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Stored energy of arbitrary metamaterial inclusions

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(Dated: 24 July 2020)

5 Electromagnetic metamaterials are generally defined and classified in terms of their effective
 parameters. They are evaluated in the far-field which limits the evaluation of its near field
 interaction in some applications such as metamaterial inspired design. An alternative ap-
 10 proach proposed in this paper is based on the modal stored energy of metamaterial inclusion.
 This approach is based on the surface current distribution which would address the challenge
 of metamaterial near-field application. This paper describes a method for quantifying the
 modal stored energy of arbitrary-shaped metamaterial inclusions based on the theory of char-
 15 acteristic modes. The theory of characteristic modes is independent of excitation, gives good
 physical insight into the behaviour of an inclusion and would be helpful for near-field applica-
 tion of metamaterials. The modal stored energy approach is also compared with the common
 effective parameter approach. It shows similarity in terms of the physical and qualitative
 analysis when far-field assumptions are accounted for. The broadside-coupled split-ring res-
 onator and the S-shaped inclusion are considered. The physical and qualitative analysis based
 on the modal stored energy approach shows a good agreement with the effective parameter
 approach.

20 Keywords: Stored energy, metamaterial antenna, modal stored energy, metamaterial, effec-
 tive parameter.

I. INTRODUCTION

55 Electromagnetic systems such as antennas are char-
 60 acterised by the way in which they dissipate, store and
 65 radiate electromagnetic energy. These quantities are use-
 70 ful for understanding the physics, design application and
 evaluation of the radiation performances such as the ra-
 75 diation efficiency and performance bounds¹⁻⁴. It is gen-
 80 erally suggested that electromagnetic artificial materi-
 als such as metamaterial can improve radiating perfor-
 85 mances in several configurations⁵. These metamaterials
 (MTMs) are defined in terms of their effective material
 parameters i.e. permeability μ and permittivity ε func-
 90 tions and always need to be extracted⁶ from their far-
 field quantity. Importantly, an interesting phenomena for
 95 electromagnetic systems application happen at the region
 of resonance^{7,8} where effective parameters are not always
 valid. Hence, with the growing near-field applications of
 100 MTM to electromagnetic systems like antenna^{9,10}, it is
 interesting to analyze MTM around its region of reso-
 105 nance using similar quantities of most electromagnetic
 systems. Unlike effective parameters which are valid in
 far-field, stored energy quantities define near-field inter-
 110 action of electromagnetic systems¹¹. Although, there are
 115 existing methods for evaluating electromagnetic energy
 such as the scattering approach given in terms of the
 conduction or polarization current¹², a more robust and
 intuitive approach is the method of moments¹³.

120 The method of moments which is applied in the the-
 125 ory of characteristic modes (TCM) brings physical insight
 through intuitive knowledge into the electromagnetic en-
 ergy of radiating structures using a modal approach¹⁴.

It expands current as a number of basis function and
 green function and by solving the derived impedance
 matrix as a generalized eigenvalue equation, electromag-
 netic energy can be calculated for any external excit-
 ing field. In other words, the application of theory of
 characteristic modes is independent of excitation, ap-
 plicable to arbitrary-shaped structures, takes into ac-
 count the nature of the material and requires only few
 modes to describe the global behaviour of electrically
 small structures¹⁴. Thus, TCM is popular for the de-
 sign of many electromagnetic systems especially antenna
 design¹⁵⁻¹⁸ for various applications. In previous work,
 the theory of characteristic modes was extended to de-
 sign MTM inclusion¹⁹. It was shown that one of the
 challenges with these inclusions especially magnetic in-
 clusion is that its magnetic properties are exhibited when
 excitation is placed in a specific polarization. Thus, it is
 important to consider excitation and polarization effect
 in describing the modal stored energy of MTM inclusion.

The modal stored energy approach for metamaterial
 inclusion is useful for selecting an inclusion to associate
 with an electromagnetic system like antenna. Already,
 many electromagnetic designs make use of modal ap-
 proach such as evaluation of antenna Q-factor²⁰⁻²², selec-
 tion of antenna excitation source²³, design of metamate-
 rial inclusion for antenna application²⁴⁻²⁷ and the study
 of electromagnetic structures²⁸⁻³⁰. This is due to the
 numerous advantages which include its independence of
 excitation source, applicability to arbitrary-shaped struc-
 130 tures and the physical insight it brings into the behaviour
 of radiating structures^{14,15}. The design of metamaterial,
 antenna and electromagnetic devices can therefore be an-

85 analyzed using similar modal quantities while leveraging on the physical insight and other advantages of modal analysis approach.

