Perforated Dallenbach microwave absorber based on dielectric polyaniline – phenolic resin composite for X-band applications

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Abstract. Design optimization to achieve broadband microwave absorption of a metal backed single layer microwave absorber in Dallenbach form is investigated by perforated designing of polyaniline (PA) reinforced novolac phenolic resin (NPR) composites in the frequency ranges of 8.2-12.4 GHz. The effect of triangular lattice pattern circularly perforated design is studied through effective complex permittivity and impedance matching condition between air-absorber interfaces. A comparative analysis of broadband absorption efficiency of perforated and non-perforated PA/NPR composite is carried out in terms of impedance matching to support the tailoring of microwave properties. The study shows a -15dB whole X band absorption bandwidth for PA3 perforated sample of thickness 3mm with a maximum absorption peak of ~-35dB at 12.4 GHz.

1. Introduction
Electromagnetic interference due to proliferation of high frequency wireless communication system demand development of efficient microwave absorber with characteristics of thin, light and broadband absorption. Dallenbach microwave absorber consist of conductor backed lossy substrate characterized by complex permittivity and quarter wavelength thickness has been reported to exhibit good absorption peak but narrow band microwave absorption [1]. According to transmission line model (TLM), one of the criteria to achieve broadband absorption is frequency independent impedance matching condition between air-absorber interfaces, which could be obtained by embedding frequency selective surface (FSS) in the substrate or circular perforation in different patterns [2,3]. The perforation in triangular lattice pattern of the dielectric substrate changes the relative permittivity of the substrate, which ascertains an effective complex permittivity and impedance matching condition. Polyaniline (PA) has been extensively studied as microwave absorbing material due to its unique properties [4]. In the present work, polyaniline-novolac phenolic resin composites have been synthesized and characterized in X-band frequency with a view to design a perforated single layer microwave with broadband absorption efficiency. The perforated Dallenbach microwave absorber is designed in circular holes with triangular lattice pattern as shown in figure 1, with the ratio of hole diameter (h) to lattice spacing(s) h/s=11/12 and this ratio is maintained with hole diameter 10 times
less than the lowest working wavelength [2,3]. The effective permittivity $\varepsilon_{\text{eff}}$ of the perforated structure can be estimated [2, 3] as

$$
\varepsilon_{\text{eff}} = \varepsilon'_{\text{eff}} - j\varepsilon''_{\text{eff}} = \varepsilon_r'(1 - \kappa) + \kappa - j\varepsilon_r''(1 - \kappa)
$$

(1)

$$
\varepsilon'_r = \varepsilon_r' \left(1 - \frac{\pi}{2\sqrt{3}} \left(\frac{b}{a}\right)^2\right) + \frac{\pi}{2\sqrt{3}} \left(\frac{b}{a}\right)^2
$$

(2)

$$
\varepsilon''_r = \varepsilon_r'' \left(1 - \frac{\pi}{2\sqrt{3}} \left(\frac{b}{a}\right)^2\right) - \frac{\pi}{2\sqrt{3}} \left(\frac{b}{a}\right)^2
$$

(3)

where $\varepsilon'_r$ and $\varepsilon''_r$ are real and imaginary effective permittivity of the perforated system of triangular lattice. Microwave absorption performance of the perforated design can be estimated from reflection loss values according to TLM as

$$
RL_c = 20\log \left[ \frac{1/\varepsilon_{\text{eff}} \tanh (j2\pi f/c)}{1/\varepsilon_{\text{eff}} \tanh (j2\pi f/c)} \right]
$$

(4)

Figure 1. Triangular lattice pattern circularly perforated metal backed Dallenbach absorber consisting of PA-NPR composite

