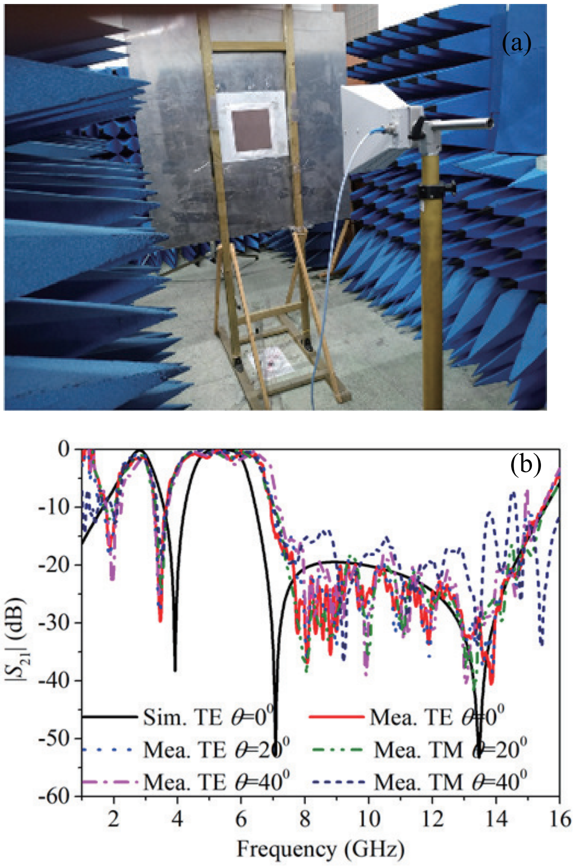


Fig. 10. Performance of the FSS. (a) 3-D FSS cell. (b) Circuit model of the FSS cell. (c) Equivalent circuit of the FSS structure.

high-power microwave (HPM), electronics warfare, and system isolation.

VI. CONCLUSION

In this investigation, recent developments of shielding and shielding effectiveness techniques and methods are reviewed, and analyzed. An example for FSS shielding structure is given, simulated, measured and discussed. From the developments of shielding structures, shielding effectiveness analysis methods, and shielding effectiveness measurements, we think the wide-band shielding structures and shielding effectiveness analysis and measurement with a high power pulse will be an interesting topic for EMP, EMI, and EMC studies. The proposed shielding structures and analysis method can also be used in MIMO engineering systems [39-46] to analyze shielding effectiveness.

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REFERENCES

[1] Y. Zhao, Y. Li, W. Shi, and W. Yu, “Mutual coupling reduction between patch antenna and microstrip transmission line by using defected isolation wall,” *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 34, no. 1, pp. 100-106, 2019.

[2] V. I. Mordachev, E. V. Sinkevich, D. A. Tsyanenka, A. J. Krachko, Y. V. Yatskevich, A. V. Shuldov, A. A. Vodchits, Y. Li, T. Jiang, and W. Xue, “Multivariant discrete analysis of EMC of on-board radio equipment with use of worst-case models,” *International Symposium on Electromagnetic Compatibility*, Amsterdam, Netherlands, 2018.

[3] X. Liu, Y. Li, Y. Zhao, and L. Zhao, “Crosstalk reduction design and analysis of the planar meander transmission lines,” *International Symposium on Antennas and Propagation*, Busan, South Korea, 2018.

[4] Y. Zhao, Y. Li, and X. Liu, “A low-profile wideband absorber using capacitive surface,” *IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM 2020)*, Penghu, Taiwan, 2020.

[5] Y. Zhao and Y. Li, “A frequency selective rasorber with two absorption bands,” *International Applied Computational Electromagnetics Society (ACES) Symposium*, California, USA, 2020.

[6] Y. Zhao, Y. Xia, Y. Li, G. Yang, “A frequency selective rasorber with wide transmission band,” *International Applied Computational Electromagnetics Society (ACES) Symposium*, Nanjing, China, 2019.

[7] Y. Zhao, Y. Li, and X. Liu, “A novel dual polarized tunable frequency selective surface with varactors,” *IEEE International Symposium on Antennas and Propagation*, Atlanta, Georgia, USA, 2019.

[8] X. Liu, Y. Li, Y. Zhao, L. Zhao, V. Mordachev, and E. Sinkevich, “Equivalent circuit model of crosstalk reduction parallel transmission lines with defected microstrip structures,” *Cross Strait Quad-Regional Radio Science and Wireless Technology Conference*, Xuzhou, China, 2018.

[9] Y. Zhao, Y. Li, and L, Zhao, “A G-shaped defected isolation wall for mutual coupling reduction between patch antenna and microstrip transmission line,” *IEEE 7th Asia-Pacific Conference on Antennas and Propagation*, Auckland, New Zealand, 2018.

