Link to publisher's version: *https://doi.org/10.1002/mop.31266*

Citation: Lashab M, Zebiri C-E, Djouablia L et al (2018) Characterization of horn antenna loaded with CLL unit cell. Microwave and Optical Technology Letters. 60(8): 1847-1856.

Author draft version accepted to Microwave and Optical letter, March, 2018

Characterization of Horn Antenna Loaded with CLL Unit Cell

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***Abstract*- In this paper, a pyramidal horn antenna loaded with unit cell of metamaterial is proposed, designed and realized for L-band that including terrestrial digital audio broadcasting T-DAB, GPS and GSM. The proposed antenna operates in the frequency range from 1.722 GHz to 1.931 GHz. The metamaterial is fabricated on a printed circuit board as Capacitive Loaded Loop (CLL). The work aims to exhibit the advantage of metamaterial loaded inside the horn antenna in terms of the gain enhancement of the radiation pattern and the resonant frequency shift towards lower frequency. The retrieval technique used show that the constitutive parameters of the unit cell as CLL have a zero index metamaterial (ZIM) from 1.34 GHz to 1.49 GHz and a near zero index of refraction from 1.495 GHz to 2 GHz, which is within the operating frequency of the horn antenna. The achieved results show that the total gain is improved over the frequency range. The simulation and the measurement are in good agreement.**

***Index terms*- Horn antenna, Metamaterial, T-DAB, CLL unit cell, Gain enhancement, Miniaturization.**

I. INTRODUCTION

In recent years investigation on horn antennas have been widely developed to improve the horn antennas performances such as High gain and dual polarization [1], higher aperture efficiency and low cross polarization [2], ultra-wide band and lager aperture [3], for various application. In this paper the proposed horn antenna is a pyramidal type loaded with metamaterial used for L-band and terrestrial digital audio broadcast T-DAB, the idea is to exhibit the gain enhancement and miniaturization of the antenna.

The research works carried out on L-band or broadband horn antenna in the literature are mainly for gain enhancement, low cross polarization and multimode [4]-[7] and [8]. For better performances horn antenna are loaded with dielectric to enhance the bandwidth and the low cross polarization, the use of dielectric in horn antenna was first introduced by Clarricoats *et al.* [9] in the late 80's, then by Lier *et al.* [10], later on other improved antennas were proposed [11]-[15].

Artificial materials such as metamaterials can be loaded on horn antennas to improve the gain and enable miniaturization effect [16], metamaterial was first used in antenna by Engheta [17], where the idea of negative permittivity and negative permeability was introduced to enable miniaturization effect for resonant cavity, the application of metamaterial in horn antenna was first introduced by Lier *et al.* [18], where interior walls of the horn antenna are loaded with near zero permittivity (ENZ) to improve the gain and reducing the cross polarization. Further works were carried out by the same authors the objective was to improve the radiation pattern and directivity and reducing the cross-polarization [19]-[21]. Metamaterial can be combined with chiral and loaded on horn antenna to enable dual circular polarization for satellite application [22].

Recent work has been investigated by Barbuto *et al.* [23]-[26], where SRR unit cell of metamaterial as magnetic resonator is inserted inside the horn antenna, the aim of the work is to make a band stop filter. Another work curried out by Ramaccia *et al.* [27]-[28], consists of loading the aperture of the horn antenna with metamaterial as epsilon near zero (ENZ), the radiation pattern performance is improved. He *et al.* in [29], have elaborated an anisotropic medium based on CLL structure, this loaded on the aperture of the horn antenna to improve the aperture efficiency.

In this paper a pyramidal horn antenna is designed to operate in the frequency range of 1.722 GHz to 1.931 GHz without unit cell. In order to increase the radiation pattern gain, the horn antenna is loaded with a unit cell of CLL given by Fig. 1. The unit cell is designed by HFSS and realized to operate in the frequency range of 1.34 GHz to 2 GHz as (ZIM) and low index of refraction, the extraction of the electric and magnetic parameters of the unit cell are obtained using the transmission and reflection coefficient. By loading the horn antenna with metamaterial, the operating frequency range becomes within 1.45 GHz to 1.55 GHz, the resonant frequency is shifted down and the bandwidth is reduced, the gain in the total radiation pattern is increased both in E-plane and in the H-plane especially around the resonant frequency of the loaded horn antenna.

