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A NOVEL CIRCULARLY POLARIZED ANTENNA BASED ON AN ARTIFICIAL GROUND PLANE

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Abstract—The paper describes a novel low profile circularly polarized antenna. The antenna is a single dipole over a particular wire formed panel with high impedance properties. Although the principles of operation for the antenna are general, in this work they are specifically applied to the design and optimization of a FM broadcasting antenna. The distinguishing feature of the design is that it incorporates the following interesting concepts simultaneously: artificial high impedance surfaces or artificial magnetic conductors, materials showing refractive indexes of less than unity ($n < 1$), and polarizing structures. Another advantageous aspect of the design is the computational efficiency emerging from this fact that the structure is entirely wire made. This way the relevant numerical analysis and optimization can be efficiently carried out by NEC, a one-dimensional (1D) MoM-based EM analyzer.

1. INTRODUCTION

Artificial magnetic conductors (AMCs) are generally planar surfaces, which are designed to imitate the behavior of a perfect magnetic conductor (PMC) at resonance. Currently, they are being widely studied as novel candidates for antenna substrates with enhanced properties [1–8]. AMCs are occasionally referred to as electromagnetic

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band gap (EBG) ground planes [1, 2] or high impedance surfaces (HIS) [5, 6, 9]. In fact, AMCs can be regarded as a special sub-category of the HIS family. This is because in general a HIS may deviate from the PMC resonance condition, i.e., it does not essentially have in phase reflection condition ($\Gamma = +1$). This feature yields more flexibility in designing antennas over HISs. For example, in [2, 4], the mushroom structure acts as the ground plane for a dipole antenna a little lower than its resonance enabling the dipole to be matched easily. A similar condition is also observed for the HISs in [5, 6]. Previously, it has been shown that HISs can be used to improve antenna performance and reduce effects of surface waves [e.g., 2, 3, 8]. The latter results in antenna miniaturization in both height and ground plane size [4]. The present work utilizes a HIS, emerging from that introduced in [5], in order to design a low profile circularly polarized (CP) panel dipole antenna for FM broadcasting. Despite most usual HISs, which are 2D [1, 2, 4, 9, 10] or 3D [1, 11], this particular HIS is 1D (like that studied in [6]). The main advantage of being 1D (i.e., wire-formed), is computational efficiency. In fact, for wire structures, modeling and design procedure can be carried out by NEC very fast. Moreover, wire-formed HISs can be applied to low frequency applications for which we scarcely see in literature designs involved in HIS structures and their benefits. It should be noted that some preliminary results of the present work has already been presented in [9].

2. DESCRIBING THE MAIN SCHEME

Our starting point is a dipole over a non-uniform high impedance surface (NU-HIS) [5] with linearly polarized radiation. The geometry is shown in Figure 1(a). Because the antenna is going to radiate waves with circular polarization, two orthogonal field components with 90° phase difference and equal magnitudes are required. The orthogonal fields can be generated by rotation of the dipole around Z-axis as in Figure 1(b). As for the phase difference, we can benefit from the array of high impedance elements situated between the dipole and the PEC ground plane (see Figure 1). These elements are capable of introducing an adjustable phase shift, provided that some delicacies be taken into account. In general, the main dipole element, in front of the whole NU-HIS panel generates two sets of fields:

- Fields directly radiated at broadside direction (E_d)
- Fields radiated towards the HIS (E_{id})

