Enhancement of Relative Permittivity of Material with Metallic Inclusions – Experimental Verification

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***Abstract* — in this project, it was shown by simulation that the permittivity of a material could be enhanced by embedding metal inclusions in the host material. Later, a series of systematic experiments were carried out with free space material measurement equipment/system to demonstrate the enhancement of permittivity with circular metal patches printed periodically on a host material to validate the simulation results.**

Keywords— relative material permittivity, dielectric constant enhancement, free space material measurement, periodic metal patch in dielectric substrate, vector network analyzer

I. INTRODUCTION

Material's relative permittivity or dielectric constant is an electrical property of a material which determines how fast or slow an electromagnetic signal can travel through this material. This electrical property is considered as the key factor in the design process of many microwave devices such as filters, directional coupler, antennas etc. Material permittivity emerges from the separation or polarization of charges in atoms under the influence of external alternating electromagnetic field. There are numerous publications to report enhancement of dielectric constant by doping microscopic impurities in the host material through costly chemical processes [1-6]. However, recently it was reported by simulation that dielectric constant was increased by embedding metal inclusions in the host material [7-11]. In this project, enhancement of material's relative permittivity or dielectric constant was realized by adding metal patterns externally on the host material with the advantage of being able to tune the material permittivity to any value practically.

II. THEORY

Under the influence of external alternating electric field ***E***, there occurs separation of charges in every atom as shown in Fig. 1. If every atom has positive charge $+q$ at one end then other end must have charge $-q$ and if the separation between $+q$ and $-q$ is d, then dipole moment or polarization from each atom is $p = qd$. Therefore, total polarization can be estimated as the summation of all individual atom's polarizations and can be expressed by the following eq. (1).

$$P = \sum qd \qquad (1)$$

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Relative permittivity or dielectric constant ϵ_r is proportional to total polarization P as expressed in the following eq. (2).

$$\epsilon_r \propto P \qquad (2)$$

Now, let's consider there is a metal pattern on the material as shown in Fig.2. The metal pattern has free valence electrons and those free electrons get polarized under the influence of external alternating electric field and give rise to additional polarization QD where Q is the magnitude of polarized charged at one end and D is the distance between the polarized charges.

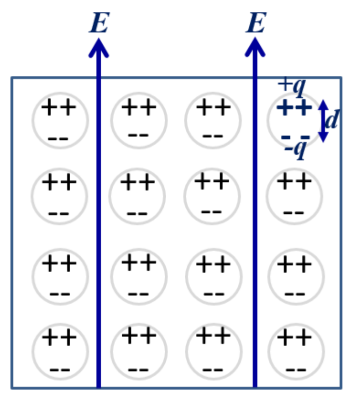


Fig. 1. Polarization of charges in atoms due to external alternating electric field

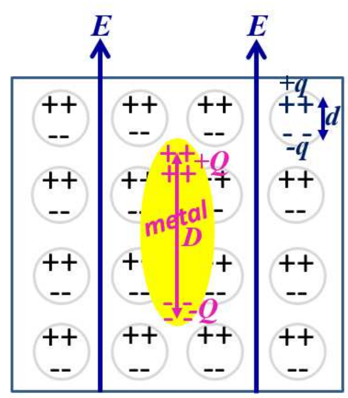


Fig. 2. Polarization of charges in atoms and metal inclusion due to external alternating electric field

With metallic inclusion, total polarization is now increased as shown in eq. (3).

$$P_{total} = P + QD \qquad (3)$$

As a result, overall or effective relative permittivity is also increased as shown in eq. (4).

$$\epsilon_r^{eff} \propto (P + QD\ ) \qquad (4)$$

III. Simulation

3D electromagnetic simulation software HFSS was used in simulation. 14 inch x 14 inch FR4 dielectric substrate with relative permittivity 4.4 and thickness 0.79 mm was considered for simulation. Three FR4 substrates with circular metal patches of diameter 1mm, 3mm and 5mm respectively printed periodically on those were considered for modeling in HFSS. Final sample was constructed with two 14 inch x 14 inch substrates, one of which was with metal patches printed on it and other one was just a plain substrate with no metal on it and sandwiching those together as shown in Fig 3(*b*). In this periodic structure, lattice constant 8.08 mm was considered in length and width direction. In the thickness direction, lattice constant (*d*) was considered (0.79mm + 0.79mm + 0.035mm for copper patch thickness) 1.61mm as evident in Fig 3(*b*).

