# Numerical Studies of Vane-type Fishnet Metamaterial Structure

Purushothaman Narasimhan
Academy of Scientific and Innovative Research (AcSIR), CSIR-HRDC, Ghaziabad – 201002, Uttar Pradesh

Microwave Wave Devices Area, CSIR-Central Electronics Engineering Research Institute (CEERI)
Pilani - 333031, Rajasthan, India.
e-mail: purushothaman.n@gmail.com

S. K. Ghosh
Academy of Scientific and Innovative Research (AcSIR), CSIR-HRDC, Ghaziabad – 201002, Uttar Pradesh

Microwave Devices Area, CSIR- Central Electronics Engineering Research Institute (CEERI)
Pilani - 333031, Rajasthan, India.
e-mail: ghoshskdr@gmail.com

*Abstract*— **Numerical studies of vane-type, double negative, fishnet metamaterial structure is presented. The constitutive electromagnetic parameters of the double-sided vane-type structure are extracted through both Kramers-Kronig (K-K) method and the parameter fitting of dispersive models (PFDM) method. The designed metamaterial structure is shown to exhibit negative refractive index, approximately, from 15-16 GHz with the lowest refractive index of -10.53 at 15.4 GHz. The double negative behavior in this frequency range is further confirmed through the simulation of the equivalent bulk medium of the designed metamaterial structure in a wedge-shaped structure. The negative refraction exhibited by the equivalent bulk medium in the wedge-shaped structure is also shown and discussed.**

***Keywords-double negative; fishnet; vane-type; PFDM; Kramers-Kronig;***

## I. INTRODUCTION

The first left-handed (LH) or double-negative (DNG) metamaterial structure was realized using split-ring resonators (SRRs) for achieving negative permeability through magnetic resonance and thin wires (TWs) for achieving negative permittivity by reducing the plasma frequency of metallic structures to microwave frequency range. This was followed by cut-wire pairs (CWPs) which were made of finite length wire pairs on top of one another separated by a dielectric spacer. The CWPs are essentially straightened out SRRs. These were found to replace SRRs in achieving negative permeability [1]. Also, the CWPs had a distinct advantage over SRRs in that they could be excited with electromagnetic radiation incident perpendicular to the plane consisting of the CWPs. Later, the CWPs were combined with continuous wires to achieve LH behavior [2]. The CWPs were then transformed into short slabs with continuous wires thus paving way for fishnet metamaterial structures [3]. Several variations of this fishnet structure have been realized since then [4-7]. The double-sided, vane-type fishnet structure presented in this paper is based on the cross-cylinder fishnet structure described in [7]. In this work, the simple cross structure has been modified by a multiple vane-type structure. This vane-type model has a higher symmetry and can also work with arbitrary polarization.

## II. VANE-TYPE FISHNET STRUCTURE

### *A. Simulation*

The unit cell of the vane-type fishnet structure is shown in fig. 1. The width of the vane (w) is 0.50 mm. The ratio of the radius of the cylindrical disc ($r_d$) and the unit cell length ($a_x = a_y = a$) is 0.62. The substrate has a relative permittivity ($\varepsilon_r$) of 9.4 with a loss tangent (tan δ) of 0.0004. The thickness of the substrate and the metallic inclusion are 0.50 mm and 0.03 mm respectively.

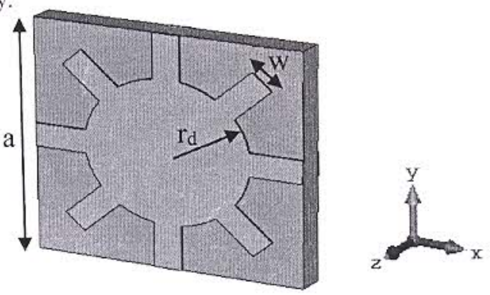



Figure 1. Unit cell of a double-sided vane-type fishnet structure (identical structure on the back of the substrate)

The unit cell has been simulated using the frequency domain solver of CST Microwave Studio [8].

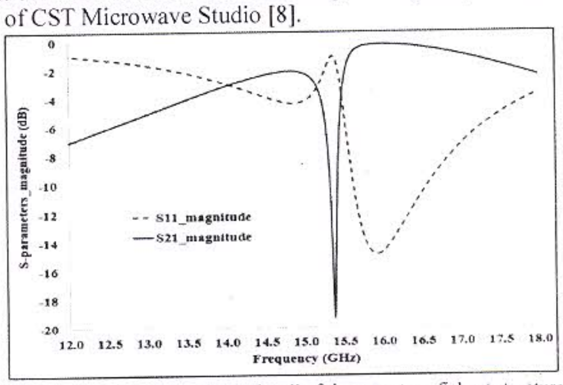



Figure 2. S-parameters of the unit cell of the vane-type fishnet structure

The structure was stimulated using plane wave excitation with open boundary along propagation direction (*z*-direction) and floquet boundary in the transverse dimensions (*x*- and *y*-directions). S-parameters were obtained from the simulation.