[10] X. Sun, B. Wei, Y. Li, and J. Yang, “A new model for analysis of the shielding effectiveness of multilayer infinite metal meshes in a wide frequency range,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 1, pp. 102-110, 2022.

[11] Z. Yan, F. Qin, and J. Cai, "Shielding effectiveness of materials under the excitation of high-power microwave," *IEEE Transactions on Electromagnetic Compatibility*, vol. 62, no. 5, pp. 2317-2320, 2020.

[12] A. A. Ivnov, M. E. Komnatnov, and T. R. Gazizov, "Analytical model for evaluating shielding effectiveness of an enclosure populated with conducting plates," *IEEE Transactions on Electromagnetic Compatibility*, vol. 62, no. 5, pp. 2307-2010, 2020.

[13] M. Wang, L. Zhao, J. Wang, X. Liang, S. Zhang, Y. Li, and W. Yu, "A low-profile miniaturized frequency selective surface with insensitive polarization," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 33, no. 9, pp. 1003-1008, 2018.

[14] M. J. A. Helvoort and D. W. Harberts, "Low-frequency electromagnetic shielding and scattering of multiple cylindrical shells," *IEEE Transactions on Electromagnetic Compatibility*, vol. 63, no. 1, pp. 46-56, 2021.

[15] K. Yu, Y. Li, and X. Liu, "Mutual coupling reduction of a MIMO antenna array using 3-D novel meta-material structures," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 33, no. 7, pp. 758-763, 2018.

[16] S.-Y. Hyun, K.-W. Lee, and J.-G. Yook, "Modeling of shielding effectiveness of reinforced concrete walls for electromagnetic pulse," *42nd European Microwave Conference*, Amsterdam, The Netherlands, pp. 779-782, 2012.

[17] A. Lopez, L. Vojtech, and M. Neruda, "Comparison among models to estimate the shielding effectiveness applied to conductive textiles," *Advances in Electrical and Electronic Engineering*, vol. 11, no. 5, pp. 387-391, 2013.

[18] K. F. Casey, "Electromagnetic shielding behavior of wire-mesh screens," *IEEE Transactions on Electromagnetic Compatibility*, vol. 30, no. 3, pp. 298-306, 1988.

[19] S. Cristina and A. Orlandi, "An equivalent transmission line model for electromagnetic penetration through reinforced concrete walls," *Transactions on Communications*, vol. E78-B, no. 2, pp. 218-229, 1995.

[20] M. S. Sarto, "A new model for the FDTD analysis of the shielding performances of thin composite structures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 41, no. 4, pp. 298-306, 1999.

[21] L. Yan, L. Xu, R. X. K. Gao, J. Zhang, X. Yang, and X. Zhao, "Angularly independent frequency selective surface with good ventilationfor millimeter wave EM shielding," *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 1, pp. 251-255, 2022.

[22] Y. Li, K. Xie, Y. Ying, and Z. Li, "An improved hybrid shielding with LC coil for wireless power transfer system," *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no.3, pp. 720-731, 2022.

[23] C. Yang, T. Wendt, M. Stefano, M. Kopf, C. M. Becker, S. Grivet-Talocia, C. Schuster "Analysis and optimization of nonlinear diode grids for shielding of enclosures with apertures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 63, no. 6, pp. 1884-1895, 2021.

[24] H. H. Park, "Analytic magnetic shielding effectiveness of multiple long slots on a metal plate using rectangular loops," *IEEE Transactionson Electromagnetic Compatibility*, vol. 62, no. 5, pp. 1971-1979, 2020.

[25] W. Bai, F. Ning, X. Yang, C. Jiao, L. Chen, "Low frequency magnetic shielding effectivenessof a conducting plate with periodic apertures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 63, no. 1, pp. 30-37, 2021.

[26] Q. F. Liu, W. Y. Yin, J. F. Mao, and Z. Chen, "Accurate characterization of shielding effectiveness of metallic enclosures with thin wires and thin slots," *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, no. 2, pp. 293-300, 2009.

[27] H. Mai, J. Chen, and A. Zhang, "A hybrid algorithm based on FDTD and HIE-FDTD methods for simulating shielding enclosure," *IEEE Transactions on Electromagnetic Compatibility*, vol. 60, no. 5, pp. 1393-1399, 2018.

[28] W. P. Carpes, L. Pinchon, and A. Razek, "Analysis of the coupling of an incident wave with a wire inside a cavity using an FEM in frequency and time domains," *IEEE Transactions on Electromagnetic Compatibility*, vol. 44, no. 3, pp. 470-475, 2002.