Since E_d is linearly polarized, it can deteriorate the overall CP radiation. A remedy to combat this impact is to someway direct the energy radiated by dipole towards the panel. By appropriately utilizing the properties of the HIS, we can reduce the E_d component so that $E_{id} \gg E_d$ ($E_d \approx 0$). In this way most of the power radiated by dipole will pass through HIS elements and therefore experience the needed phase shift for CP radiation. To provide such a condition, the wire elements of the NU-HIS (NU-HIS structure excluding the PEC plane) are tuned so that they act as an artificial material with $n < 1$. It has well been studied [e.g., 12] that a material with $n < 1$, if realizable, has the aptitude to improve the directivity of an adjacent radiation source. Specifically speaking, such materials are able to direct the fields radiated by the source towards themselves so that the whole structure shows more gain on one side and less gain on the side that the source is located. Looking from another perspective, it can be said that the NU-HIS elements in Figure 1 act very much like the super directive EBG superstrates presented for example in [13]. However, the difference is that here the main aim is not to achieve super directivity but to direct power towards the panel as much as possible. Another difference is that the elements of these NU-HIS are wire made (1D), but the elements usually used in references like [12, 13] are 2D periodic elements such as patch, loop, cross, etc.

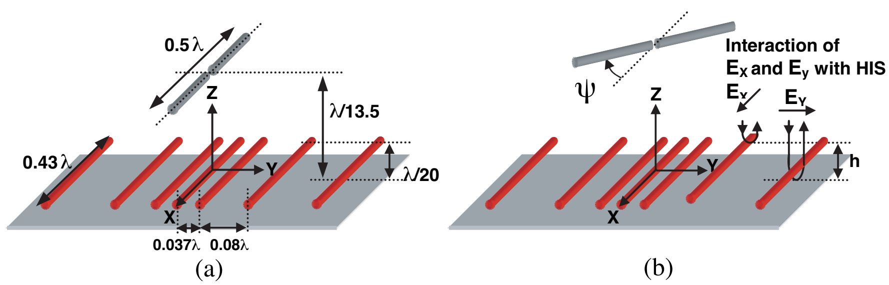


Figure 1. (a) The dipole antenna over the NU-HIS in [5], (b) applying rotation to obtain circular polarization.

Up to this point it was described how we can remove E_d and just keep E_{id}. Hereafter, we try to illustrate how the E_{id} should be treated to provide the conditions for CP radiation. If the dipole is rotated around Z-axis by $\psi°$ ($\psi \neq 0$), E_{id} will contain two orthogonal components, E_x and E_y. This is shown in Figure 1(b) in which it is observed that the E_x component is fully coupled with the HIS elements while the E_y is orthogonal with no or negligible coupling. Therefore, E_x is reflected from HIS nearly in phase (more exactly, with $\angle\Gamma \approx 90°$ to allow easy input matching as addressed in [2]), while E_y is reflected by the PEC with $\Gamma = -1$ ($\angle\Gamma = \pm 180°$). In light of the above descriptions, it can be deduced that the NU-HIS elements (NU-

HIS structure excluding the panel), are actually acting as a polarizing structure/material. More specifically, the waves radiated by the dipole pass through this polarizing material, are reflected by PEC, again pass through this polarizer, and finally are radiated in CP format at broadside direction (see Figure 1 for geometry).

For a pure CP condition we need to provide:

- $|E_x| = |E_y|$
- $|\angle E_x - \angle E_y| = 90^\circ$

The first condition can be achieved by adjusting ψ around 45°, while the second is achievable through applying a slight tuning to "h" and the length of HIS element (see Figure 1) in order to provide correct phase difference. It is obvious that because, in practice, these conditions have to be provided simultaneously with some other objectives, such as acceptable VSWR, the whole tuning and adjustment procedure can not be made manually and should be entrusted to an automatic optimization procedure. In the following, as a tangible example, it will be described how the antenna is optimized to provide some properties desirable for FM broadcasting stations.

It is important to highlight that a remarkable advantage of using the proposed scheme for achieving CP radiation, is that there is no need for Branch Line Coupler (BLC) to supply two separate dipole antennas with quadratic phases. As well-known, a BLC is an integral part of the prevalent CP dipole antennas (e.g., panel crossed dipole). In order to have better insight about CP radiation using only one dipole antenna, readers are encouraged to refer to [14] because the idea there, although different in mechanism, frequency range and HIS cells, has something in common with that of the present work.

