

Numerical and Experimental Analysis of Microstrip Antennas Loaded with a Single DNG Resonator

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Abstract This paper deals with the numerical and experimental analysis of the effects of non-conventional materials on antenna performance. The paper is divided into two main sections: numerical simulations and experimental characterization. First, a microstrip antenna loaded with a Double-Negative (DNG) substrate is numerically simulated to study its effect on size and performance. Then the same antenna using conventional substrate is top loaded with a novel single-sided resonator (referred as diamond dipole resonator or DDR) showing DNG behavior. The antenna is manufactured and measurements are performed. The results show that the use of the DDR produces a dramatic 73.9% return loss improvement as well as a frequency shift. Issues about size reduction and negative refractive index effects are further presented and discussed.

Keywords DNG: Double-Negative material, SRR: split ring resonator, FSS: Frequency Selective Surfaces, HFSS™: High Frequency Structure Simulator, DDR: diamond dipole resonator

1. Introduction

Recent research on antennas based on non-conventional materials has indicated many advantages over those of traditional dielectric substrates, which make them a new borderline for microwave design. Using non-conventional materials is a potential and promising solution to size reduction, increased bandwidth and obtaining multiple resonances. The proposed paper intends to carry out numerical and experimental investigation of metamaterial-based microstrip antennas. Recent developments in most consumer electronic products are toward miniaturization. The technology of integrated circuit is widely applied in the field of communication baseband modules and RF modules to make communication products smaller in size. However, the technology of integrated circuits is difficult to use to design a compact antenna and antenna arrays. Therefore, the design of compact planar structures becomes a critical technique to reduce the size of communication products. In recent years, novel engineered materials with characteristics that may not be found in nature have been considered in the design of microwave antennas and arrays. The studies in the area showed increased directivity and bandwidth, reduced observability, and frequency shift that can be used to reduce dimensions for fixed working frequencies[1] –[6]. These encouraging results are the leading idea behind the present work. Artificial material with novel electromagnetic

properties are often conceptualized and realized as particulate composite materials. If the particles are electrically small, the effective constitutive parameters and properties can be estimated via various homogenization formalisms. The synthesis and fabrication of new materials has to be matched by the development of new experimental characterization techniques. The novel electromagnetic performance can be usefully employed to substantially reduce the patch size with a corresponding improvement in terms of weight and space occupation[7]-[8].

Currently, DNG materials for antenna applications are used to replace conventional substrates. To this end, the substrate is conceived as a periodic repetition of a single unit called unit-cell. This approach entails a considerable effort from a simulation and manufacturing point of view. In order to simplify both the simulation and manufacturing efforts, this paper proposes to use one single-unit resonator to analyze its effect on the antenna performance and hence, confirm the advantages mentioned above. The structure of the paper is as follows. In section 2 microstrip antenna design formulas are provided. The results from numerical simulations are reported in Section 3. Sections 4 and 5 explain the theoretical methodology behind the proposed approach and the novel DNG geometry adopted. In Section 6 experimental results to show the capabilities and the effectiveness of the design technique developed in the paper are reported.

2. Antenna Design

Within the microwave and millimeter wave frequency bands, microstrip antennas (MSA) have proved to be excellent radiators for many applications in the commercial and

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specialized application frequency domains of microwaves and millimetre waves. Aircraft and ship antennas, satellite communications, mobile radio, and biomedical are just few of the application areas of such devices. A MSA consists of a radiating patch on one side of a dielectric substrate that has a ground plane on the opposite side. The radiating patch dimension width (W) and length (L) are related to the substrate relative permittivity and thickness through the transmission line model as follows[9]:

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{\text{eff}} + 0.3)(W/h + 0.264)}{(\epsilon_{\text{eff}} - 0.258)(W/h + 0.8)}$$

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

$$L = \frac{c}{2f_r \sqrt{\epsilon_{\text{eff}}}} - 2\Delta L$$

Where f_r is the antenna resonance frequency, c the free-space speed of light, ΔL represent the effective length that accounts for fringe effects, and ϵ_{eff} the effective dielectric constant static value given by:

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \sqrt{1 + 12 \frac{h}{W}} \quad (2)$$

Equations (1) served as a starting point in the antenna design; dimensions are then optimized through the simulation phase to achieve the desired antenna performance as described in the following section.

