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COMPACT BASE STATION ANTENNAS USING METAMATERIALS

X. Liu[1], S. N. Burokur[1, *], A. de Lustrac[1], G. Sabanowski[2], and G.-P. Piau[2]

[1]IEF, Univ. Paris-Sud, CNRS, UMR 8622, Orsay Cedex 91405, France

[2]EADS IW, Suresnes 92000, France

Abstract—The paper deals with the modelling, practical implementation and characterization of a directional antenna controllable through 360° in the [2–2.5 GHz] frequency band. The antenna is composed of a central omnidirectional broadband monopole feed surrounded by a metamaterial made of one or two controllable layers of metallic strips printed on a dielectric substrate, which can be electrically continuous or discontinuous. Following the electrical state of these strips, the metamaterial can be reflective or transparent. Then by controlling the distribution of reflective and transparent regions of the latter metamaterial around the central feed, a directional emission having an angular beamwidth lower or equal to 60° and controllable through 360° is produced in the UMTS and WIFI frequency bands, demonstrating the wideband operation of this antenna.

1. INTRODUCTION

Metamaterials are intensely used for the design of directive antennas [1–4]. In [1], Enoch et al. proposed to use the refractive properties of a low optical index material interface in order to achieve a directive emission. In [2], Ourir et al. have shown the possibility of using a novel composite metamaterial surface as a partially reflective metasurface in a Fabry-Pérot (FP) cavity system to produce an ultrathin highly directive antenna. Recently reported coordinate transformation concept has also been used to design directive antennas from metamaterials showing electric and magnetic resonances [3, 4]. However, all these structures have been designed in a

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* Corresponding author: Shah Nawaz Burokur (shah-nawaz.burokur@u-psud.fr).

planar configuration. In this present study, we present the design, implementation and characterization of a broadband compact base station antenna operating in the [2 GHz–2.5 GHz] frequency range. The proposed antenna makes use of a controllable metamaterial composed of one or two layers of metallic strips printed on a thin dielectric film. The metamaterial is then conformed on a cylinder made of a foam dielectric.

Metamaterials composed of continuous or discontinuous metallic wires present very interesting features that can be applied to directive antennas [5, 6]. Indeed a controllable electromagnetic band gap material made of metallic wires incorporating PIN diodes had been previously proposed as electronic commutation devices [5]. This idea was developed and generalized in several works [6–9] for applications to directive antennas and smart antennas. In these previous papers, the lattice of metallic wires was considered as an electromagnetic band gap (EBG) material with an inter-layer of about a quarter of the working wavelength. The main drawback of this EBG material is then the overall thickness. However, Pendry et al. have demonstrated that a periodic lattice of thin continuous metallic wires with a period much lower than the wavelength can be considered as a metamaterial presenting a negative permittivity for frequencies under the equivalent plasma frequency of the lattice [10]. Then, the material is reflective for a wide frequency band determined by the geometrical parameters of the lattice and also by the dielectric permittivity of the host medium in which the wires are inserted. Conversely, a lattice made of electrically discontinuous wires presents a positive effective equivalent permittivity and is transparent at low frequencies [5]. In [7, 8], cylindrical antennas based on the concept of electromagnetic band gap materials with a distance between two consecutive layers varying between $\lambda/4$ and $\lambda/3$ and with the necessity of using a number of layers sufficient to obtain a correct bandwidth were studied. These constraints thus lead to large structures having a diameter approaching 2λ. In [11], Edalati and Denidni overcome this difficulty by considering only one layer, but with the constraint of having a limited operating frequency band. In contrast with these previous studies, we propose here a structure based on the concept of metamaterial with distance between layers less than $\lambda/7$ and we show that only two layers are sufficient to provide the desired bandwidth, beamwidth and transmission switching. This leads to the design of more compact antennas (diameter around λ) presenting wider frequency bandwidth compared to the case of Ref. [11]. We also show that the use of two layers allows a better control of the beamwidth and transmission switching.