The results of the simulation (fig. 2) show that $S_{21}$ rises between 15-16 GHz indicating transmission.

*B. Parameter Extraction*

The negative refractive index (NRI) behavior of the designed structure has been shown by the relative permittivity ($\varepsilon_r$) and relative permeability ($\mu_r$) extracted from the S-parameter data (fig. 2). Two approaches have been followed for the parameter extraction. One is the Kramers-Kronig (K-K) relation which has the advantage of solving the branching ambiguity that exists in the NRW approach [9]. The other method is the parameter fitting of dispersion models (PFDM) which, besides extracting $\varepsilon_r$ and $\mu_r$, also yields the parameters for bulk material modeling using Drude and Lorentz models [10]. The constitutive parameters extracted by the K-K method are shown in fig. 3.

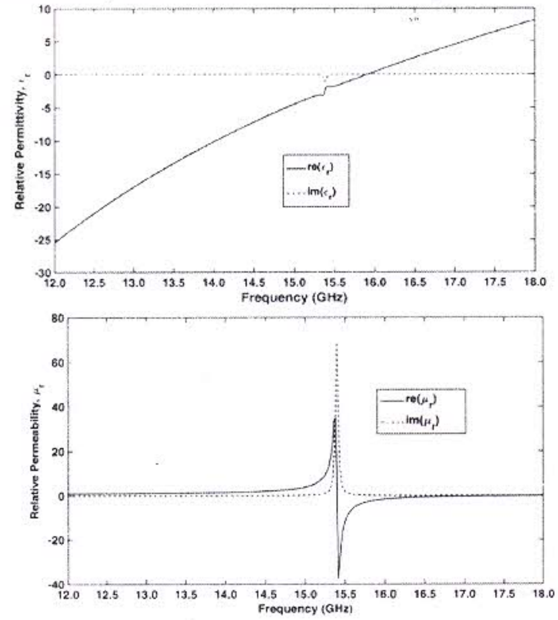


Figure 3. Real (solid) and imaginary (dotted) parts of $\varepsilon_r$ (top) and $\mu_r$ (bottom) extracted through K-K method

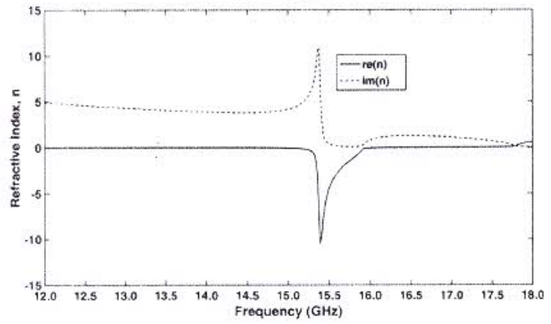


Figure 4. Refractive index of the vane-type fishnet structure

The refractive index (n) as seen in fig. 4 has a peak value of -10.53 at 15.4 GHz. However, the imaginary part of the refractive index is observed to be larger. This would result in higher loss.

The PFDM approach has been adopted to determine the equivalent bulk medium parameters. $\varepsilon_r$ is given by the Drude model as, $\epsilon_r(\omega) = \epsilon_\infty - \omega_p^2/\{\omega(\omega - i\nu_c)\}$ and $\mu_r$ is given by the Lorentz model as, $\mu_r(\omega) = \mu_\infty + (\mu_s - \mu_\infty)\omega_0^2/\{\omega_0^2 + i\omega\delta - \omega^2\}$. $\epsilon_\infty$ and $\mu_\infty$ are the high frequency limits of permittivity and permeability respectively. $\mu_s$ is the lower frequency limit of permeability, $\omega_p$ is the radial plasma frequency, $\nu_c$ is the collision frequency, $\omega_0$ is the radial resonant frequency, $\delta$ is the damping frequency and $\omega$ is the radial frequency. PFDM uses optimization algorithms to deduce the bulk medium parameters. In this work, genetic algorithm has been used for arriving at the coefficients of the Drude and Lorentz models. Through PFDM, the values of these parameters have been determined as follows: $\mu_s = 1.24, \mu_\infty = 1.09, \omega_0 = 96.68 \times 10^9\ \text{rad/s}, \delta = 1.26 \times 10^9\text{Hz}, \epsilon_\infty = 33.98, \omega_p = 58.79 \times 10^{10}\ \text{rad/s and}\ \nu_c = 1.25 \times 10^8\text{Hz}$. The bulk DNG medium thus modeled, when implemented in a wedge shaped structure, has been observed to exhibit negative refraction at 15.7 GHz as shown in fig. 5. Although the negative peak value of 'n' exists at 15.4 GHz, the imaginary part of 'n' is higher and the negative refraction is weak. Hence, a strong negative refraction is seen at a higher frequency of 15.7 GHz.