2. Experimental

2.1. Synthesis of polyaniline:

Simple polymerization method (chemical oxidation) was employed in the polymerization of aniline and was achieved in hydrochloric acid medium in equimolar proportion to aniline to obtain HCL protonated PANI, where, aniline exists as an anilinium cation, aniline hydrochloride was used as a monomer and potassium persulfate as oxidant. Raw materials, aniline obtained from Aldrich Co. (Steinheim, Germany), hydrochloric acid and potassium Persulfate (K2S2O8) as analytical-reagent-grade chemicals (Merck, Darmstadt, Germany) were used as received. Double distilled water was used for all purposes. A three-necked, round-bottom flask (500mL) was equipped with a thermometer, a nitrogen inlet and a dropping funnel. Aniline (0.2mol) was dissolved in 100mL of a 1.5M aqueous solution of HCl and an aqueous solution of 50mL (0.25mol) of potassium persulfate was placed in a dropping funnel, which was added very slowly to the aniline solution while the temperature was maintained in a range close to 273–278 K with vigorous stirring for 2 h. The monomer to initiator molar ratio was maintained at 4:5 for the standard preparation of PA [4]. The reaction mixture was then allowed to stir at room temperature (300 K) for another 2 h. The precipitates of the PA were first
washed with 1.5M HCl and then by distilled water and 500mL of ethanol and finally dried in vacuo to use as reinforcer in developing microwave absorber.

2.2. Synthesis of polyaniline-novolac phenolic resin composites
The PA and resin powder were mixed uniformly in different wt. % ratios (10, 20 and 30wt. %) with the help of mixture and grinder to obtain uniform PA-resin compound. The mixture was poured in a cavity mould placed on the hot plate of a hydraulic press. At temperature between 95–100 °C, pressure was applied slowly on the die mould and then kept for isothermal heating at 150 °C for 2 h. Samples (PA1, PA2, PA3) for 10, 20 and 30 wt. %, respectively, having dimension of 10.38 mm x 22.94 mm x 3 mm were obtained for X band microwave characterization.

3. Results and Discussion
Microstructural studies are carried out using X-ray diffraction (XRD) (Rigaku miniflex, Cu Kα, 1.54). XRD pattern of PA had a broad peak at about 2θ = 25.8°, a characteristic peak of amorphous PA that confirms the conformation of PA.

![Figure 2](image)

Figure 2. (a)XRD patterns of Polyaniline, (b) WR-90X11644A compatible to E8362C VNA, TRL calibration set up

![Figure 3](image)

Figure 3. Complex permittivity of PA1-PA3 composites (a) Real permittivity and (b) Imaginary permittivity.

Microwave characterization of the developed PA1-PA3 composites were carried out using Nicolson and Ross [5] method employing Agilent 85071E material measurement software compatible with Agilent E8362C VNA in the X-band, as shown in figure 2(b). Characterization showed dielectric nature of the composites PA1-PA3 by providing various complex permittivity (εr) values along with the constant \( \mu_r(\omega) = 1 - j.0 \) value. From the measured values of complex permittivity (εr) of PA1-
PA3 composites, real ($\varepsilon'_r$) and imaginary ($\varepsilon''_r$) parts are plotted against X-band in figures 3(a) and 3(b). In the X-band range, real and imaginary parts of $\varepsilon_r$ for all the composites are found to enhance with the enhancement of fillers (PA) wt. % in the composites. As observed from figures 3 (a) and (b), at 8.2 GHz, $\varepsilon'_r$ values increases from ~ 2.74 to ~ 6.50 and $\varepsilon''_r$ values from ~ 0.4 to ~ 2.6. Increase in the above microwave properties of PA1-PA3 composites due to higher filler (PA) content in the matrix may be attributed to the enhancement in the polarizability of the composites, since, $\varepsilon'_r$ is a measure of the polarizability of a material. In PA1-PA3 composites, chief contributors of polarizability are expected to be (i) orientational polarization and (ii) interfacial polarization [6,7] and both enhances with the displacement current (bound charges-dipoles) and conduction current (free charges - polaron/bipolaron [8]) i.e. with the conductivity of the composites due the presence of higher filler wt. % in the matrix. Formation of large orientational and interfacial polarizations (real part $\varepsilon'_r$) in the composites also leads to the loss (imaginary part $\varepsilon''_r$) mechanism through associated relaxation phenomenon in the presence of external electric field. Using expressions (2) and (3) and from the measured values of real ($\varepsilon'_r$) and imaginary ($\varepsilon''_r$) complex permittivity of PA1-PA3 composites, the $\varepsilon'_{eff}$ and $\varepsilon''_{eff}$ values of the perforated design were estimated and plotted in figures 4(a) and (b). It is observed that the $\varepsilon'_{eff}$ and $\varepsilon''_{eff}$ values for perforated samples have reduced in comparison to non-perforated one and approaches towards the value of free space i.e. $\varepsilon'_r$~1 and$\varepsilon''_r$~0. A MATLAB program is developed based on equation (4) to calculate the minimum reflection loss value of non-perforated and perforated samples by optimizing the thickness parameters within the limit from 0.5 mm to 4 mm over the X-band and are plotted in figures 5(a) and 5(b). Figure 5a, showing a $RL_C$ ~ −29 dB for PA3 of thickness 2.3 mm at 11.9 GHz, $RL_C$ ~ −10 dB for PA2 of thickness 4 mm at