3. DESIGN OF A FM BROADCASTING ANTENNA BASED ON THE IDEA

Although the idea proposed is general and usable to a large variety of frequency bands and applications, in this part it is specifically applied to the design of a FM broadcasting antenna. To this end, the antenna structure is optimized to provide the properties desired for a FM broadcasting station antenna. In the following, the features considered for the optimization procedure are outlined.

3.1. Objectives

The objectives which are going to be fulfilled are:

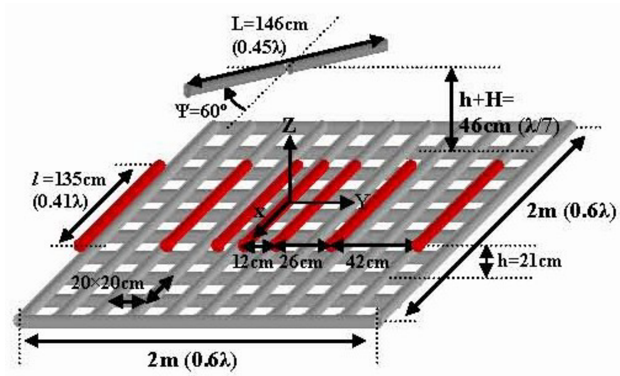


Figure 2. The dipole antenna over the NU-HIS in [5], optimized to be a standard circularly polarized FM broadcasting antenna; the radius for all wires is 1.6 cm ($\approx \lambda/200$).

- VSWR < 1.3 all over 88–92.5 MHz (BW ≈ 5%, including 22 stereo FM channels); 1.3 level is recommended by FCC for FM broadcasting [15].
- Axial ratio < 3 dB all over 88–92.8 MHz (BW ≈ 5%); 3 dB level is recommended by FCC for FM broadcasting [15]. This level should also be satisfied all over the $|\text{Theta}| < 40^\circ$ spatial cone (see the coordinate system in Figures 1 or 2).
- $h < \lambda/7$ in order for the antenna overall height not to be very large, where λ is free space wavelength at 90.25 MHz.

3.2. Variables

The parameters which are varied during the optimization process include "h", "H", and "ψ" where, $14\,\text{cm} < h < 24\,\text{cm}$, $8\,\text{cm} < H < 30\,\text{cm}$, and $30^\circ < \psi < 70^\circ$. It is noted that "$L$" and "$l$" are also varied however the related variations are so slight that they can be considered as a small tuning ($L = 160\,\text{cm} \pm 10\%$ and $l = 140\,\text{cm} \pm 7\%$).

3.3. Constants

It is obvious that in the design of a practical antenna, a PEC ground plane should be practical. It is well-known that for low frequency broadcasting antennas the antenna weight and wind-loading are of crucial importance [15]. Therefore, we should model the PEC plane by an optimum equivalent wire grid. In order for this modeling to be accurate and efficient, we have used a well-experienced rule of thumb called the “same surface area” [16]. This rule directs us to choose an appropriate wire radius and grid size. In brief, it states that for nearly accurate modeling of a solid surface with wire grids, the surface area of all modeling wires, which are parallel to one linear polarization, should be equal to the surface area of the solid surface. The grid size of 20 cm (0.06λ) and grid wire radius of 1.6 cm ($\lambda/200$), shown in Figure 2, have been chosen based on this criterion. It is also noted that the spacings between the NU-HIS elements are kept fixed (relative to λ) to be the same as those given in [5]. The only change is to scale them to work around the center frequency of 90.25 MHz instead of 180 MHz. After scaling, these dimensions do not change during the optimization. The radius for all wires in the structure is also fixed at 1.6 cm, which nearly equals to the scaled version of the radius suggested in [5].