This paper shows a method to quantitatively evaluate the modal stored energy of MTM inclusions using TCM. 90 TCM is independent of excitation and only takes into account the properties and structure of the material. The methodology is applied to MTM inclusions with known effective parameter quantity. In order to provide a qualitative appreciation by comparison to common effective 95 parameters, new steps are introduced to the modal stored energy approach to account for the polarization and excitation dependence of MTM inclusions. Two elementary structures, broadside-coupled split-ring resonator (BC-SRR) and S-shaped unit cell are considered to demonstrate our approach. The commercial method of moment (MoM) based characteristic modes analysis tool (FEKO)³¹ is used to evaluate the eigenvalue, modal surface current distribution and modal weighting coefficient. The impedance matrix is extracted and used to evaluate 105 the stored energy.

II. FORMULATION FOR MODAL STORED ENERGY EVALUATION BASED ON THEORY OF CHARACTERISTIC MODES

The modal stored energy formulation is based on the Theory of Characteristic Modes (TCM) which represents 130 a structure in terms of its surface impedance Z^{14} . The surface impedance Z is given as:

$$Z = R + jX, \quad (1)$$

where R is the real part and X is the imaginary part of the impedance. Using the derived impedance Z , a solution is found for the generalized eigenvalue equation given in equation (2) as:

$$[X][I] = \lambda_n[R][I], \quad (2)$$

110 where λ_n is the eigenvalue of each n mode and I is the eigen-current.

Although this paper uses TCM based method for the presented formulation of the modal stored energy, TCM is not explicitly dealt here and can be found in the literature^{14,15,32,33}. The value of λ_n is directly related to the nature of the modal stored energy by the imaginary part of the impedance matrix X with λ_n greater than zero indicating a stored magnetic energy, λ_n less than zero indicating a stored electric energy and λ_n equal to zero indicating that both the magnetic energy and electric energy are of equal magnitude which results in total radiation with no stored energy^{2,15,34}. This modal stored energy deductions are however only qualitative¹⁴. On the other hand, modal quantitative stored energy value of MTM inclusion provides a new way to reliably analyze 115 artificial materials. This would aid their choice for specific applications especially in cases where the near-field behaviour needs to be predicted such as its association to antennas¹⁰ and sensors.

Using the surface impedance Z derived from TCM, the modal stored energy operator (W_{sto}) derived in^{35,36} and as applied to antenna design² is:

$$W_{sto} = W_m + W_e = \frac{1}{4\omega} I^H X' I, \quad (3)$$

where ω is the angular frequency, I is the eigen-current from the generalized eigenvalue equation, I^H is the Hermitian transpose of the eigen-current and X' is given in² as equation (4):

$$X' = \omega \frac{\partial X}{\partial \omega}. \quad (4)$$

Separating W_{sto} into electric energy (W_e) and magnetic energy (W_m) component², we have equation (5) and (6):

$$W_m = \frac{1}{8\omega} I^H X_m I, \quad (5)$$

and

$$W_e = \frac{1}{8\omega} I^H X_e I, \quad (6)$$

where,

$$X_m = X' + X, \quad (7)$$

and

$$X_e = X' - X. \quad (8)$$

X being a 3D matrix complicates the implementation of X' , thus further simplification is carried out by splitting the impedance Z into its inductive and capacitive component as:

- For X as an inductive impedance:

$$X = \omega L, \quad (9)$$

differentiating both sides with respect to ω ,

$$\frac{\partial X}{\partial \omega} = L. \quad (10)$$

But from equation (4),

$$X' = \omega \frac{\partial X}{\partial \omega}$$

substituting equation (10) into equation (4),

$$X' = \omega \frac{\partial X}{\partial \omega} = \omega L, \quad (11)$$

therefore substituting equation (9) into equation (11),

$$X' = X. \quad (12)$$

- For X as a capacitive impedance:

$$X = \frac{-1}{\omega C}, \quad (13)$$

differentiating both sides with respect to ω ,

$$\frac{\partial X}{\partial \omega} = \frac{1}{C\omega^2}. \quad (14)$$

But from equation (4),

$$X' = \omega \frac{\partial X}{\partial \omega}$$

substituting equation (14) into equation (4),

$$X' = \omega \frac{\partial X}{\partial \omega} = \omega \frac{1}{C\omega^2} = \frac{1}{C\omega}, \quad (15)$$

therefore substituting equation (13) into equation (15),

$$X' = -X. \quad (16)$$

135 The conclusion therefore is that X' equals $|X|$ and the two possible analytical solution for X' depends on the nature of W_{sto} as either electric or magnetic. This conclusion has been qualitatively concluded using the first derivative of λ_n with respect to the frequency²¹.