2. DESIGN OF THE PRIMARY SOURCE

In this work, we favor the design of a base station antenna operating in UMTS and WIFI frequency bands. To do so, we first require a primary source able to radiate over the desired frequency bands. The schematic structure of a broadband conical monopole acting as the primary radiating source is shown in Figure 1(a). The ground plane considered for the monopole is a metallic disk of radius $R_g = 10\,\text{cm}$. The centre frequency and the frequency band are determined by the length and also by the ratio between the diameter of the upper part (Φ_u) and that of the lower part (Φ_l) of this monopole [12]. The simulated monopole feed has a working band extending from 1.3 GHz to 3.1 GHz

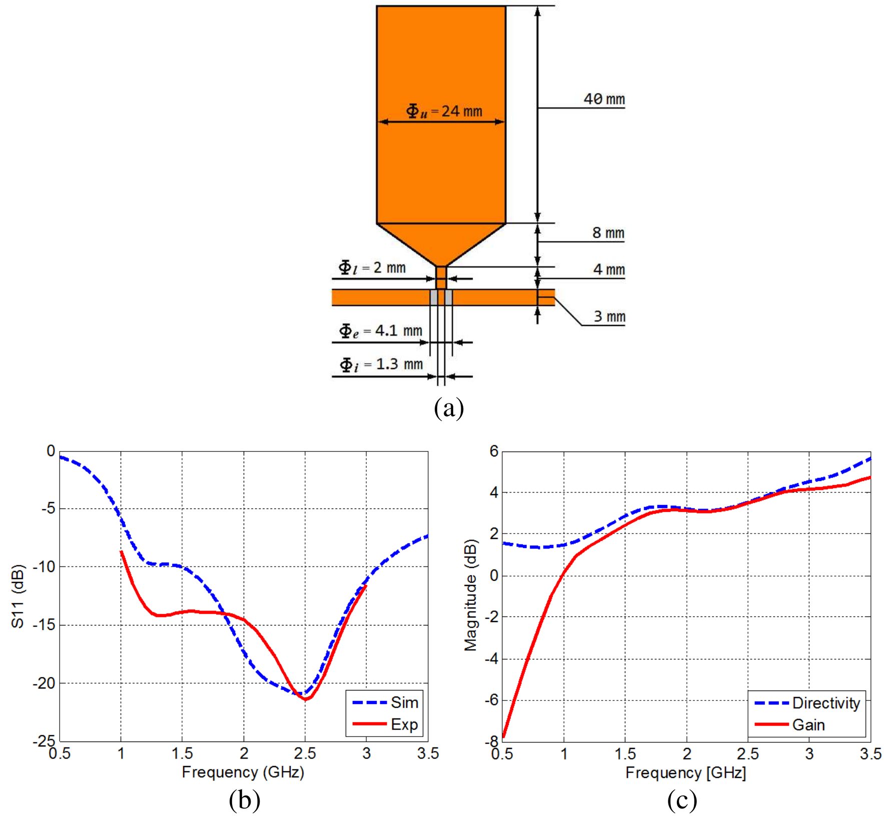

Figure 1. (a) Schematic view of the conical monopole primary source. (b) Simulated and measured S_{11} parameter. (c) Simulated directivity and gain.

as illustrated by the S_{11} parameter shown in Figure 1(b). Figure 1(c) shows that the conical monopole source presents a directivity varying from 2.2 to 4.5 dBi in the same frequency range. The measured S_{11} parameter agrees very well with the simulated one and shows good matching ($S_{11} < -10\,\text{dB}$) over the range 1.05 GHz–3 GHz.

3. METAMATERIAL UNIT CELLS

Figure 2(a) shows the elementary cells of the metallic continuous and discontinuous copper strips lattices printed on a thin dielectric film having a thickness of 60 µm and presenting a relative permittivity of 2.9. The lattice period and the strips width are respectively 10 mm ($\lambda/15$ at 2 GHz) and 0.6 mm. The film is then disposed on a foam dielectric substrate with relative permittivity 1.07. Concerning the discontinuous strips, the cut width is 0.3 mm. Figure 2(b) shows the calculated transmission and reflection (S-parameters) of one and two layers of both lattices for a normal incident wave with the E-field parallel to the metallic strips. In the case of the two layers, the inter-layer distance is 1.6 cm as used in the final antenna prototype. Calculations are performed using the finite element commercial code HFSS from Ansys in the [1 GHz–3 GHz] frequency band. The S-parameters show that the continuous strips structure is reflective whereas the discontinuous strips structure is transparent on a wide frequency band extending from 1 to 3 GHz, covering the frequency band of the conical antenna presented above. The difference in transmission level between both lattices is respectively around 12 dB for one layer and 29 dB for two layers at 2 GHz. Equivalent effective parameters are retrieved using the Nicolson-Ross method [13]. Figure 2(c) shows the calculated equivalent permittivities for the metamaterial with two layers. When the layers are made of continuous wires, the equivalent permittivity is negative with a Drude-like frequency dependency. The material is then reflective over the whole frequency range of interest. When the layers are made of discontinuous wires, the equivalent permittivity is positive with values close to 1 and the material is then transparent. One interesting feature of this metamaterial is that it can be conformed on simple shapes such as a cylinder, without deteriorating their electromagnetic properties [9]. Based on these electromagnetic properties, a base station antenna presenting wide beamwidth in the azimuth plane and directive beamwidth in the elevation plane is designed.