3. Numerical Simulation

A micro strip fed patch antenna working at 10GHz and loaded with conventional FR4 material was simulated. The resonant frequency is chosen in order to match with the frequency where the metamaterial displayed double negative properties. The antenna was then simulated on a dielectric slab modelled to have the same parameters as that of the metamaterial. The DNG patch antenna was then shrunk until it operated at the same frequency as that of the patch antenna that used the conventional dielectric. The original patch size, with the conventional dielectric, was 13 mm by 16 mm. By shrinking the patch to 9.94 mm by 8.94 mm, while using the metamaterial for the dielectric, the antenna resonated at the same frequency as that of the antenna with the conventional dielectric. This provided a 57 percent decrease in the area of the antenna's patch and a 26.9% of bandwidth improvement. A result comparison is showed in Table 1[10].

Table 1. Results comparison

Material	Patch size (mm)		Patch area (mm ²)	Bandwidth (MHz)
FR4	13	16	208.00	390
DNG	8.94	9.94	88.87	1450

4. Electromagnetic Parameters Retrieval

As stated in the introduction, an important rule when designing a metamaterial is to keep the size and periodicity of the scattering elements significantly smaller than the operating wavelength ($\lambda/10$ or smaller) as this allows for meaningful interpretation of the material's bulk properties based on the behavior of the unit cell (effective medium). Nevertheless, this paper proposes a scattering element with dimensions that resemble the wavelength in free space. Given the unit-cell size, the proposed structure cannot be classified as bulk metamaterial, which is conceived as discrete media composed of a combination of unit cells of small electrical size at the frequency of interest[11]-[14]. Experimental analysis will show that such a medium presents DNG behavior and that the effective medium theory can still be applied. In addition, the novel designed implant is single sided which improves and simplifies the manufacturing process. The permittivity ϵ and the permeability μ for a DNG medium must be simultaneously negative over a certain frequency range. In order to achieve this result several numerical and experimental models have been proposed in the literature[15]. The model proposed in this paper consists of diamond ring resonator and wire strips on a hosting isotropic dielectric medium (Fig. 1).

Once the effective medium theory can be applied, the engineered medium can be characterized through macroscopic parameters such as dielectric permittivity and magnetic permeability. The characterization can be carried out by applying a parameter retrieval procedure based on the calculation or measurements of scattering parameters followed by the derivation of macroscopic indicators such as refractive index n and wave impedance z . The S-parameter retrieval techniques that have been utilized recently to characterize metamaterials have been shown to be valid for metamaterials having symmetric unit cells, even when the optical path length (kd) is on the order of the unit cell size. The refractive index and the wave impedance can be related to the calculated scattering parameters as follows:

$$n = \frac{1}{kd} \cos^{-1} \left(\frac{1 - S_{11}^2 - S_{21}^2}{2S_{21}} \right) \quad z = \sqrt{\frac{(1 + S_{11}^2) + S_{21}^2}{(1 - S_{11}^2) + S_{21}^2}} \quad (3)$$

Once refractive index and wave impedance are extracted from the scattering parameters, the corresponding ϵ and μ can be found using $\epsilon = n/z$ and $\mu = n z$ [16],[17].

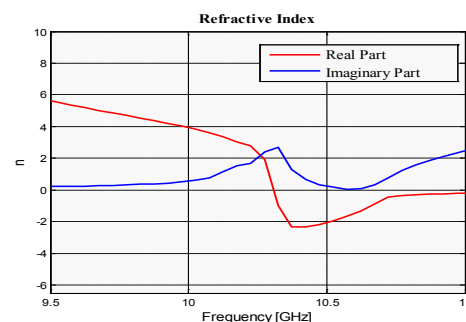


Figure 1. Novel proposed single-sided Diamond Dipole Resonator (DDR)

5. Diamond Dipole Resonator

The DNG behavior of an artificial material can be obtained through the introduction of conductive impurities in a host medium. The shape of the inclusions is chosen according to two main factors: a) it must provide the double-negative behavior to the hosting dielectric medium; and b) it must take into account manufacturing limitations. The former guarantees that the shape contributes to a simultaneous formation of both electric and magnetic dipole moments while the latter assures that the shape can be manufactured according to the current technology. In this paper a novel single-sided metamaterial, referred as diamond dipole resonator (DDR), is proposed to improve antenna performance. The novel designed unit cell shows DNG behavior at about 10 GHz (Fig. 2), allowing the metallization to be located only on one side of the dielectric slab, thus simplifying the manufacturing process[18].