140 To ensure uniformity of the modal stored energy value, just as it is done for W_{sto} in antenna applications for evaluation of Q-factor, W_m and W_e are normalized with respect to the radiated power (P_r)^{2,20,37} in equation (17):

$$P_r = I^H R I. \quad (17)$$

145 III. EVALUATION AND ANALYSIS OF MODAL STORED ENERGY OF MTM INCLUSION

In this section, the W_{sto} formulation is applied to MTM inclusions to determine their modal magnetic and electric energies. The difference between the magnetic and electric energy ($W_m - W_e$) is used to determine the dominant energy with zero value indicating a vanishing energy (resonance)³⁴. Two elementary inclusions with known effective parameters are considered; the Broadside-Coupled Split-Ring Resonator (BC-SRR) and the S-shaped inclusion. While the BC-SRR is a well known and extensively studied magnetic MTM inclusion, the S-shaped inclusion exhibit both the electric and magnetic behaviour at different resonant frequencies. The analysis for the structures are done in the frequency range of 1 GHz to 4 GHz to cover the resonance of both inclusions.

150 III.A. Broadside-Coupled Split-Ring Resonator (BCSRR)

The BC-SRR which is known to exhibit artificial magnetism is made up of two circular symmetric loops of PEC material and placed on the two opposite sides of a teflon substrate of effective permittivity, ϵ_r 2.2. It resonate at 2.35 GHz and its dimension is given in figure 1.

155 The artificial magnetic behavior of this BC-SRR was shown by Rabah et al.¹⁹ using characteristic modes and static polarizability. The TCM commercial software was used for the modal analysis of the structure to solve the generalized eigenvalue equation and the obtained result of the TCM analysis for the structure is represented by 175

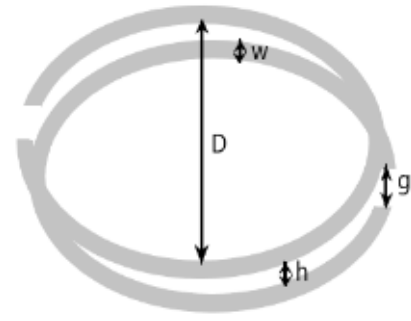
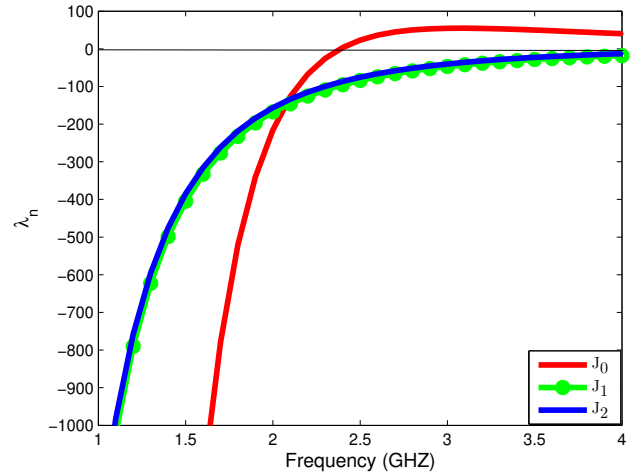
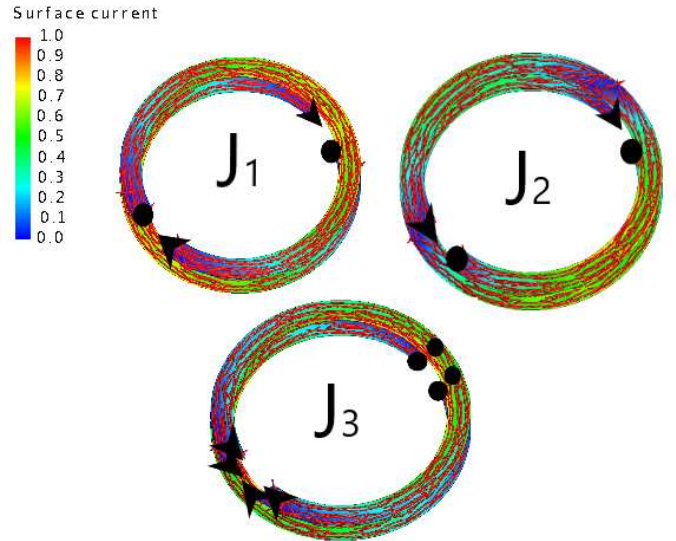


FIG. 1: BC-SRR with dimensions: $D = 11.25$ mm, $W = 1$ mm, $g = 1.95$ mm, $h =$ substrate height $= 1.08$ mm.



