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# Periodic frequency selective surface coupled highly efficient, broadband, single layer microwave absorber

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Microwave absorbing materials and structures have been widely utilized in aeronautic applications and platform. Improving the working absorption bandwidth of traditional microwave absorbing materials (MAMs) has greatly challenged the scientists due to the restriction of the available material parameters. Therefore, in this paper an attempt has been made to develop a broadband absorber using synthesized ferrite nanocomposite and periodic frequency selective surface (FSS) in X-band frequency range. The effect of two different kinds of substrates (i.e., conventional FR4 and synthesized ferrite nanocomposite) has been studied over microwave absorption characteristics of FSS loaded composite structures. The significant enhancement has been observed in -10 dB absorption bandwidth after impacting of FSS over the substrate. The use of ferrite substrate results in superior absorption properties as compared to FR4 substrate. A 2.55 mm thick synthesized ferrite substrate loaded with square loop FSS, provides a minimum reflection coefficient (RC) of -43.2 dB at 9.9 GHz with corresponding bandwidth of 3.7 GHz. The finding reveals a flexible and promising strategy to improve the -10 dB absorption bandwidth of existing MAMs.

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*Keywords:* Microwave absorber, Microwave absorbing material, Ferrite, nanocomposite, Frequency selective surface, Aeronautics, Stealth technology

## 1. Introduction

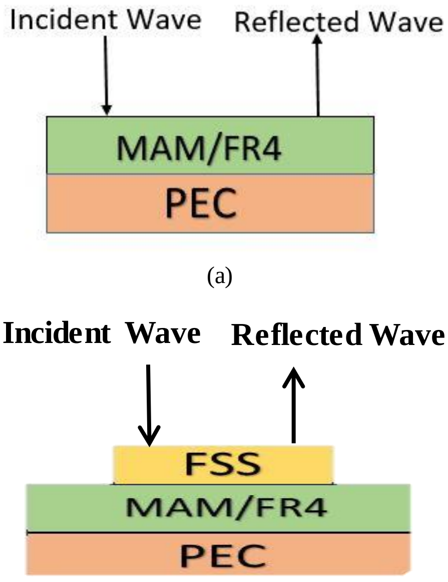
Microwave absorbing materials (MAMs) and structures are highly attractive due to their significance in the cutting-edge microwave communication technologies, like antenna, radome, stealth, and anechoic chambers, etc. [1]-[3]. Researchers have also attempted to utilize MAMs for the electromagnetic interference (EMI) suppression, i.e., to reduce the harmful effect of the radiation [1]. The frequency regime of 8.2 to 12.4 GHz (i.e., X-band) is the most concerned band in the microwave spectrum due to its potential application in radome and stealth structures. Certainly, for aeronautical applications, an ideal MAM should be thin, broadband, weather resistant, and cost-effective, obviously along good microwave absorption characteristics [1]-[2].

With a tremendous progress in the field of nanotechnology, distinct nanocomposites with remarkable EM properties have been well documented for microwave absorbing applications. In particular, the ferrite based nanocomposites have been widely investigated in the X-band due to their good dielectric and magnetic properties, which is required to maintain an appropriate impedance matching [4]. Recently, an extensive attention on FSSs has been paid for their potential civilian and military applications, due to their spatial filtering characteristics [5]-[18]. FSSs are arbitrary shaped, generally impacted over a dielectric substrate. Such periodic structure based advanced EM structure, is one of the efficient methods for expanding the range of operation frequencies of absorbers. A great deal of research has been fostered on active (i.e., smart or reconfigurable), three-dimensional (3D) FSS, textile/fabric based FSS, fractal FSSs, multilayered FSSs, and metamaterials (i.e., artificial materials), etc. for the development of efficient microwave absorbers [5].