3.4. Algorithm

Because the available NEC version is not equipped with optimization ability, we utilize the same two-way software interface between NEC and MATLAB, which is used in [17]. A MATLAB m-file exports a set of dimensions to NEC, runs NEC to analyze the antenna with the exported dimensions, next imports the results to MATLAB, then analyzes the results for competence, and this procedure is repeated until the optimization objectives are fulfilled. In fact, the m-file handles all the stages required automatically. The optimization algorithm used is a globally optimal one introduced in template matching in image processing [18]. The distinguishing feature of this method is the capability of recognition of proper results in the defined region by means of low-resolution search in the first step, in order to stop the processing on undesired region and wasting time.

The geometry of the optimized antenna and the relevant results are shown in Figures 2, 3 and 4, respectively. As deduced from these

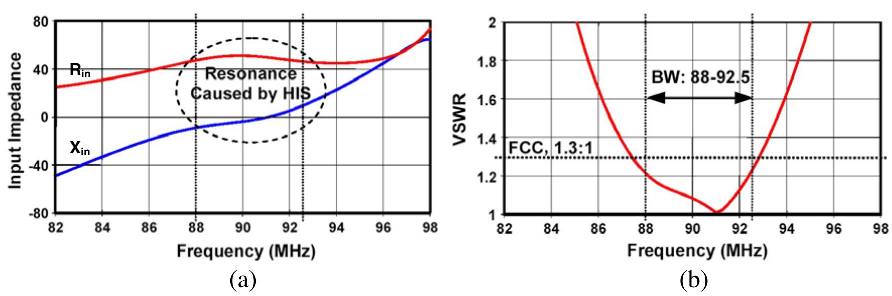
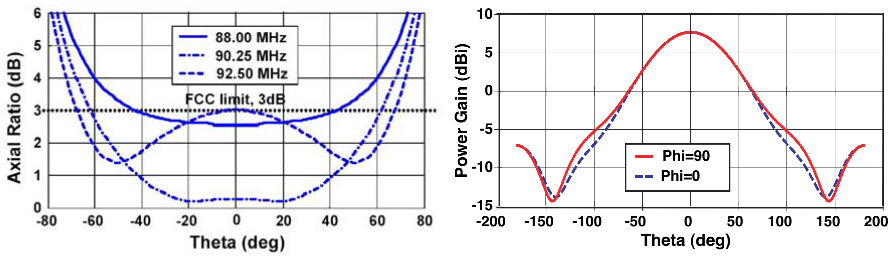


Figure 3. Impedance matching characteristics for the structure in Figure 2, (a) input impedance, (b) VSWR.



(a) (b)

Figure 4. Axial ratio and radiation pattern for the structure in Figure 2, (a) axial ratio in Phi = 90° plane, at both edges of the desired frequency range, (b) radiation pattern at 90.25 MHz.

figures, the antenna renders the following features.

- Front-to-back ratio (F/B) > 14 dB;
- Common bandwidth (BW) ≈ 5%, from 88 to 92.5 MHz; common bandwidth is where we have both VSWR < 1.3 and axial ratio < 3 dB;
- Antenna dimensions: $0.6\lambda \times 0.6\lambda \times \lambda/7$. (see Figure 2).

It is worth mentioning that apart from providing the conditions needed for CP radiation, the whole NU-HIS structure (NU-HIS elements together with PEC) helps in input impedance matching. In Fig. 3 (a) it is clearly observed that there is a resonance in input impedance ($X_{in} \approx 0$ & $R_{in} \approx 50\,\Omega$). As a result, as shown in Fig. 3 (b), a decrease in VSWR (VSWR<1.3:1) is observed meaning that we have a very good matching condition. It is well-known that a dipole requires height around $\lambda/4$ over PEC plane to be able to be matched so appropriate. However, for the current design, this good matching is obtained with the overall height of $\lambda/7$ that is quite smaller than $\lambda/4$. This height reduction is an effect typically observed when using a HIS/AMC ground plane instead of a PEC one [1, 2, 4–6]. Therefore, it is deduced that the combination of NU-HIS elements and PEC plane is an artificial high impedance surface in the view of the dipole. Although this surface is not a perfect PMC with infinite surface impedance, it is at least a surface with impedance very larger than the impedance of a PEC plane.