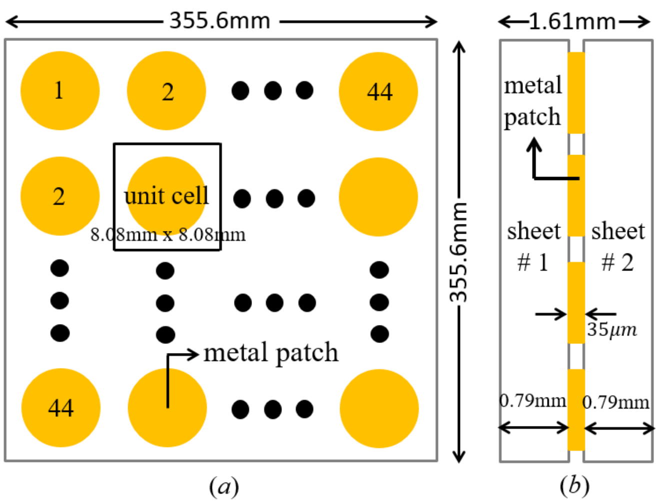


Fig. 3. Schematic demonstration of host dielectric substrate FR4 and metal patches printed periodically on it for HFSS modeling. (*a*) Top view, (*b*) side view

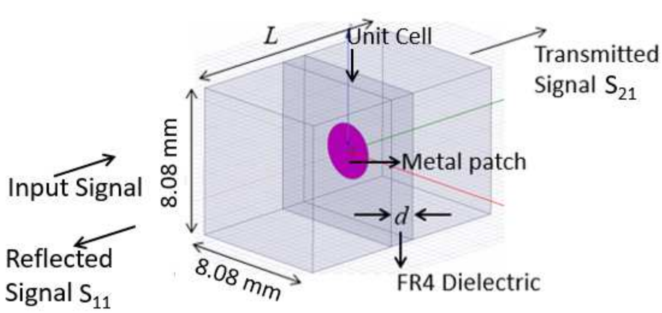


Fig. 4. HFSS simulation arrangement showing a unit cell with all physical parameters along with reflection (S_{11}) and transmission (S_{21}) coefficient

This is worth to mention here that all the numbers and dimensions mentioned above were decided by taking into consideration the following constraints: (a) available capacity of vendor company (sunstone.com) in substrate fabrication (b) frequency limits of the existing experimental system which can cover X band from 8 GHz to 12 GHz, (c) avoidance of half wave resonance phenomenon in the circular metal patch at the highest frequency of X band 12 GHz, (d) to have integer number (44 here) of unit cells in the 14 inch x 14 inch board.

The simulation arrangement was shown in the Fig.4 where unit cell dimension was 8.08mm x 8.08mm in *x* and *y* direction and 1.61mm (as explained before) was in the direction of plane wave propagation. The unit cell was placed inside a parallel plate waveguide (of length *L*) for plane wave excitation with electric field polarized in *y* direction. Now, if reflection and transmission coefficients are S_{11} and S_{21} at angular frequency w at the ports respectively, then effective relative permittivity or dielectric constant ϵ_r^{eff} of the material inside the unit cell can be calculated using the following eq. (5) [12].

$$S_{21}S_{12} - S_{11}S_{22} = \frac{\exp\left(\frac{-j2\omega d\sqrt{\epsilon_r^{eff}}}{c}\right) - \left(\frac{1-\sqrt{\epsilon_r^{eff}}}{1+\sqrt{\epsilon_r^{eff}}}\right)^2}{1 - \exp\left(\frac{-j2\omega d\sqrt{\epsilon_r^{eff}}}{c}\right) \times \left(\frac{1-\sqrt{\epsilon_r^{eff}}}{1+\sqrt{\epsilon_r^{eff}}}\right)^2} \times \exp\left(\frac{-j2\omega(L-d)}{c}\right) \qquad (5)$$

For a symmetric unit cell, as in this case, $S_{21}=S_{12}$ and $S_{11}=S_{22}$.

Figure 5 showed simulated effective relative permittivity at 10 GHz (midpoint frequency of X band) with metal patch diameter 1mm, 3mm and 5mm using speed of light $c = 3\text{x}10^8$ m/s, length of parallel plate waveguide L = 11.61mm and thickness of unit cell d=1.61mm.