(a)



(b)

FIG. 2: BC-SRR inclusion: (a)eigenvalue (λ_n) with respect to frequency (b)surface current distribution

the plot of λ_n with respect to frequency in figure 2a and the surface current distribution in figure 2b.

Only the fundamental mode J_0 in red cross the zero mark at 2.35 GHz as shown in figure 2a hence, only one resonance occur. The W_e and W_m are of equal magnitude and no energy is stored at this frequency of 2.35 GHz. Also, this resonance frequency of 2.35 GHz is close to that of the BC-SRR analyzed by Rabah et al.¹⁹ which was referred to as the fundamental DC mode of a circular loop. The other modes J_1 and J_2 in green and blue have negative values of λ_n through out the considered frequency band and indicates that they store more W_e . From the current profile shown in figure 2b, the black arrow head show the direction of the current flow, the black dot show the starting point of the current flow. The behaviour of the modes can be easily described as magnetic or electric. J_0 show a magnetic current distribution with both loops having similar direction of current flow while J_1 and J_2 show a current distribution pattern similar to that of an electric dipole with the current flowing in the opposite direction on both loops.

To quantify the energies with respect to frequency for each mode, the impedance matrix is extracted from the commercial software and the W_{sto} formulation of section II is applied to determine the modal magnetic and electric energies. The result of the dominant energy is represented by the normalized $(W_m - W_e)$ with respect to frequency in figure 3.

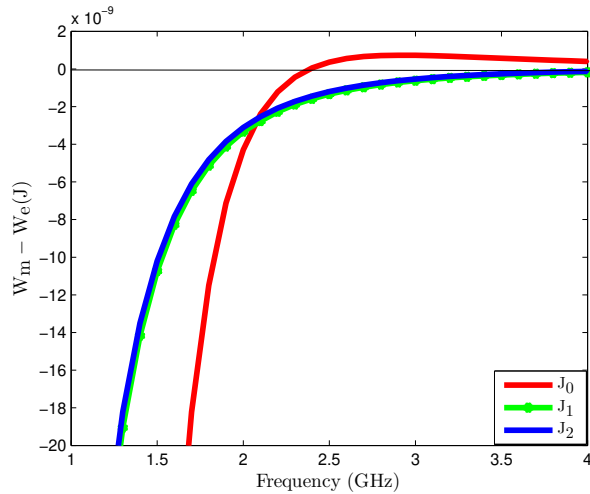


FIG. 3: Normalized $(W_m - W_e)$ with respect to frequency of BC-SRR.

The value of W_e and W_m are equal at 2.35 GHz for mode J_0 in red thus, the value of normalized $(W_m - W_e)$ is 0 J at this frequency. J_1 and J_2 in green and blue both have negative values of $(W_m - W_e)$ within the considered frequency band and implies that W_e remains greater than W_m . The $(W_m - W_e)$ quantity agrees with the qualitative deductions of the eigenvalue (λ_n) curve.

III.B. S-shaped MTM inclusion

The S-shaped inclusion exhibit both the electric and magnetic behaviour due to its bianisotropic character³⁸. It is made of a PEC sheet forming an S-shape and its dimensions are shown in figure 4.