[29] S. Benhassine, L. Pinchon, and W. Tabbara, "An efficient finite-element time-domain method for the analysis of the coupling between wave and shielded enclosure," *Transactions on Magnetics*, vol. 38, no. 2, pp. 709-712, 2002.

[30] F. Haddad, B. Bayard, and B. Sauviac, "Low frequency relation between transfer impedance and shielding effectiveness of braided cables and grid shields," *IEEE Transactions on Electromagnetic Compatibility*, vol. 62, no. 6, pp. 2423-2430, 2020.

[31] B. Bayard, F. Haddad, and B. Sauviac, "A wide frequency range relationship between transfer impedance of braided cables and shielding effectiveness of corresponding plate shields," *IEEE Transactions on Electromagnetic Compatibility*, vol. 66, no. 6, pp. 1837-1843, 2021.

[32] E. F. Vance, "Shielding effectiveness of braided wire shields," *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-17, no. 2, pp. 71-77, 1975.

[33] W. Luo, Y. Liao, Z. G. Zhao, J. Wang, J. H. HU, H. Xie, J. Y. Zhao, Q. F. Liu, L. Zhou, and W. Y. Yin, "Accurate simulation of shielding effectiveness of metallic cabins using an improved Calderon preconditioner-based time-domain integral equation method," *IEEE Transactions on Electromagnetic Compatibility*, vol. 60, no. 1, pp. 200-208, 2019.

[34] B. L. Nie, P. A. Du, Y. T. Yu, and Z. Shi, "Study of the shielding properties of enclosures with apertures at higher frequencies using the transmission-line modeling method," *IEEE Transactions on Electromagnetic Compatibility*, vol. 53, no. 1, pp. 73-81, 2011.

[35] L. Cao, Y. Z. Xie, and M. X. Gao, "Analysis of time-domain shielding effectiveness of enclosures above lossy half-space using an improved half-space FDTD method," *IEEE Transactions on Electromagnetic Compatibility*, vol. 62, no. 5, pp. 2076-2083, 2020.

[36] G. Wu, P. Chen, L. Xie, and W. Wang, "Analytical correlation between time and frequency domain shielding effectiveness of metallic enclosures with apertures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 62, no. 6, pp. 2773-2784, 2020.

[37] J. H. Wang, H. H. Park, C. H. Hyoung, and J. H. Kwon, "Shielding effectiveness measurement with wide dynamic range for a small enclosure in a nested reverberation chamber," *IEEE Transactions on Electromagnetic Compatibility*, vol. 63, no. 5, pp. 1407-1416, 2021.

[38] M. Wang, "Research and design of miniaturized multi-band frequency selective surface," Harbin Engineering University, Master's thesis, 2020.

[39] W. Shi, X. Liu, and Y. Li, "ULA fitting for MIMO radar," *IEEE Communications Letters*, vol. 26, no. 9, pp. 2190-2194, 2022.

[40] F. Liu, J. Guo, L. Zhao, G. L. Huang, Y. Li, and Y. Yin, "Ceramic superstrate-based decoupling method for two closely packed antennas with cross-polarization suppression," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 3, pp. 1751-1756, 2021.

[41] L. Zhao, F. Liu, X. Shen, G. Jing, Y. Cai, and Y. Li, "A high-pass antenna interference cancellation chip for mutual coupling reduction of antennas in contiguous frequency bands," *IEEE Access*, vol. 6, pp. 38097-38105, 2018.

[42] J. Li, X. Zhang, Z. Wang, X. Chen, J. Chen, Y. Li, and A. Zhang, "Dual-band eight-antenna array design for MIMO applications in 5G mobile terminals," *IEEE Access*, vol. 7, pp. 71636-71644, 2019.

[43] K. L. Chung, A. Cui, M. Ma, B. Feng, and Y. Li, "Central-symmetry decoupling technique for circularly-polarized MIMO system of tightly packed Chinese-character-shaped patch antennas," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 36, no. 9, pp. 1125-1131, 2021.

[44] T. Jiang, T. Jiao, Y. Li, and W. Yu, "A low mutual coupling MIMO antenna using periodic multi-layered electromagnetic band gap structures," *Applied Computational Electromagnetics Society (ACES) Journal,* vol. 33, no. 3, pp. 305-311, 2018.

[45] S. Song, Y. Da, B. Qian, X. Huang. X. Chen, Y. Li, and A. A. Kishk, "Dielectric resonator magnetoelectric dipole arrays with low cross polarization, backward radiation, and mutual coupling for MIMO base station applications," *China Communications*, 2022.

[46] B. Liu, Y. Da, X. Chen, and A. Kishk, "Hybrid decoupling structure based on neutralization and partition schemes for compact *large-scale* base station arrays," *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 2, pp. 267-271, 2022.

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