The structure of the paper is as follow. In section II a theoretical aspect of the CLL is presented with geometrical design then extracted permittivity and permeability are shown, section III is presenting the geometrical design of the horn antenna and the feeding. Section IV contains the numerical results and discussion.

II. METAMATERIAL DESIGN

A- Theoretical aspect

The extraction of constitutive parameters of any material usually needs experimental tests or analytical models [30]. Drude–Lorentz model [31], known as dispersion model is very accurate, in which the magnetic permeability and electric permittivity are extracted analytically using mathematical model [32].

In this paper the constitutive parameters of the unit cell as metamaterial are obtained using the well-developed characterization method of metamaterials known as the standard retrieval procedure [33], where the effective permittivity and effective permeability refractive values of the metamaterial unit cell can be extracted from the S-parameters assuming that this latter is symmetric with respect to the (x–y) plane show in Fig. 2, which means that $S_{11} = S_{22}$ and $S_{21} = S_{12}$. The relative impedance is found with respect to the S-parameters using the following formula:

$$Z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \qquad (1)$$

And,

$$n = -j.\ln\left(\frac{S_{21}}{1 - S_{11}\left(\frac{Z-1}{Z+1}\right)}\right)\frac{1}{k_0 d} \qquad (2)$$

Where k_o the free space propagation and (d) is the thickness of the unit cell, here "d" is chosen to be 40 mm. The constitutive parameters can be derived from the above equation as:

$$\mu_{eff} = n.Z \quad \text{And} \quad \varepsilon_{eff} = n/Z$$

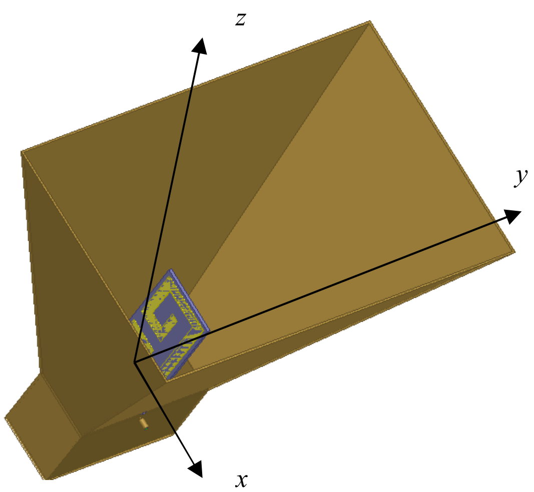


Fig. 1, Horn antenna loaded with metamaterial

B- Unit Cell Design

The CLL unit cell is designed by HFSS and realized as printed circuit board, Fig. 3 shows the schematic view of the front and Bottom sides, figure 2 presents the geometrical dimensions of the unit cell, the x-y axis denotes the symmetry presented by the cell. The substrate is a FR4 with relative permittivity ε_r = 4.4 and dielectric loss tangent δ = 0.02, the thickness of the substrate is 1.6 mm.

The transmission and reflection coefficient of the unit cell are presented by Fig. 4, showing two resonant frequencies the first one on 1GHz and the second on 1.38 GHz.