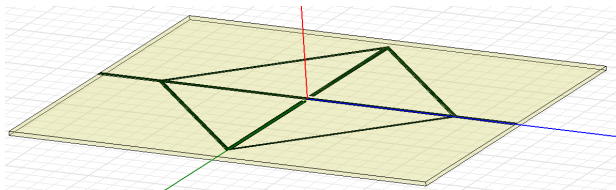


Figure 2. DDR refractive index obtained from the parameter retrieval

The negative refractive index shown in Fig. 2 was achieved through scattering parameter retrieval procedure. The DDR has been manufactured and tested. A periodic thin-wire medium is responsible for the negative effective permittivity, whereas the periodic diamond structure provides negative effective permeability. DDR and wire patterns are fabricated on the front sides of FR4 (0.254 mm thick) printed circuit boards. The metal used for deposition is one Oz copper (1.4 mil = 0.0355 mm) for a total slab thickness of 0.2895 mm. A single DDR cell size is 20X25mm, has a diameter of 18 mm, and the width of metallization is 0.212 mm.

6 Experimental Results

DNG metamaterial structures can be used to introduce changes in antenna impedance and, consequently, to obtain improvement in antenna response. However, currently available metamaterial-loaded antennas at RF and microwave frequencies are restricted in their overall miniaturization due to limitation in packing several metamaterial inclusions in a small volume, in part due to having metallization on both sides of the dielectric slab. Moreover, multiple scattering from such inclusions causes impurities in polarization. Being able to employ a single DNG micro-resonator instead of an array would address both of these issues while adding ease of implementation. In this paper a single DNG DDR metamaterial inclusions is proposed to induce changes in a conventional microwave antenna behavior. The microstrip antenna is based on a 1.52 mm thick substrate

(RO4350B) with a permittivity/dielectric constant of 3.66. The patch measures 9.6x6.6 mm and is fed with a $\lambda/4$ transmission line to match a 50 Ω characteristic impedance.

The fabricated antenna shows excellent radiation properties with a total gain as high as 5 dBi (Fig. 3).

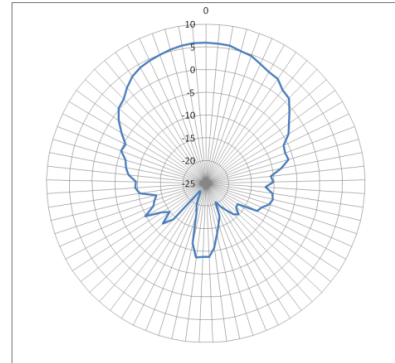


Figure 3. Conventional MSA radiation pattern (vertical polarization).

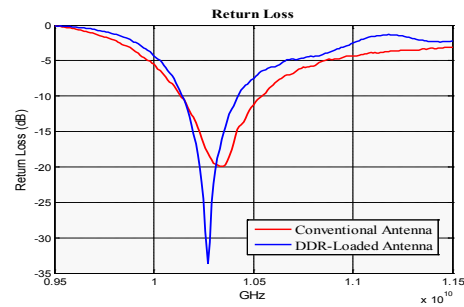


Figure 4. Microstrip antenna experimental results

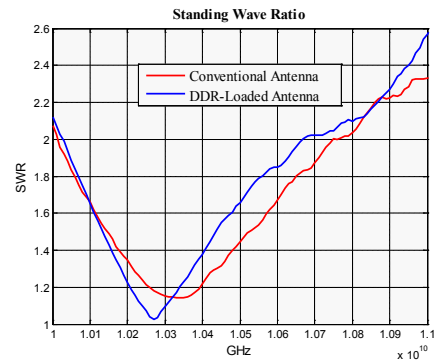


Figure 5. SWR comparison.