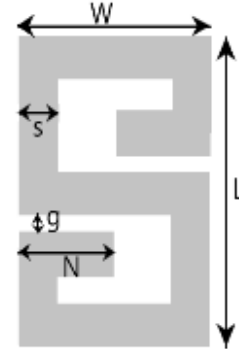


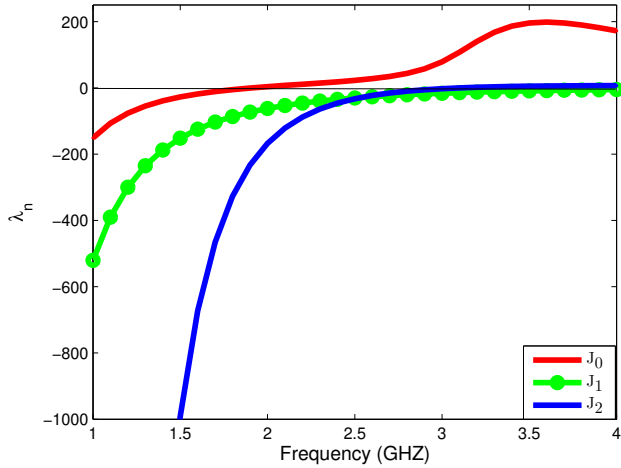
FIG. 4: S-shaped inclusion with dimensions: $L = 27$ mm, $W = 13$ mm, $g = 1.1$ mm, $N = 4$ mm, $s = 1.5$ mm.

The S-shaped structure has its fundamental resonance at 1.92 GHz. The same analysis followed for the BC-SRR inclusion was carried out for the S-shaped inclusion. The TCM commercial software was used for the modal analysis of the structure and the obtained result of the TCM analysis is represented by the plot of λ_n with respect to frequency in figure 5a and the surface current distribution in figure 5b.

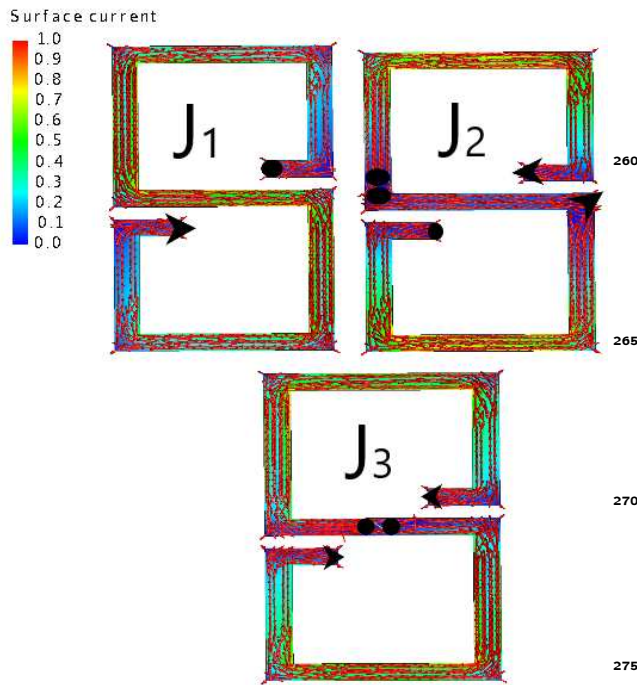
J_0 and J_2 of figure 5a in red and blue cross the zero mark at 1.92 GHz and 3.1 GHz respectively. This corresponds to the resonance frequencies and indicates that W_e and W_m are of equal magnitude at these frequencies and no modal stored energy. J_1 on the other hand remains with negative values of λ_n with respect to the considered frequency band implying that W_e is dominant. The behaviour of the modes as electric or magnetic can also be analyzed using the surface current distribution in figure 5b. The black arrow head show the direction of the current flow and the black dot shows its starting point. The current distribution of J_0 is similar to that of an electric dipole with the current flowing in one direction. J_1 also show an electric dipole current distribution splitted into two halves with the current flowing in opposite directions on the two halves. J_2 show a magnetic current distribution with the current flowing in the same direction when the S-shape is split into two equal halves.

To quantify the modal energies with respect to frequency for each mode, the impedance matrix is extracted from the commercial software and the W_{sto} formulation of section II is applied to determine the modal magnetic and electric energies. The result of the dominant energy is represented by the normalized $(W_m - W_e)$ with respect to frequency in figure 6.

J_0 and J_2 of figure 6 in red and blue show that at the resonance frequency of 1.92 GHz and 3.1 GHz respectively, $(W_e - W_m)$ is 0 J and the magnitude of W_m and



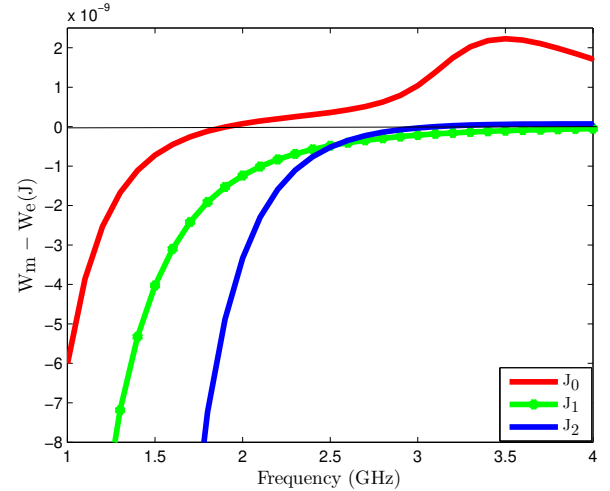
(a)