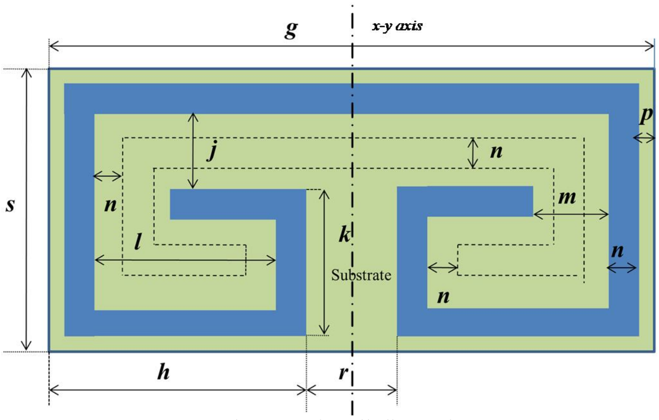
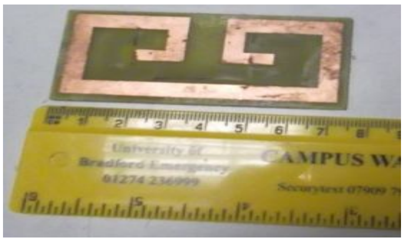
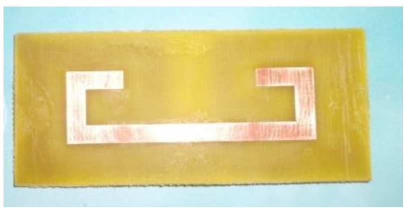


Fig. 2, Unit cell dimensions;
g = 74mm, s= 34mm, h = 31mm, r = 10mm,
l = 23 mm, k = 19mm, m =11mm, j = 18mm, n =4mm, p =2mm.



(a)



(b)
Fig. 3, Physical unit cell of metamaterial
(a) Front side, (b) bottom side

The refractive index of the unit cell is presented in Fig.5, low index of refraction (n<1) is observed from 1.495 GHz to 2 GHz and Zero index of metamaterial (ZIM) is observed from 1.34 GHz to 1.49 GHz.

The simulated unit cell on HFSS has shown very interesting results, Fig. 6.a and Fig. 6.b present the imaginary and real parts of respectively the permittivity and the permeability, the permittivity has near zero real parts (ENZ) from 1.34 GHz up to 1.65 GHz and the permeability has near zero real parts (MNZ) from 1.34 GHZ to 2 GHz.

In the literature [20], a clear DNG media (Double Negative, $\varepsilon_r \langle 0, \mu_r \langle 0$), involve application in the electromagnetic phenomena of reflection, absorption, radiation, cloaking, refraction, and sub-wavelength imaging, also low index of refraction [34,35], is subject of gain enhancement and high directivity.