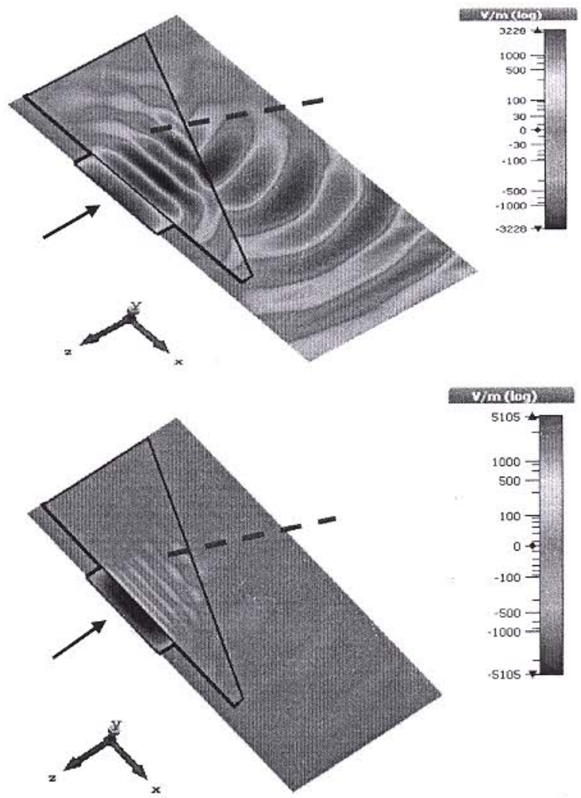


Figure 5. Equivalent homogeneous bulk medium of the vane-type fishnet structure modelled as a wedge. NRI observed at 15.7 GHz (top) and 15.4 GHz (bottom). Red dashed line – normal to the wedge, black solid line – direction of incidence.

This is also quantified by the figure of merit (FoM) which is defined as -real(n)/imag(n) and shown in fig. 6.

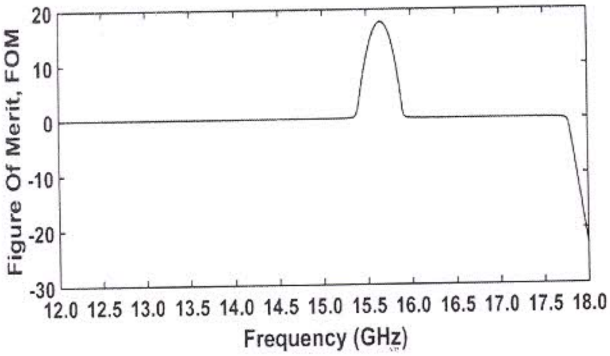



Figure 6. Figure of merit (FoM) of the vane-type fishnet structure

Although 'n' is at a minimum value at 15.4 GHz, due to the losses in the structure, FoM is at its highest at 15.66 GHz. The value of FoM at 15.66 GHz is 17.65.

The surface current distribution at 15.7 GHz (where both $\varepsilon_r$ and $\mu_r$ are negative) is shown in fig. 7. The current flow on both the sides of the structure are in the opposing directions indicating a strong diamagnetic response leading to negative permeability.

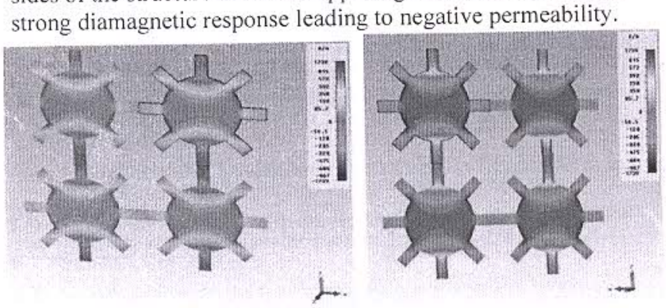
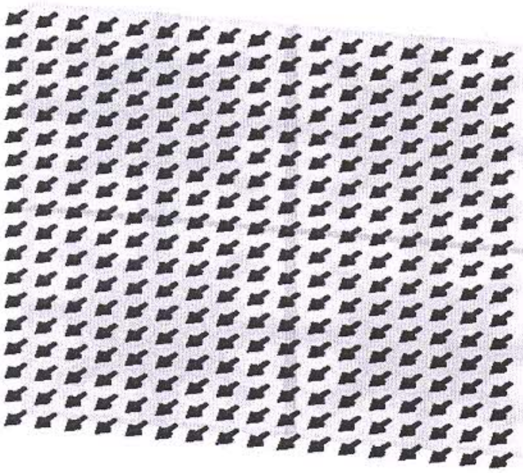
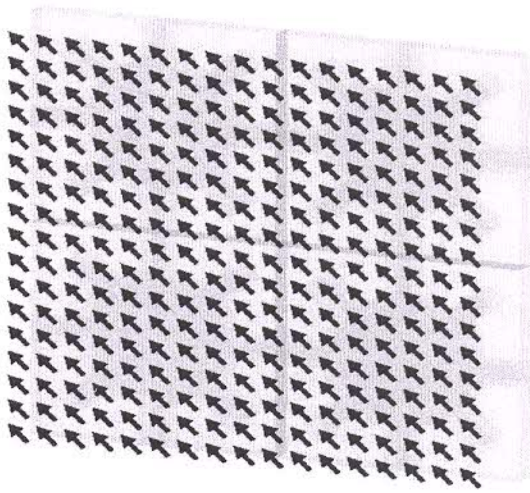