The components of a microwave absorber decides the EM properties and microwave absorption capability. According to the development of stealth structure design, it is clear that most of the efforts have been massively focused over nanocomposites and the tuning of their EM parameters on the basis of morphology and physical properties, etc. Alternatively, FSS inspired EM structures have been employed to manipulate the resonance peaks. Researchers began to focus over the combination of FSS and MAM in order to develop thin and broadband absorbers [6]-[18]. Much research has been devoted over the combination of FSS with either dielectric or magnetic material. But very few studies are available about the effect of substrate material (i.e., commercially available FR4 and synthesized ferrite nanocomposites) over microwave absorption. Therefore, in this paper, an effort has been made to examine the effect of substrate material over microwave absorption capability of FSS impacted structures. Such study provides an effective way for the realization of an efficient microwave absorbing structure.

## 2. Design of single layer absorber

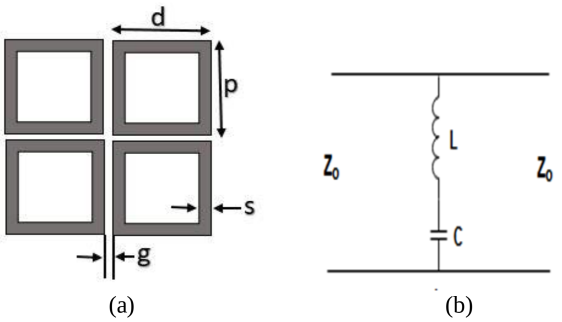
The complete absorber structural model is composed of periodic FSS impacted substrate backed with a ground plane, i.e., perfect electric conductor (PEC). Figs. 1 (a) and 1 (b) present single layer, PEC backed absorber without FSS and with FSS, respectively. A 2.0 mm thick Al alloy sheet has been employed as a PEC. Two kinds of substrate materials have been utilized: commercially available FR4 and synthesized ferrite (i.e., MAM). The Ba hexaferrite substituted with Ni and Zn synthesized using sol-gel autocombustion method, has been utilized as a substrate material. The electromagnetic characterization of synthesized material has been carried out using a standard waveguide based microwave measurement setup [2]. The square loop geometry has been used an FSS for the realization of the proposed microwave absorbing structure.



(a)

(b)

*Fig. 1. Distinct MAS configurations (a) PEC backed MAM/FR4 substrate without FSS layer, and (b) PEC backed MAM/FR4 substrate loaded with square loop and Minkowski loop FSS geometries*



(a) (b)

*Fig. 2. FSS topology (a) Square loop with corresponding design variables (i.e., d, p, g, and s), and (b) Equivalent circuit model*

Fig. 2 depicts the square loop FSS with a corresponding equivalent circuit diagram. The frequency response of the FSS has been determined by the geometry of the structure in one period, called a unit cell. The square loop length (d), the gap between square loops (g), periodicity (p), and strip width (s) are the design variables for square loop FSS as shown in Fig. 2. Due to the periodicity of the structure, a unit cell has been cut and analyzed separately. The unit cell has been simulated and optimized using HFSS followed by a critical parametric analysis, which utilizes Finite Element Method (FEM) to determine the EM behavior of the structure. The optimal design variables for square loop FSS loaded ferrite and FR4 substrates are depicted in Table 1. The Floquet port has been used for the excitation of periodic structures. The usage of this theorem can lead to link the various periodic cells to each other in terms of the exponential function. The periodic FSS leads to the creation of minima at a particular frequency where the phase criteria to match the surface impedance to the free space impedance is satisfied.

*Table 1. Optimal design variables of square loop FSS loaded ferrite and FR4 substrates*

| Absorber Configuration | Optimized design variables (in mm) | | | | |
|---|---|---|---|---|---|
| | p | d | g | s | t |
| FSS loaded ferrite | 14 | 4 | 10 | 1 | 2.55 |
| FSS loaded FR4 | 20 | 10 | 10 | 1 | 3.2 |

## 3. Results and discussion

Fig. 3 shows the FESEM image of the synthesized ferrite nanocomposites with an interconnecting structure. The particle size of the sample has a wide range of distribution. The synthesized ferrite particles are seemed to be very small (< 100 nm), which results in high surface tension, causing them to agglomerate, and leading to the formation of narrowly distributed agglomerated powders constitutes multiple morphologies (like spherical, cubical, and hexagonal, etc.) as clear from the FESEM image. Fig. 4 (a) depicts the frequency dependent complex dielectric permittivity and complex magnetic permeability values for the synthesized ferrite nanocomposites in the range of 8.2 to 12.4 GHz. These values have been extracted based on the frequency dependent scattering parameters (s-parameters). The maximum values for real part of complex dielectric permittivity (ε') and complex magnetic permeability (μ') are 8.6 and 1.0, respectively. On the other hand, the maximum values of the imaginary parts for complex dielectric permittivity (ε") and complex magnetic permeability (μ") are 4.7 and 0.06, respectively.