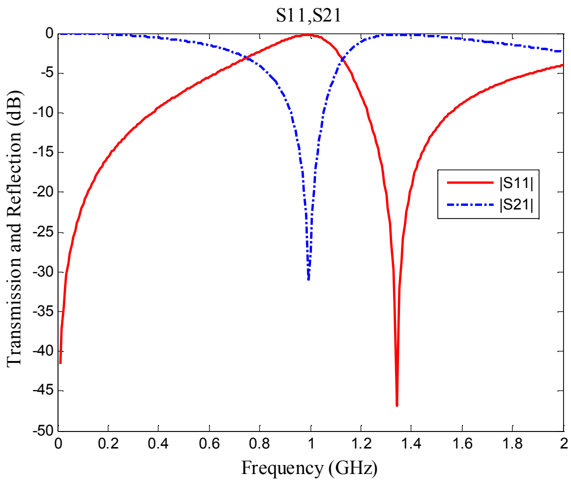


Fig. 4, Transmission and reflection coefficients

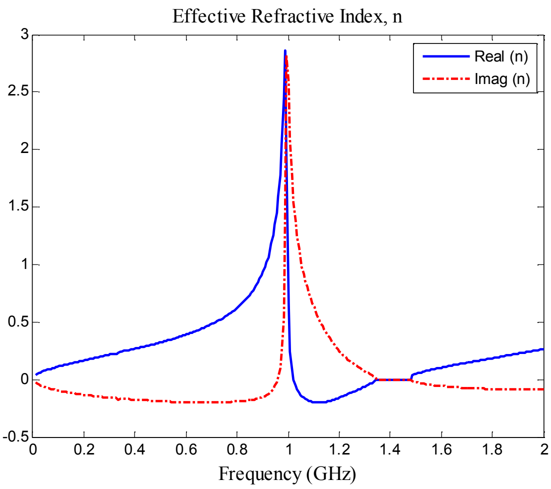
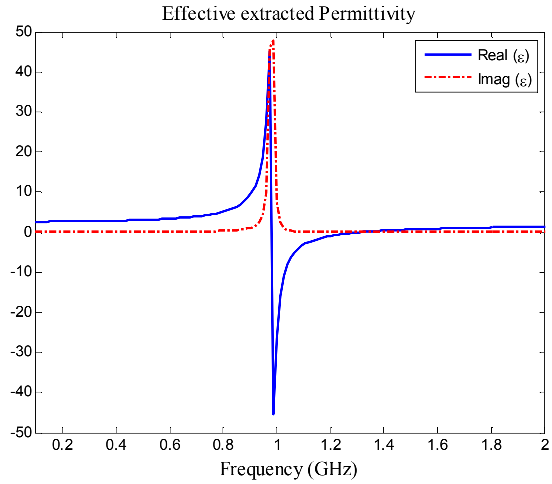
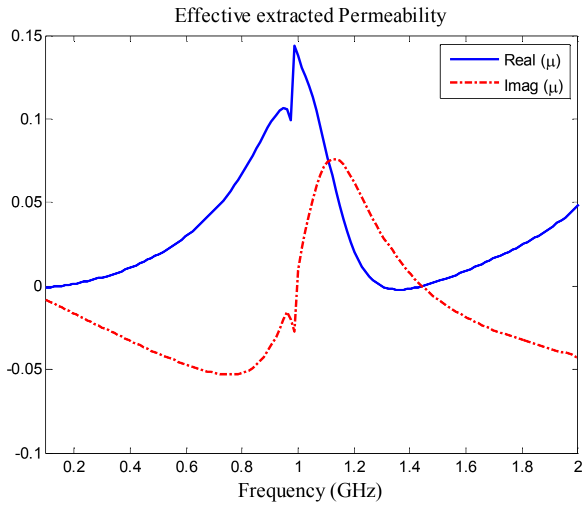


Fig. 5, Real and imaginary parts of the unit cell refractive index



(a)



(b)

Fig.6, Real and Imaginary parts of the unit cell permittivity (a); Real and Imaginary parts of the unit cell permeability (b).

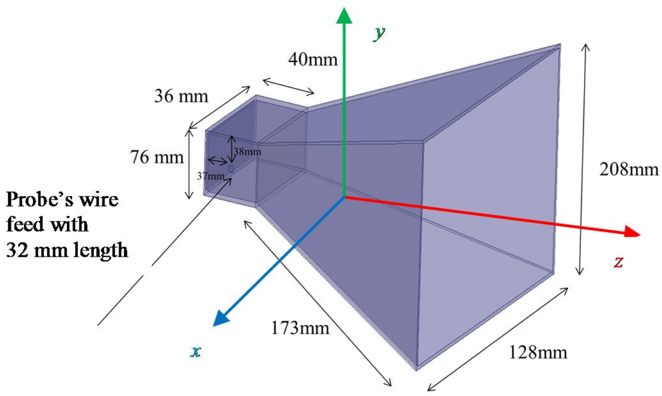


Fig. 7, Horn antenna dimensions.

Here in this paper the operating frequency for the horn antenna without metamaterial is 1.722 GHz to 1.931 GHz, since we are using a (ZIM) and low index within this range of frequency, subsequently this is leading to possible gain enhancement [36].

III. Horn Antenna Loaded with CLL

The horn antennas used in this study with or without metamaterial is operating in the range L-band, feed by a probe, having wire of 32 mm length as shown by Fig. 7. The CLL considered as metamaterial is placed vertically above the probe's wire as shown by Fig. 1, and Fig. 9, the geometrical dimension of the horn antenna is given by Fig. 8.