Figure 7. Surface current distribution at 15.7 GHz at the front (left) and back (right) sides of the designed fishnet structure



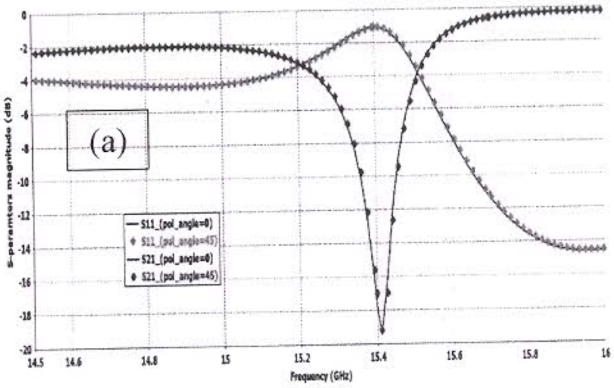
(a)

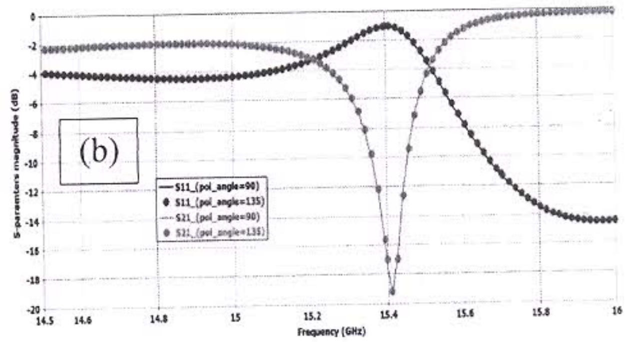


(b)

Figure 8. TE polarized plane wave excitation of the vane-type fishnet structure polarized at $135^0$. (a) E-field and (b) H-field. The unit cells are seen in the background.

The designed vane-type fishnet structure is also polarization insensitive. Due to the eight vanes oriented $45^0$ to each other, this structure exhibits identical response to TE and TM polarization, as well as for oblique polarization angles (shown in fig. 8 for TE case and angle $135^0$). The S-parameter response for different angles of polarization is shown in fig. 9. It can be seen that for polarization angles of $0^0$, $45^0$, $90^0$, $135^0$ and $180^0$, the response remains the same. This polarization insensitivity property also makes the vane-type fishnet structure a potential candidate as perfect absorber.



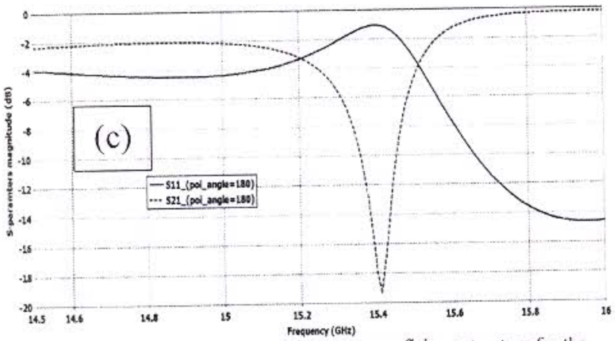



Figure 9. $S_{11}$ and $S_{21}$ response of the vane-type fishnet structure for the polarization angles, (a) 0, 45, (b) 90, 135 and (c) 180 degree

## III. CONCLUSION

A vane-type double negative fishnet structure has been designed and its constitutive electromagnetic properties have been extracted with a peak negative refractive index of -10.53 at 15.4 GHz. The designed structure has also been shown to exhibit negative refraction in the designed frequency range through the wedge experiment carried out through numerical simulation.

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