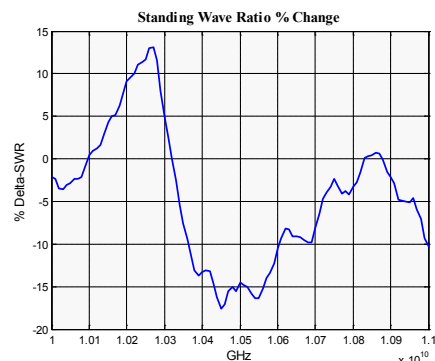


Figure 6. SWR percentage change.

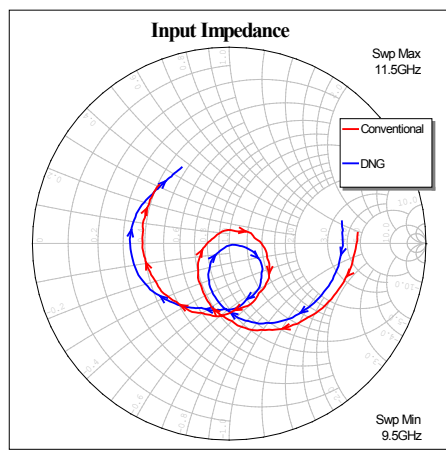


Figure 7. Input impedance comparison.

Numerical analysis and experimental measurements have been performed using a single unit of the DDR to load several planar microwave antennas. A microstrip antenna working in the X-band frequency range was simulated, fabricated and tested with the DDR resonator collocated on top of the patch. Numerical results showed an improvement in the impedance matching of 28.8%. Furthermore, the bandwidth of the resonant frequency was almost unaffected by the DDR. Experimental results confirmed the positive effect of the DDR showing a measured return loss of -34.54 dB that, compared with the antenna without the DDR, produces a dramatic 73.9% improvement in its performance (Fig. 4). However, the presence of the DDR metamaterial caused a shift in the resonance frequency of the dipole antenna of 83 MHz. Another important parameter that can be used to determine the antenna efficiency is the voltage-standing-wave-ratio (VSWR). Figure 4 shows the measured VSWR for the conventional and DNG-loaded antenna. As a rule-of-thumb an antenna is considered performing if the VSWR is $< 2:1$. From the picture in Fig. 5 it can be noticed that this value is achieved over a 950 MHz band providing a matched VSWR bandwidth approximately equal to 94% considering the antenna resonating at 10.27 GHz [19]. The SWR percentage change is also shown (Fig. 6). It can be noticed that the use of the DNG single resonator improved the antenna SWR of about 13-14%. Finally Fig. 7 reports the experimental input impedance comparison for the two antennas. Remarkably the DNG-loaded antenna shows a matching improvement with a normalized value at 10.27 GHz as low as $1.001-j 0.02$ confirming the benefit associated to the use of non-conventional materials in antenna design.

7. Conclusions

The performance of a microstrip antenna on a DNG layer was investigated using the commercial software HFSS and experimental measurements using a single DDR. The return loss was considered and a comparison between iso-

tropic and DNG dielectric was carried out. From the results it can be highlighted that by using the DNG substrate a miniaturization is achievable with an improvement in weight and performance; also, the experimental results show a return loss improvement of 73.9%. The benefits of using DNG materials in antenna design are also confirmed by other measured parameters such as VSWR and input impedance. The proposed technique allows achieving performance improvement in a very simple way.