The position and the length of the probe's wire are optimized by HFSS in order to have desired resonant frequency and desired bandwidth. The excitation is considered to be TE_{01}, only the fundamental mode (oy axis) is allowed, the position of the feed is also optimized as shown by figure 7, 37 mm to the (z) axis and 38 mm to the (y) axis, Fig. 9 shows the metamaterial placement above the probe's wire, optimized to 2mm.

Fig. 8, Physical horn antenna.

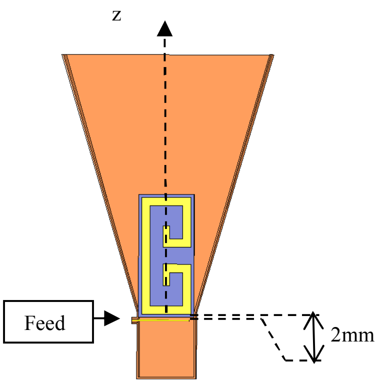


Fig.9, Horn antenna loaded with metamaterial.

In the experimental set, the unit cell was attached to the walls of the horn antenna with small pieces of Foam, which we think has no effect on the radiation pattern.

IV. Numerical Results

The reflection coefficient in Fig. 10, contains the measured and simulated results of the horn antenna without metamaterial, the resonant frequency is about 1.81 GHz, the bandwidth is from 1.722 GHz to 1.931 GHz, giving a bandwidth of 209 MHz. The measured and simulated results are almost in good agreement.

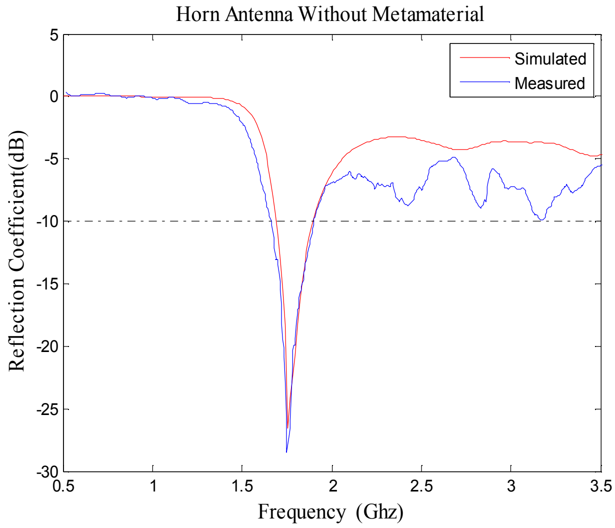


Fig. 10, Reflection coefficient, Horn antenna without metamaterial.

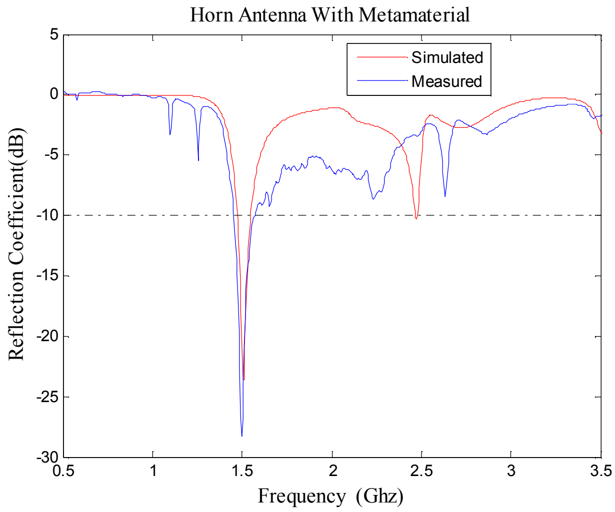


Fig. 11, Reflection coefficient of horn antenna with metamaterial.

The reflection coefficient shown in Fig. 11, presents the case of horn antenna loaded with metamaterial, it is clear that, the resonant frequency is shifted from 1.81 GHz to 1.5 GHz, a displacement of 17%, the bandwidth is slightly reduced from (1.722-1.931 = 0.209 GHz) to (1.45-1.55 = 0.1 GHz), there is a bandwidth reduction of 52%. Again the experimental and simulation results are almost in good agreement. The resonant frequency shift is considered as an advantage because it enables miniaturization effect.