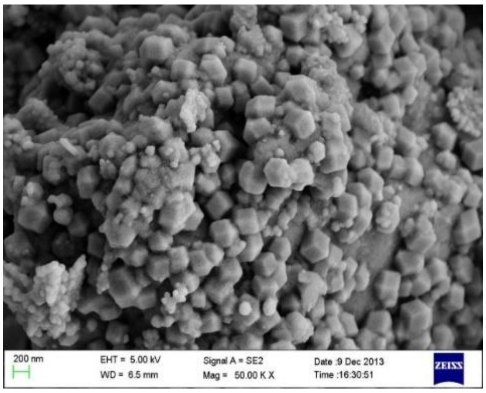
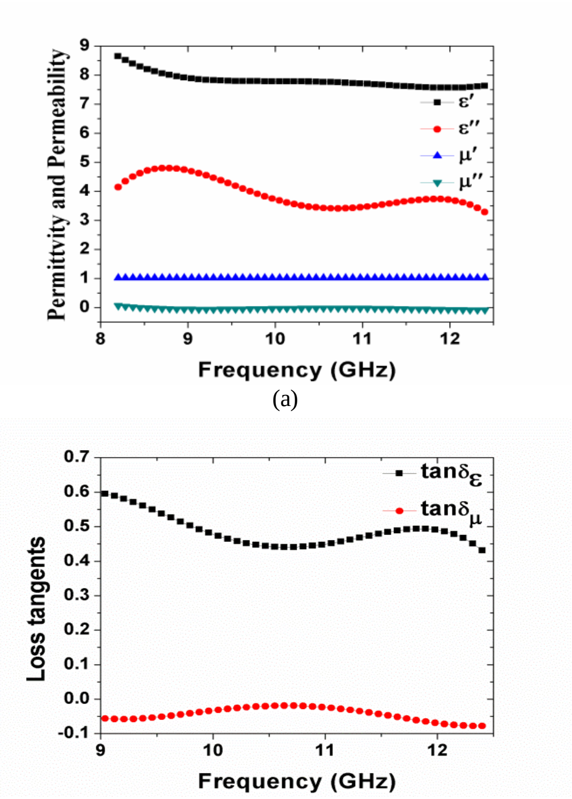


*Fig. 3. FESEM image of synthesized ferrite nanocomposite*



(a)

(b)

*Fig. 4. Frequency dependent (a) complex dielectric permittivity & complex magnetic permeability values, and (b) Dielectric and magnetic loss tangents in the range of 8.2 to 12.4 GHz*

Fig. 4 (b) shows the loss tangent-frequency spectra's of ferrite, obtained from the frequency dependent ε', μ', ε'' and μ'' values (shown in Fig. 4 (a). The maximum value of dielectric loss tangent is 0.6 at 8.8 GHz; on the other hand, the maximum value of the magnetic loss tangent is 0.06 at 8.2 GHz. The dielectric loss tangent values are found to be dominating over the magnetic loss tangent values; therefore, dielectric losses may be considered as the primary reason for the microwave absorption in case of synthesized ferrite nanocomposite based substrate. Fig. 5 shows the frequency dependent RC characteristics of synthesized ferrite nanocomposite without FSS, FSS loaded ferrite nanocomposite, and FSS loaded FR4 in the range of 8.2 to 12.4 GHz. A corresponding analysis of microwave absorption properties of these single layers, X-band microwave absorbing structures is presented in Table 2. The peak RL for the single layer synthesized ferrite has been obtained based on transmission line mathematical formulations as reported in [1]. It is well known that the peak RC value strongly depends on the operating frequency (f) as well as absorber layer coating thickness (t). The optimal coating thickness is the thickness value, at which the maximum absorption of wave takes place. The optimal coating thickness for synthesized ferrite nanocomposite is 2.7 mm, which is found to significantly reduce to 2.55 mm, after loading of square FSS over the synthesized ferrite nanocomposite layer. In this manner, the optimal absorber layer coating thickness for FSS loaded ferrite nanocomposite is 2.55 mm only.