4. CASE STUDY

In this section, we are going to demonstrate and confirm the foregoing claim stating that the design is benefiting from an artificial material

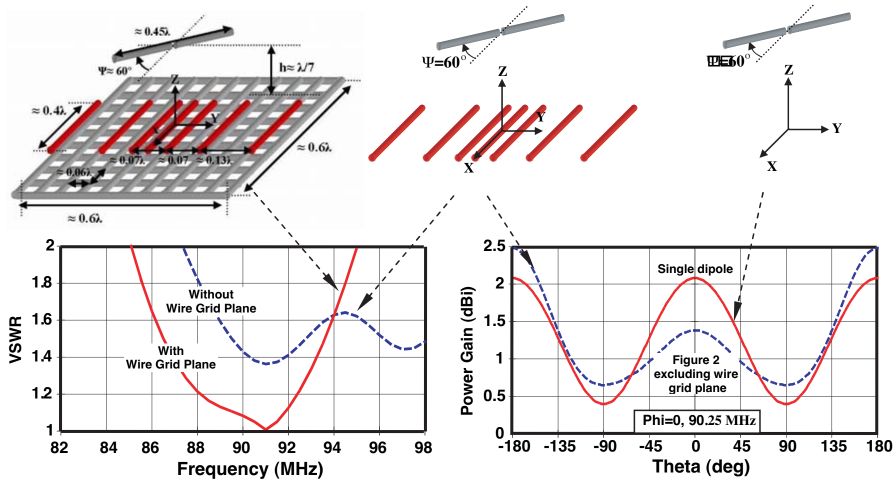


Figure 5. (a) VSWR of the structure in Figure 2 with and without the wire grid plane, (b) radiation pattern for the structure in Figure 2 without the wire grid plane together with that for a single dipole in free space.

with "$n < 1$" and a material with "high impedance properties". This is achieved by removing the wire grid ground plane in Figure 2 and analyzing the remaining structure again. The resultant VSWR and gain against frequency are shown in Figure 5. As seen in Figure 5(a), removing the plane has slightly changed the VSWR frequency response, but still we have a good input matching (VSWR < 2 : 1) over a large part of the range shown. This implies that the dipole is nearly isolated from the wire grid plane due to the presence of NU-HIS elements. Also, as for "$n < 1$" behavior, the gain results in Figure 5(b) shows that when the wire grid plane is removed, the radiation pattern is directed towards the NU-HIS elements. For comparison, the gain of a dipole antenna in free space has also been added for which there is no NU-HIS element to direct and reshape the radiation pattern. The comparison confirms that, as explained earlier in the paper, these elements are acting as an equivalent directive material, which exhibits $n < 1$ [12].

5. CONCLUSION

The paper introduces a single dipole antenna placed over a panel capable of radiating circular polarization. The antenna benefits from a newly introduced wire-formed HIS. To demonstrate aptitudes of the underlying idea, it is applied to a real application, the design of a CP panel dipole antenna for FM broadcasting. It is shown that the designed and optimized antenna renders F/B > 14 dB, BW ≈ 5% (VSWR < 1.3 : 1, according to the FCC recommendation), and the overall dimensions of $0.6\lambda \times 0.6\lambda \times \lambda/7$. The distinguishing feature of the idea is that, while being developed, it deliberately utilizes a blend of the following three scopes: a) HIS/AMC structures, b) artificial materials exhibiting $n < 1$, c) polarizing structures.