(b)

 FIG. 5: S-shaped inclusion: (a)eigenvalue λ_n with respect to frequency (b)surface current distribution

W_e are of the same value. The region of the curve that lies in the negative part indicates that W_e is dominant while the region in the positive part indicates that W_m is dominant. J_1 in green has negative values across the considered frequency band hence, W_e is dominant across the considered frequency band. The $(W_m - W_e)$ quantity agrees with the qualitative deductions of the eigenvalue (λ_n) curve.


 FIG. 6: Normalized $(W_m - W_e)$ with respect to frequency of S-shaped inclusion.

IV. COMPARISON BETWEEN STORED ENERGY AND EFFECTIVE PARAMETERS OF MTM INCLUSION

Generally, the physical behaviour of MTM are described in terms of effective parameters^{39–42}. The later are calculated from far-field complex reflection and transmission coefficient^{41,42} using classical approach of extraction techniques^{40,43,44}. The effective parameters of MTM structures are represented as the permittivity ϵ and permeability μ values which describes them as electric or magnetic MTM⁴⁵. If this provides physical insight, the association of MTM to devices at microwave frequencies in the near-field region such as for antenna and sensor designs^{46–48} can not be studied in a reliable manner based on effective parameters.

Modal stored energy on the other hand is a quantity derived from modal current and account for near-field effects¹. It permits studying the behaviour of shapes separately from its feeding structure. This means that the modal quantities of the structure is calculated once while the effect of the feeding can be superimposed^{20,49}. The modal stored energy being quantitative and independent of excitation is believed to be a more reliable analysis of MTM since the properties of MTM are based on their shapes⁵⁰.

In this section, we present a comparison between the effective parameter and the dominant stored energy such that within a given frequency band, one can appreciate the convergence in terms of physical and qualitative analysis. Most inclusions especially magnetic inclusion have their magnetic properties exhibited when excitation is placed in a specific polarization¹⁹. The TCM based energies W_m and W_e are excitation and polarization independent whereas, the effective parameters are excitation and polarization dependent. To enable a comparison between the two approach, new steps are introduced to the

295 calculation of the differential stored energies (i.e. W_m
 - W_e) to account for the polarizability of the inclusions.
 Additional steps are introduced to the calculation of (W_m
 - W_e) in figure 7. 335

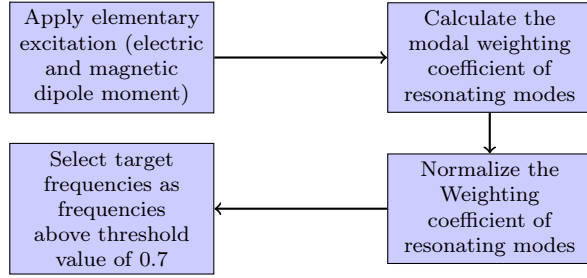


FIG. 7: Additional steps for calculating ($W_m - W_e$).

300 The block diagram in figure 7 describes the procedure
 to take into account the effect of excitation and polariza-
 tion in the modal stored energy analysis of MTM inclu-
 sion. First, an elementary excitation (electric and mag-
 netic dipole moment) is applied to the structure and the
 modal weighting coefficient MWC_n ¹⁴ is derived from the
 TCM based commercial software where MWC_n is given
 305 as equation (18):

$$MWC_n = \frac{V^i J_n}{1 + j\lambda_n}, \quad (18)_{340}$$

where V^i is the applied excitation, λ_n is the eigenvalue
 and J_n is the surface current of the n^{th} mode.