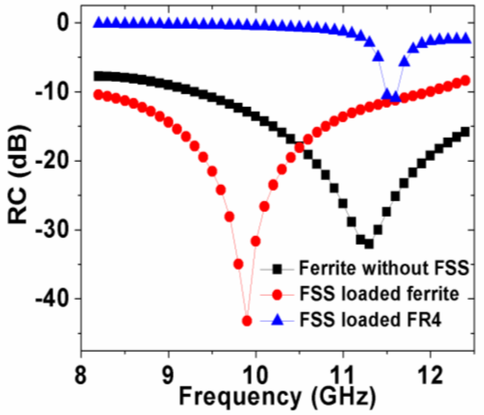


*Fig. 5. Frequency dependent RC of the ferrite nanocomposite without FSS (t= 2.55 mm), FSS loaded ferrite nanocomposite (t = 2.55 mm), and FSS loaded FR4 (t=3.2 mm) in the range of 8.2 to 12.4 GHz*

*Table 2. Microwave absorption properties of distinct X-band microwave absorber configurations*

| Absorber configuration | Min. RC (dB) | f (GHz) | -10 dB BW (GHz) |
|---|---|---|---|
| Ferrite layer without FSS | -32.0 | 11.3 | 3.1 |
| FSS loaded ferrite | -43.2 | 9.9 | 3.7 |
| FSS loaded FR4 | -10.8 | 11.6 | 0.1 |

The synthesized ferrite nanocomposite based absorber (t= 2.55 mm) with square loop FSS geometry is found to provide a peak RC of -43.2 dB at 9.9 GHz. The absorption bandwidth corresponds to RC ≤ -10 dB is 3.7 GHz. On the other hand, the synthesized ferrite nanocomposite with a same coating thickness (i.e., 2.55 mm) possess a peak RC value of -32 dB at 11.3 GHz, with a corresponding -10 dB absorption bandwidth of 3.1 GHz. A further effect of the substrate material has been studied over the absorption capability of considered microwave absorbing structures. The commercially used FR4 substrate has been utilized to examine this effect. The microwave absorption properties of commercially available FR4 loaded with square loop FSS are compared with FSS impacted ferrite nanocomposite. The structure loaded with FSS with FR4 as a substrate material, is found to possess a minimum RC of -10.8 dB at 11.6 GHz. The bandwidth corresponds to RC ≤ -10 dB for this structure is only 0.1 GHz. The resonance phenomena due to FSS-wave interaction and dielectric loss of the ferrite nanocomposite are two primary reasons behind the strong microwave absorption exhibited by FSS impacted ferrite nanocomposite. The performance of the proposed single layer FSS impacted ferrite nancomposite absorber is compared to other state-of-the-art, thin and broadband absorbers, reported in the open literature as presented in Table 3. It is evident that the microwave absorption properties of square loop FSS impacted ferrite nanocomposite absorber is in quite good agreement with other reported works [6]-[18].

*Table 3. Comparison of the present work with other reported single layer structures at X-band*