REFERENCES

- [1] Y. Rahmat-Samii, "Metamaterials in antenna applications: classifications, designs and applications," IEEE International Workshop on Antenna Technology Small Antennas and Novel Metamaterials, March 6-8, 2006, pp.: 1-4.
- [2] Tam, W.Y.; Kuisong Zheng; , "Transmission line model for rectangular microstrip antennas with ϵ -negative metamaterials," Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE , vol., no., pp.1-4, 11-17 July 2010.
- [3] Mittra, R., Li, Y. and Yoo, K. (2010), A comparative study of directivity enhancement of microstrip patch antennas with using three different superstrates. *Microw. Opt. Technol. Lett.*, 52: 327-331.
- [4] Zheng, K.S.; Tarn, W.Y.; Ge, D.B.; , "Impedance Matching of Rectangular Microstrip Antennas partially loaded with DNG metamaterials," Microwave Conference, 2008. EuMC 2008. 38th European , vol., no., pp.678-681, 27-31 Oct. 2008.
- [5] G. Singh, "Double Negative Left-Handed Metamaterials for Miniaturization of Rectangular Microstrip Antenna," *Journal of Electromagnetic Analysis and Applications*, Vol. 2 No. 6, 2010, pp. 347-351.
- [6] Ma, J.J.; Cao, X.Y.; Liu, T.; , "Design the size reduction patch antenna based on complementary split ring resonators," Microwave and Millimeter Wave Technology (ICMMT), 2010 International Conference on , vol., no., pp.401-402, 8-11 May 2010.
- [7] F. Urbani, and Y. Zhou, "Design of a Compact Dual-Band Microstrip Antenna Loaded with Anisotropic Substrate," *Proceedings of the 28th Annual Symposium of the Antenna Measurement Techniques Association (AMTA)* October 22-27 2006, Austin, Texas.
- [8] F. Urbani, and L. Vegni, "Analysis of Frequency Selective Surfaces Loaded by Chiral Substrates," *Proceedings of the 2005 IASTED International Conference on Antennas, Radar, and Wave Propagation (ARP2005)*, Banff, Alberta, Canada, July 19-21, 2005.
- [9] Constantine A. Balanis, "Antenna Theory: Analysis and Design," Wiley-Interscience, 3rd Edition, 2005.
- [10] F. Urbani and C. Garcia, "Design of Miniaturized Double-Negative Microstrip Antennas using Electromagnetic Parameter Retrieval," *IEEE International Workshop on Antenna Technology: iWAT2009*.
- [11] C. A. Kyriazidou, H. F. Contopanagos, W. M. Merrill, and N.

- G. Alexopoulos, "Artificial versus Natural Crystals: Effective Wave Impedance of Printed Photonic Bandgap Materials," *IEEE Trans. Ant. and Prop.*, vol. 48, no. 1, pp. 95–106, Jan. 2000.
- [12] H. F. Contopanagos, C. A. Kyriazidou, W. M. Merrill, and N.G. Alexopoulos, "Effective response functions for photonic band gap materials", *JOSA A*, vol. 16, no. 7, pp. 1682-1699, July 1999.
- [13] C. A. Kyriazidou, H. F. Contopanagos, and N. G. Alexopoulos, "Monolithic Waveguide Filters Using Printed Photonic-Bandgap Materials", *IEEE Microwave Theory and Techniques*, vol. 49, no.2, pp. 297-307, Feb. 2001
- [14] R. Marques, F. Martin, and M. Sorolla, "Metamaterials with Negative parameters: Theory, Design, and Microwave Applications," *Wiley Series for Microwave and Optical Engineering*, 2008.
- [15] F. Capolino, "Theory and Phenomena of Metamaterials," *CRC Press*, 2009.
- [16] X. Chen, T. M. Grzegorzczuk, B. Wu, J. Pacheco, and J. A. Kong "Robust method to retrieve the constitutive effective parameters of metamaterials," *Phys. Rev. E* 70, 016608, (2004).
- [17] D. R. Smith, D. C. Vier, Th. Koschny, and C. M. Soukoulis "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Phys. Rev. E* 71, 036617 (2005).
- [18] F. Urbani, "Experimental Analysis of Novel Single-Sided Left-Handed Metamaterial," *IEEE Antennas and Wireless Propagation Letters*, Volume: 9, page(s): 720 – 723, 2010.
- [19] Yaghjian, A.D.; Best, S.R.; , "Impedance, bandwidth, and Q of antennas," *Antennas and Propagation*, *IEEE Transactions on* , vol.53, no.4, pp. 1298- 1324, April 2005.