310 The MWC_n give information of the modal response
 to the applied excitation. The MWC_n of the resonant
 modes are normalized with their maximum value. Stored
 energy is related to bandwidth by Q-factor definition^{51,52}
 hence, we evaluate the modal half power bandwidth using
 the TCM bandwidth definition. This represents the
 315 region of frequencies that participate in radiation and
 is given as frequencies with a modal significance above
 0.7¹⁵. The dominant energy within the modal bandwidth
 (i.e. having a value above 0.7 of the normalized MWC_n)
 are considered and referred to as target frequencies. They
 320 account for the behaviour before and after the resonance
 frequencies which are important for electromagnetic ap-
 plications. To quantitatively describe an inclusion, the
 dominant energy ($W_m - W_e$) within the target frequen-
 cies are summed up and the sign of the summation indi-
 325 cates the dominant energy within the modal bandwidth
 of the structure. It tells if the inclusion is electric or mag-
 netic. A positive value, indicates dominant W_m and the
 inclusion is magnetic while a negative value, implies that
 W_e is dominant and the inclusion is electric. 360

330 This procedure is applied to the inclusions whose dom-
 inant modal energy values ($W_m - W_e$) were evaluated in
 the previous section. 365

IV.A. Broadside Coupled Split Ring Resonator (BCSRR)

The BC-SRR is excited with a magnetic dipole mo-
 ment and only the resonant mode J_0 is considered. The
 normalized MWC_n with respect to frequency extracted
 from the TCM based simulation software is shown in fig.
 8.

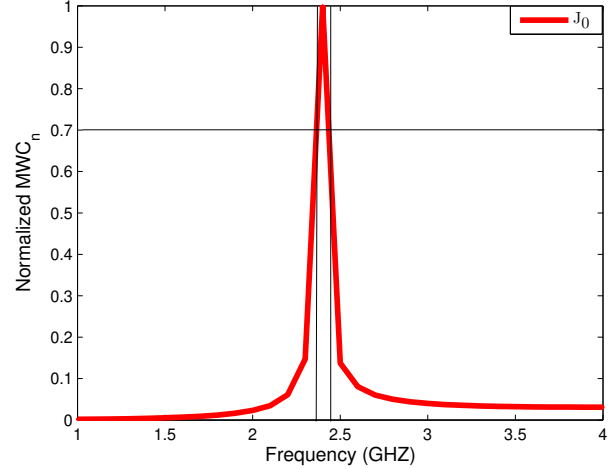


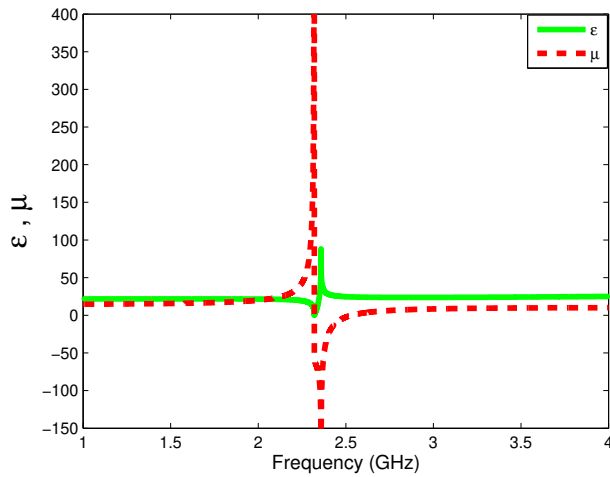
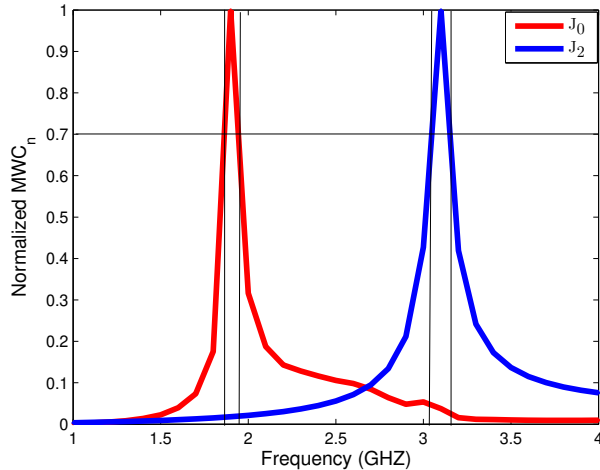
FIG. 8: Normalized MWC_n with respect to frequency of
 BC-SRR.

The horizontal thin black line in figure 8 show the
 threshold value of 0.7 which indicates the region of the
 target frequencies between 2.35 GHz and 2.43 GHz. The
 shift of the centre frequency from the resonance is due to
 the coupling of the excitation with the structure. The
 summation of the normalized ($W_m - W_e$) at the target
 frequencies from the previous section for the BC-SRR is
 4.1969×10^{-10} J. The value is positive hence, one can
 conclude that J_0 of BC-SRR exhibits a magnetic behav-
 iour and therefore it is a magnetic inclusion. This analysis
 agree with the current profile of BC-SRR. In comparison
 to the classical approach of effective parameters of the
 BC-SRR, the plot of effective parameters (ϵ and μ) with
 respect to frequency is shown in figure 9.