Figure 4. Effective complex permittivity of PA1-PA3 composites. (a) Real and (b) Imaginary parts

Figure 5. Calculated Reflection loss in X-band. (a) Non-perforated design (b) Perforated design
Figure 6. Complex impedance (Z) in X-band. (a) Non-perforated design (b) Perforated design

11.8GHz and RLc ~ -9 dB for PA1 of thickness 4 mm at 11.7 GHz. In comparison, the RLc values for perforated design showed significant enhancement in absorption bandwidth. A -10dB whole X band absorption bandwidth is observed for all the perforated samples and -15dB absorption bandwidth is shown by PA3 sample with maximum absorption peak of RLc ~ -35 dB at 12.4 GHz. This broadband performance could be explained on the basis of impedance matching condition depicted by figure 6(b). Considering the real and imaginary impedances for perforated PA3 sample at 12.4 GHz, Zreal ~ 443Ω and Zimag ~ -132Ω are closest to free space impedance condition in comparison to non-perforated design. Similarly, throughout the whole X-band, combination of real and imaginary impedance of perforated design approached the free space impedance condition and hence there is broadband absorption in comparison to non-perforated design.

4. Conclusion
The perforated Dallenbach microwave absorber designed on PA-NPR substrate estimated an efficient and broadband absorption with -15dB bandwidth from 8.4-12.4 GHz. The analysis reveals that the dominant mode of absorption is impedance matching phenomenon facilitated by effective complex permittivity tailored by circular perforation in triangular lattice pattern on the PA-NPR substrate of Dallenbach absorber. Thus, the design structure shows a promising microwave absorber for possible application in X-band frequency.

References
1. Ruck G T, Darrick E B and Stuart W D 1970 Radar Cross Section Handbook Vol. 2 (New York: Plenum)
2. Iqbal M N, Malek F, Ronald S H, Shafiq M, Juni K M and Chat R 2012 Prog. Electromagn. Res. 131 19
3. Petosa A and Ittipiboon 2003 IEEE Proc. Microw. Antennas Propag. vol 150 p 309
4. Saini P, Choudhary V, Sood K N and Dhawan S K 2009 J. Appl. Poly. Sci. 11 33146
5. Nicolson A M and Ross G F 1970 IEEE. Trans. Instrum. Meas. IM-19 377
6. Zhang X F, Guan P F and Dong X L 2010 Appl. Phys. Lett. 96 223111
7. Ku C C and Liepins 1987 Electrical Properties of Polymers (Munich: Hanser Publishers) p 25
8. Ohlan A, Singh K., Amita C, Singh V N and Dhawan S K 2009 J. Appl. Phys. 106 044305