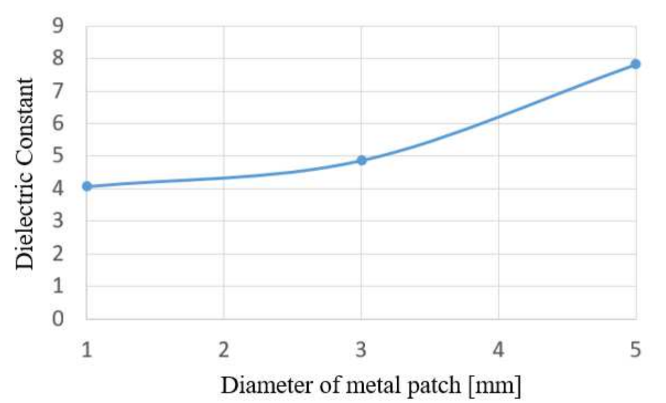
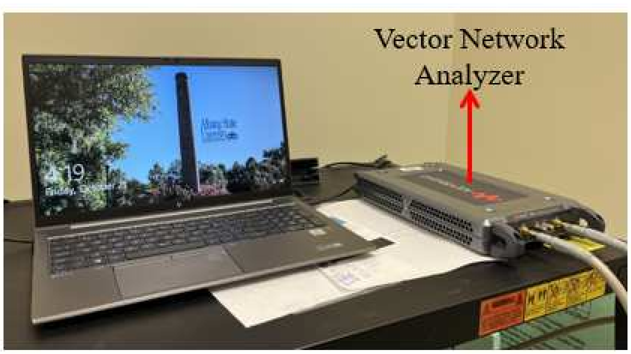


Fig. 5. Simulated effective relative permittivity at 10 GHz frequency for metal patch diameter 1mm, 3mm and 5mm

IV. EXPERIMENT

Metal patches were printed on FR4 substrate by Sunstone.com Company. Free space material measurement equipment/system from KEYSIGHT Technologies was used to determine the sample's overall or effective relative permittivity within the frequency of X band 8 GHz to 12 GHz. Figure 6 showed the components and set up of this material measurement system. Two antennas (Fig. 6*a*) were connected to two ports of a Vector Network Analyzer (VNA) (Fig. 6*b*) which was equipped with a Notebook computer to record reflection (S_{11}) and transmission (S_{21}) coefficient data for calculation of effective relative permittivity of the sample.

(*a*)



(*b*)

Fig. 6. Free space material measurement system for determination of material's relative permittivity (*a*) sample and two antennas, (*b*) Vector Network Analyzer

Experimental samples were prepared by sandwiching one printed substrate and one plain substrate together as shown in Fig. 3(*b*). To check the functionality and accuracy of the whole system, a Teflon sample whose dielectric constant was known to be 2.1 was used first in material parameter extraction. Experimentally determined dielectric constant of Teflon was around 1.9 which was slightly less than 2.1 as shown in Fig. 7. Figure 7 also showed experimentally extracted effective dielectric constant of FR4 substrate with circular metal patch of diameter 1mm, 3mm and 5mm. Finally dielectric constant of plain FR4 substrate was also determined to demonstrate the enhancement of dielectric constant due to the inclusion of metal patches of various sizes.

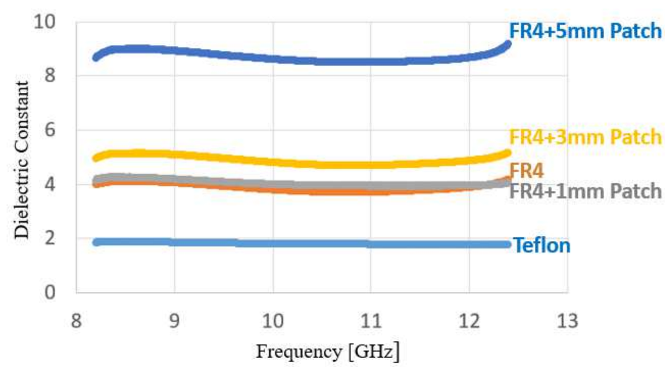


Fig.7. Experimental demonstration of dielectric constant enhancement due to inclusion of metal patches of diameter 1mm, 3mm, and 5mm

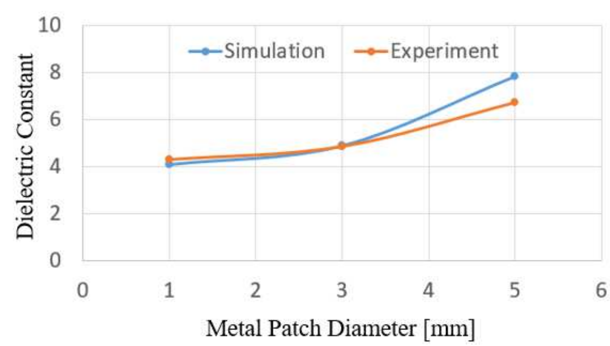


Fig. 8. Comparison between simulated and experimentally determined dielectric constant of FR4 substrate with metal patches of different diameters embedded in the host material