| Substrate | FSS shape | Min. RC (dB) | -10 dB BW (GHz) | Thickness (mm) | Ref. |
|---|---|---|---|---|---|
| Glass fiber reinforced composite | Square patch | -18.7 | 3.3 | 3.9 | [6] |
| Polymer composites filled with carbonyl iron and Co$_2$Z ferrite | Ring | -18 | Nil | 2.0 | [7] |
| Kapton, Rohacel and FR4 | Ring | -16 | 4.2 | 5.0 | [8] |
| FR4 | Jerusalem cross slot | -24 | 1.2 | 1.5 | [9] |
| Flake ferrous based magnetic material | Square patch | -30 | 4.2 | 5.0 | [10] |
| Dielectric substrate ($\varepsilon_r$=1.5) | Crisscross and fractal square patch | -11 | 4.2 | 4.0 | [11] |
| Magnetic-polymer composite | Square patch | -25 | 4.2 | 2.4 | [12] |
| Magnetic film | Square loop and patch | -23 | ~1.5 | 1.5 | [13] |
| C/Al$_2$O$_3$ | Circular patch | -40 | ~1.5 | 2.0 | [14] |
| ITO and soda-lime glass | Square patch array | -35 | ~2.2 | 2.1 | [15] |
| Duroid | Square patch | -26 | 2.4 | 3.0 | [16] |
| Soda-lime glass | Metal mesh | -23 | ~3.2 | 2.1 | [17] |
| FR4 | Cross dipoles with lumped resistors | -16 | 3.0 | 3.94 | [18] |
| Ferrite | Square loop | -43.2 | 3.7 | 2.55 | This work |

## 4. Conclusions

We have successfully demonstrated an approach to improve the microwave absorption capability of conventional MAMs using FSSs. The design strategy and relevant results are presented and discussed with in reference to ferrite nanocomposite and FR4 based substrate materials. Results reveal that substrate dielectric properties greatly affect the minimum RC values of the FSS impacted composites. It has been shown that the application of a square loop FSS allows one to enhance the -10 dB absorption bandwidth of ferrite nanocomposite absorber along with a corresponding reduction in the coating thickness. Such characteristics of FSS loaded synthesized ferrite nanocomposite absorber makes it suitable for the stealth applications.

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## References

[1] K. J. Vinoy, R. M. Jha, Radar absorbing materials: from theory to design and characterization, Boston, 1996.

[2] R. Panwar, J. R. Lee, Measurement Science and Technology **29**(6), 062001 (2018).

[3] B. A. Munk, Frequency selective surfaces: theory and design, Wiley, New York, 2000.

[4] R. Panwar, J. R. Lee, Aerospace Science and Technology **66**, 216 (2017).

[5] R. Panwar, S. Puthucheri, D. Singh, IEEE Transactions on Magnetics **54**(5), 1 (2018).

[6] W. J. Lee, J. W. Lee, C. G. Kim, Composites Science and Technology **68**, 2485 (2008).

[7] H. Y. Chen, H. B. Zhang, L. J. Deng, IEEE Antennas and Wireless Propagation Letters **9**, 899 (2010).

[8] F. Costa, A. Monorchio, G. Manara, IEEE Transactions on Antennas and Propagation **58**, 1551 (2010).

[9] H. X. Liu, B. F. Yao, L. Li, X. W. Shi, Progress in Electromagnetics Research B **31**, 261 (2011).

[10] L. Sun, H. Cheng, Y. Zhou, J. Wang, IEEE Antennas and Wireless Propagation Letters **11**, 675 (2012).

[11] L. K. Sun, H. F. Cheng, Y. J. Zhou, J. Wang, Opt. Exp. **20**, 4675 (2012).

[12] L. Zhang, P. Zhou, H. Zhang, L. Lu, G. Zhang, H. Chen, IEEE Transactions on Magnetics **50**, 4004305 (2014).

[13] H. Zhou, L. Yang, S. Qu, K. Wang, J. Wang, H. Ma, Z. Xu, IEEE Antennas and Wireless Propagation Letters **13**, 114 (2014).

[14] Z. Yang, F. Luo, M. Sun, J. Xu, W. Zhou, Y. Qing, D. Zhu, Z. Huang, Materials Letters **151**, 109 (2015).

[15] I. P. Hong, Microwave and Optical Technology Letters **57**, 2023 (2015).

[16] M. W. B. Silva, A. L. P. S. Campos, L. C. Kretly, Microwave and Optical Technology Letters **57**, 928 (2015).

[17] I. G. Lee, S. H. Yoon, J. S. Lee, I. P. Hong, Electronics Letters **52**, 555 (2016).

[18] D. Kundu, A. Mohan, A. Chakrabarty, IEEE Antennas and Wireless Propagation Letters **15**, 1589 (2016).

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