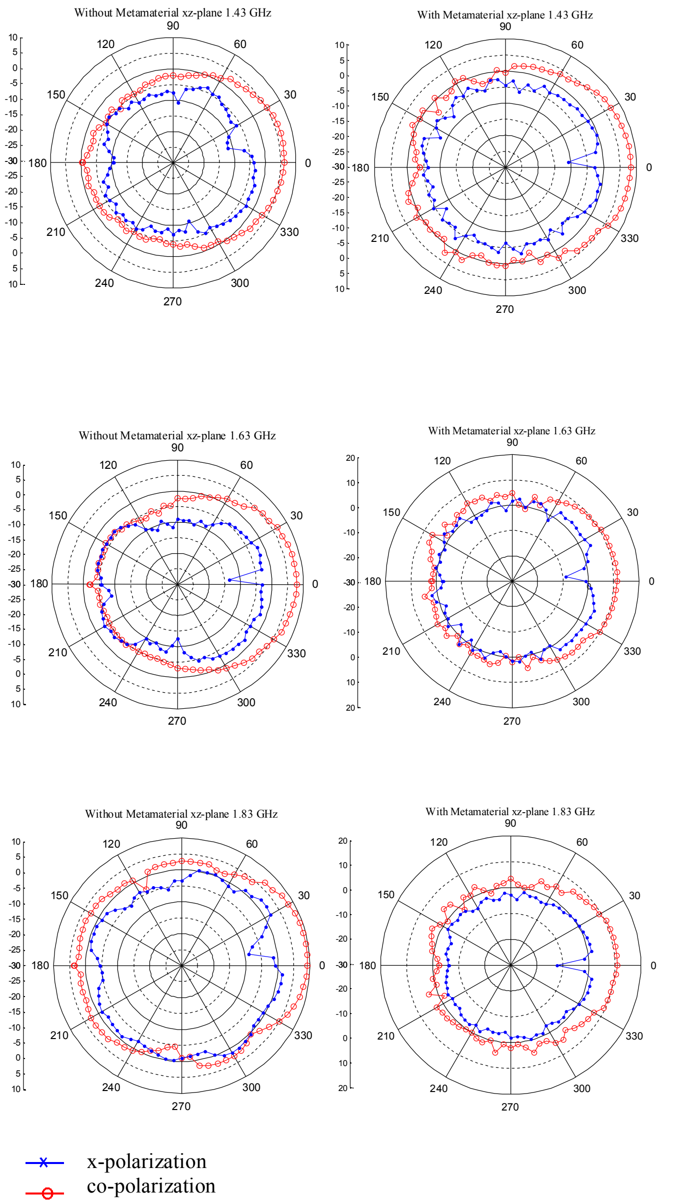


Fig. 12, Radiation pattern for the xz-plane with and without metamaterial, for three frequencies ; 1.43 GHz, 1.63GHz and 1.83 GHz.

The radiation pattern given in Fig. 12 is obtained by measurement for the x-z plane, left antenna without metamaterial and right antenna with metamaterial, three frequencies are presented; 1.43 GHz, 1.53 GHz and 1.63 GHz. It is noticed that for 1.43 GHz the co-polarization is increased from 6 dB to 8dB considered as an increase of 33%, for 1.63 GHz the co-polarization is increased from 7.5 dB to 11.5 dB considered as 53%, where as for the frequency 1.83 a very slight increase was observed. The cross-polarization is almost the same for all frequencies.