REFERENCES

1. Sievenpiper, D., L. Zhang, R. F. Jimenez Broas, N. G. Alexopolous, and E. Yablonovitch, "High impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Trans. Microwave Theory Tech.*, Vol. 47, No. 11, 2059–2074, Nov. 1999.
2. Yang, F. and Y. Rahmat-Samii, "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications," *IEEE Trans. Antennas Propagat.*, Vol. 51, No. 10, 2691–2703, 2003.
3. Li, Z. and Y. Rahmat-Samii, "PBG, PMC, and PEC ground planes: A case study of dipole antennas," *IEEE AP-S Symp. Dig.*, Vol. 2, 674–677, July 2000.
4. Mosallaei, H. and K. Sarabandi, "Antenna miniaturization and bandwidth enhancement using a reactive impedance substrate," *IEEE Trans. Antennas Propagat.*, Vol. 52, No. 9, 2403–2414, Sep. 2004.
5. Hosseini, M., A. Pirhadi, and M. Hakkak, "Design of a non-uniform high impedance surface for a low profile antenna," *Journal of Electromagnetic Waves and Applications*, Vol. 20, No. 11, 1455–1464, 2006.
6. Hosseini, M., A. Pirhadi, R. Fallahi, and M. Hakkak, "Bandwidth enhancement of a low profile antenna by applying non-uniformity to its high impedance ground plane," *IEEE Mathematical Methods in Electromagnetic Theory*, 202–204, Kharkiv, Ukraine, 2006.
7. Poilasne, G., "Antennas on high-impedance ground planes: On the importance of the antenna isolation," *Progress In Electromagnetics Research*, PIER 41, 237–255, 2003.
8. Shaban, H., H. Elmikaty, and A. A. Shaalan, "Study the effects of electromagnetic band-gap (EBG) substrate on two patch microstrip antenna," *Progress In Electromagnetics Research B*, Vol. 10, 55–74, 2008.
9. Hosseini, M. and S. Bashir, "Circularly polarized radiation by

a dipole antenna over an innovative artificial ground plane," *Loughborough Antennas and Propagation Conference*, 453–456, Loughborough, UK, Mar. 2008.

10. Yang, F. R., K. P. Ma, Y. Qian, and T. Itoh, "A novel TEM waveguide using uniplanar photonic-bandgap (UCPGB) structure," *IEEE Trans. Microwave Theory Tech.*, Vol. 47, No. 11, 2092–2098, Nov. 1999.
11. Hosseini, M., A. Pirhadi, and M. Hakkak, "Compact angularly stable AMCs utilizing skewed cross-shaped FSSs," *Microwave and Optical Technology Letters*, Vol. 49, No. 4, 781–786, Apr. 2007.
12. Bin, L., W. Bian, and L. Chang-Hong, "A study on high gain circular waveguide array antenna using metamaterial structure," *IEEE International Workshop on Antenna Technology*, 249–252, Mar. 2006.
13. Ge, Z. C., W. X. Zhang, Z. G. Liu, and Y. Y. Gu, "Broadband and high-gain printed antennas constructed from Fabry-Perot resonator structure using EBG or FSS cover," *Microwave and Optical Technology Letters*, Vol. 48, No. 7, 1272–1274, July 2006.
14. Yang, F. and Y. Rahmat-Samii, "A low profile single dipole antenna radiating circularly polarized waves," *IEEE Trans. Antennas Propagat.*, Vol. 53, No. 9, 3083–3086, 2005.
15. Johnson, R. C. and H. Jasik, *Antenna Engineering Handbook*, 2nd edition, McGraw-Hill, NY, 1984.
16. Ludwig, A. C., "Wire grid modeling of surfaces," *IEEE Trans. Antennas Propagat.*, Vol. 35, No. 9, 1045–1048, 1987.
17. Hosseini, M. and R. Fallahi, "Design of a wideband panel sleeve dipole antenna for FM broadcasting applications," *IEEE AP-S Symp.*, 4683–4686, Albuquerque, New Mexico, USA, July 2006.
18. Gharavi-Alkhansari, M., "A fast globally optimal algorithm for template matching using low-resolution pruning," *IEEE Transactions on Image Processing*, Vol. 10, No. 4, 526–533, Apr. 2001.