ϵ and μ in green and red respectively give informa-
 tion of the dominant property of the BC-SRR. Around
 the resonance frequency of 2.35 GHz, the values of μ are
 higher than that of ϵ and the magnetic behaviour of the
 structure dominates thus, the inclusion is magnetic. This
 qualitative description is in agreement with that of the
 dominant stored energy analysis.

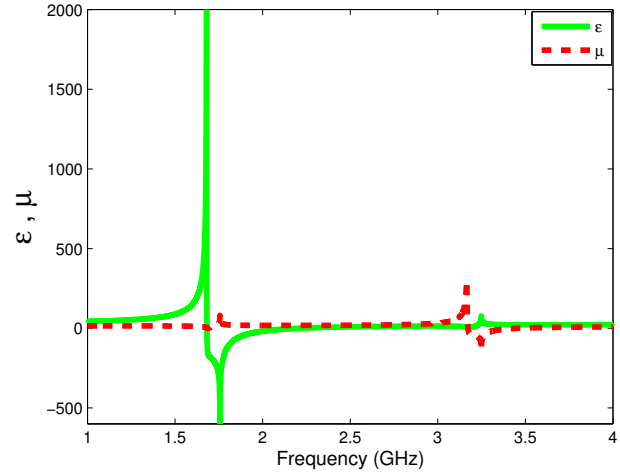
IV.B. S-shaped MTM inclusion

The S-shaped inclusion has two resonant modes J_0 and
 J_2 with different behavior. The S-shaped inclusion is ex-
 cited with an electric dipole moment and the normal-
 ized MWC_n with respect to frequency which has been
 extracted from the TCM based simulation software is
 shown in figure 10.


 FIG. 9: ϵ and μ with respect to the frequency of BC-SRR.

 FIG. 10: Normalized MWC_n with respect to frequency of S-shaped inclusion.

The horizontal thin black line in figure 10 show the threshold value of 0.7 which indicates the region of the target frequencies between 1.86 GHz and 1.94 GHz for mode J_0 in red and between 3.05GHz and 3.2 GHz for mode J_2 in blue. The shift of the centre frequency from the resonance frequency is due to the coupling of the excitation with the structure. The summation of the $(W_m - W_e)$ values at the target frequencies from the previous section for the S-shaped inclusion is -1.2×10^{-10} J and 2.5545×10^{-11} J for J_0 and J_2 respectively. The value for J_0 is negative indicating that the inclusion behave as an electric structure around the first resonance. J_2 has a positive value which implies that the inclusion behave as a magnetic structure at its second resonance. This analysis agree with the current profile of the S-shaped inclusion. In comparison to the classical approach of effective parameters of the S-shaped inclusion, the plot of

effective parameters (ϵ and μ) with respect to frequency is shown in figure 11.


 FIG. 11: ϵ and μ with respect to the frequency of S-shaped inclusion.

ϵ and μ in green and red respectively give information of the dominant property of the S-shaped inclusion. Around the fundamental resonance frequency of 1.92 GHz, the values of ϵ are higher than that of μ and the electric behaviour dominates the magnetic behaviour hence, the structure behave as an electric inclusion. On the other hand, the values of μ are higher than that of ϵ at the second resonance of 3.01 GHz and the structure behave as a magnetic inclusion at this frequency. This qualitative description is in agreement with that of the dominant stored energy analysis for the S-shaped inclusion.

V. CONCLUSION

In comparison to the effective parameters approach of defining metamaterial inclusions which are valid in the far-field region and may not be reliable for near-field analysis and modal design of electromagnetic devices, this paper presents a modal stored energy approach which is based on modal current and account for near-field effects. This method can be applied to any resonant metamaterial structure and it is based on the theory of characteristics modes which is independent of excitation and brings physical insight into the resonant property of a structure. Two elementary inclusions, BC-SRR and S-shaped inclusions were considered for demonstration. Also, a comparison between the effective parameters and the modal stored energy approach is done to show the convergence in terms of physical and qualitative analysis. This comparison is achieved by introducing additional steps into the calculation of modal stored energy to take into account the polarization and excitation dependence of inclusions. Both methods show good agreement in their physical and qualitative analysis. This approach

is useful in the application of modal analysis for design-485
 ing metamaterial-inspired structures including antenna,
 sensor and cloaks.

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