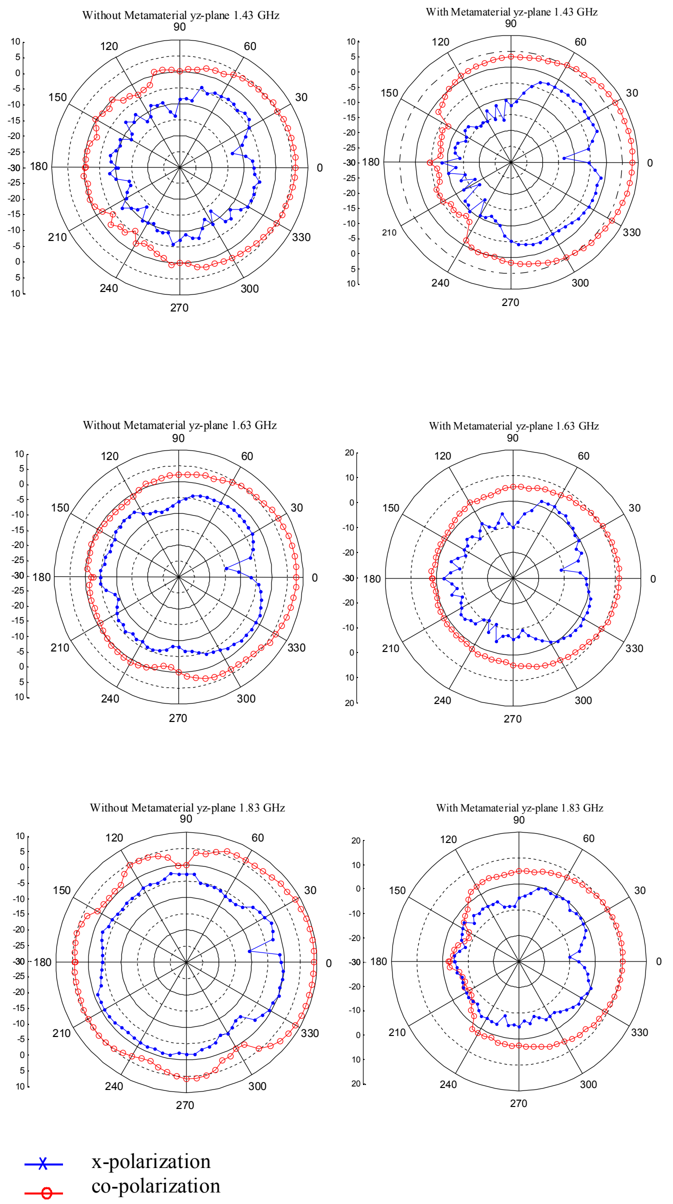


Fig. 13, Radiation pattern for the yz-plane with and without metamaterial, for three frequencies ; 1.43 GHz, 1.63GHz and 1.83 GHz.

Fig. 13 presents the measured radiation pattern of the yz-plane, it is remarkable that the co-polarization has almost increased with the same amount comparatively to the xz-plane.
Concerning the cross-polarization it is shown that there are slight decreases for all the frequencies comparatively to the xz-plane. By these facts it seems that in this special application the

yz-plane is more interesting than the xz-plane regarding the cross-polarization.

Fig. 14 presents the effect of the CLL unit cell loaded on the horn antenna regarding the total gain of the radiation pattern, from this figure it is clear that the effect on the gain starts from 1.45 GHz and ends on 2.1 GHz. Maximum gain is observed at 1.49 GHz where an increase of almost 3dB is remarked, this figure is recorded from HFSS and it is almost in agreement with the measured radiation pattern given above.