So far material permittivity was extracted using one sample with dimension 355.6mm x 355.6mm x 1.61mm and 44x44=1936 metal patches as shown in Fig. 3. Sample's material permittivity is actually the average effect all types of polarizations such as microscopic polarizations from host atoms and macroscopic polarizations from metal patches as discussed earlier in this paper. Now a legitimate question might arise whether one sample could provide a stable value of permittivity. To address this issue, let's estimate the number of atoms in host material and number of metal patches. If the average diameter of an atom is in the order of 10^{-10} m, then the number of atoms in the host material could be estimated 2.6×10^{19} and this huge number could be thought enough to give a stable permittivity value. But the number of metal patches in the sample was only 1936 which apparently might not be enough to contribute a stable value in the overall effective permittivity. To get more information in this matter, material permittivity (with 3mm diameter metal patch) was extracted using two layers together and then three layers together as shown in Fig. 9. Of course, experiment with one layer was already done before (Fig.7) and displayed again in Fig. 10 along with results from two layers together and three layers together for comparison.

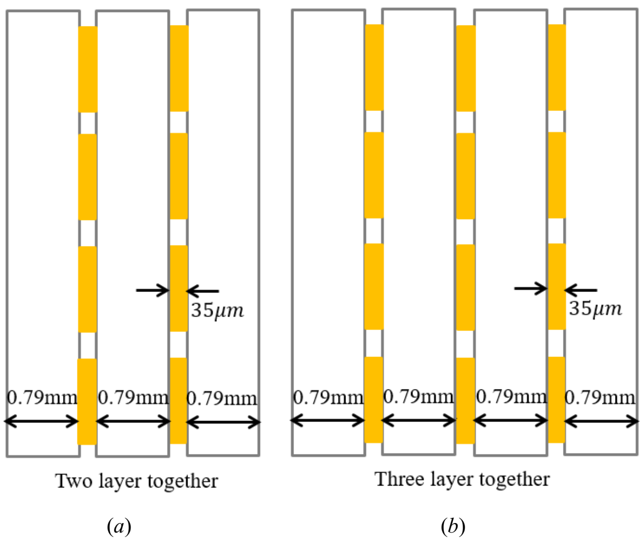


Fig. 9. Schematic diagram of samples (*a*) two layers together (*b*) three layers together

It was evident from Fig. 10 that effective relative permittivity for one layer, two layers and three layers (with metal patches) were almost same ranging between 5 and 6. Therefore, one could safely assume that 1936 metal patches on one layer were enough to provide a stable permittivity value when current experimental system were used.

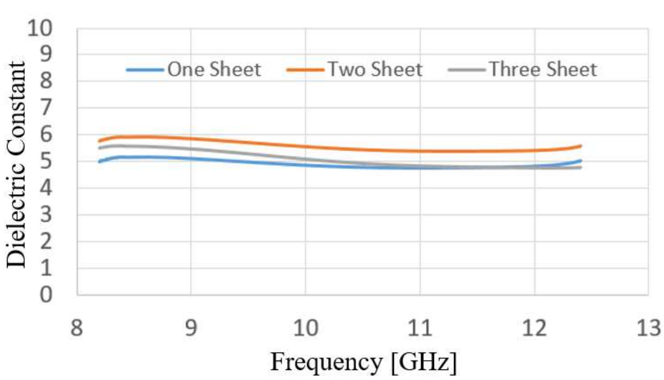


Fig. 10. Experimentally determined effective permittivity of one layer, two layers together and three layers together with 3 mm diameter metal patch on each layer

V. Conclusion

Experimentally extracted dielectric constant of Teflon and FR4 substrate was around 1.9 and 4.0 while manufacturing data for those were 2.1 and 4.4 respectively to reveal the fact that experimental system had some systematic error in estimating relative permittivity at a lower value. Material's relative permittivity increased exponentially as diameter of metal patches increased and theoretically it was possible to obtain any value of dielectric constant by adjusting the size of the metal patches. But metal patch diameter could not be increased indefinitely. Maximum length of metal patch diameter was limited by the operating frequency at which half wave resonance phenomenon could have occurred in the metal patch. Material permittivity controlling technique with metal pattern, as described in this research, could find potential application in the design of microwave absorber where specific value of permittivity might require for absorbing a particular frequency.

Acknowledgment

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