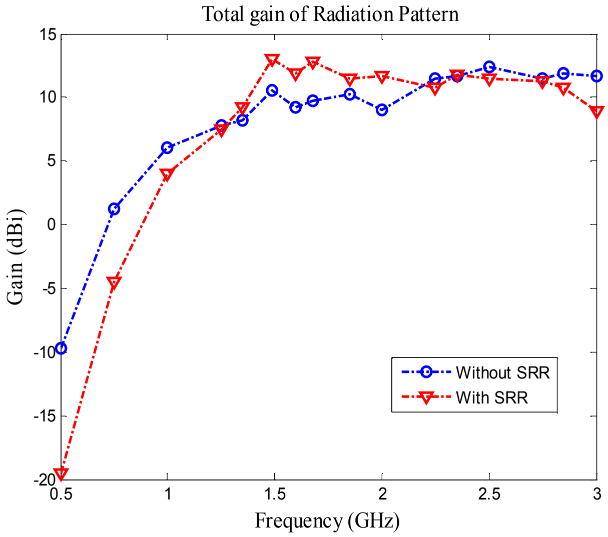
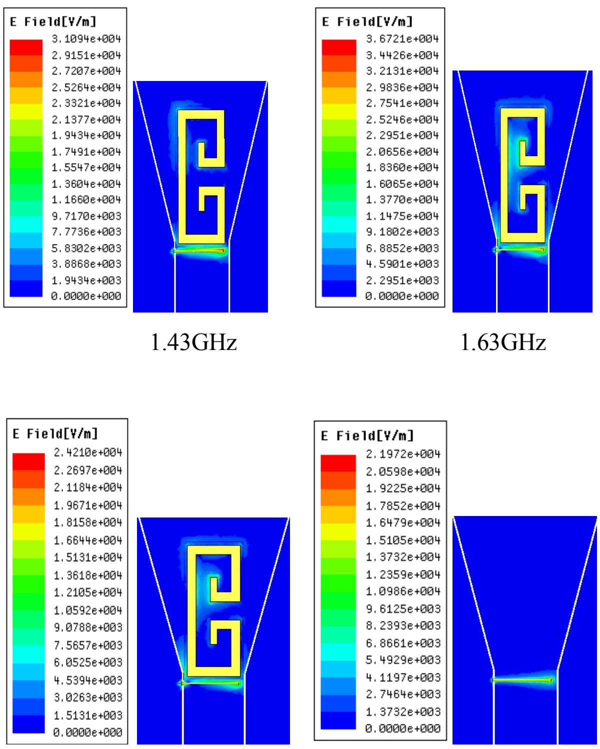


Fig. 14, Effect of the CLL on the total gain radiation pattern.



1.83 GHz 1.81GHz

Fig.15, Electrical field distributions with and without metamaterial for three frequencies; 1.43 GHz, 1.63 GHz, 1.81 GHz and 1.83 GHz.

The electric field distribution presented by Fig.15 shows that central frequency 1.63 GHz is presenting great field intensity either in the monopole antenna or in the CLL unit cell, compared to the case of frequency 1.83 GHz and 1.43 GHz. The case of horn antenna without CLL given for the resonant frequency 1.81 GHz presents lower field intensity.

It seems that the CLL unit cell enable more electric field, this due to the interaction between the probe's wire and the unit cell or probably the resonant frequency of the unit cell regenerates an intense electric field.

The electrical field intensity has increased from 2.19 10^4 V/m to 3.67 10^4 V/m, case of horn antenna with and without CLL for the frequency 1.63 GHz, an increase considered as 63%.

V. Conclusions

Horn antenna loaded with metamaterial for L-band and digital audio broadcast (T-DAB) application has been presented. The constitutive parameters of the CLL unit cell were retrieved by the standard procedure. The permeability and the permittivity of the unit cell have near zero values with low index of refraction that exhibits zero index metamaterial (ZIM) in supporting gain enhancement.

The results obtained by simulation and experimentally, show that, by loading the horn antenna with metamaterial, the resonant frequency was shifted of 17% towards lower frequencies and the bandwidth was reduced to 52%. The resonant frequency shift can be used to enable miniaturization effect. The radiation pattern gain in the xz-plane and the yz-plane has increased by 33% for the frequency 1.43 GHz; 52% for the frequency 1.63 GHz, and the cross-polarization in the yz-plane was slightly reduced compared to the xz-plane in the case horn antenna loaded with CLL. The Electrical field intensity has been increased by maximum of 67%, by loading the horn antenna with one CLL.

Further work can be done to improve the gain for both plane xz-plane and yz-plane, and improve the cross-polarization reduction, by just increasing the number of CLL unit cells or modelling new type of metamaterial.

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