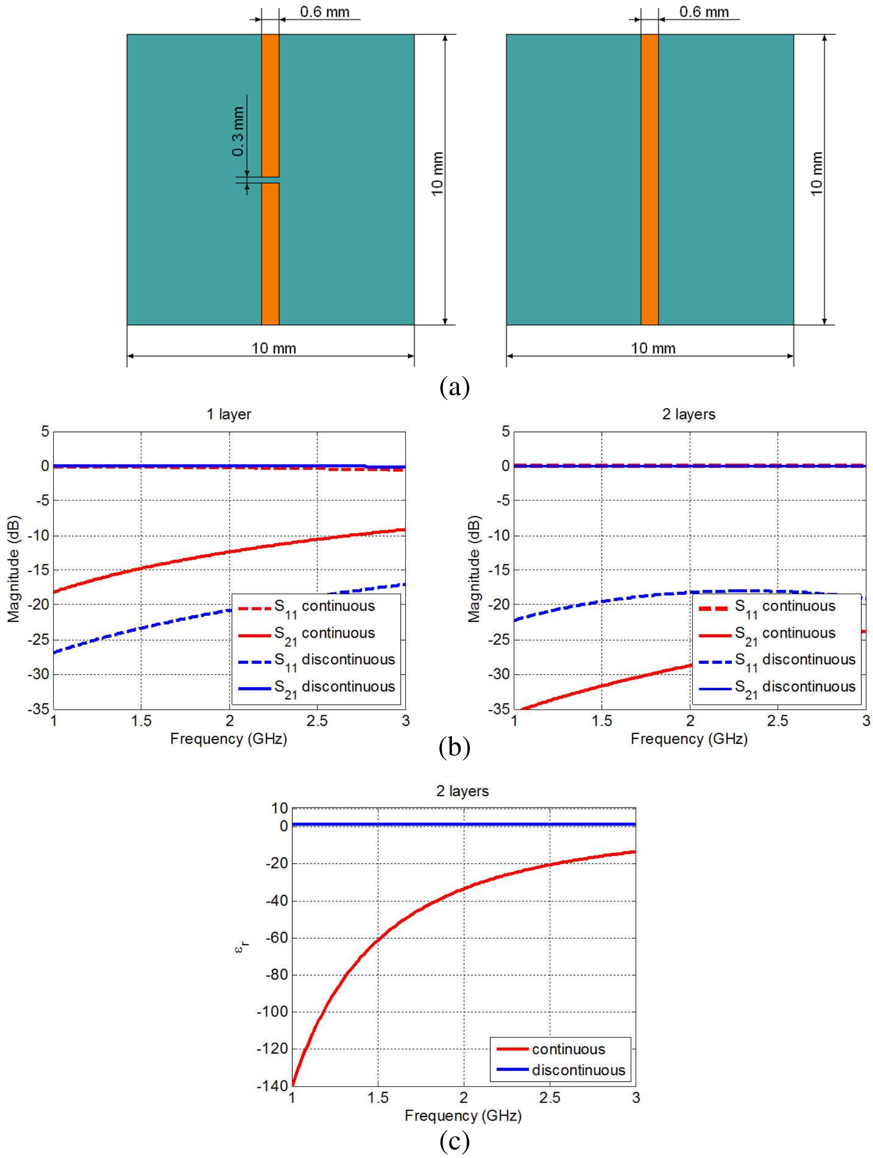

Figure 2. (a) Elementary cells of a lattice made of a layer of respectively continuous and discontinuous metallic strips. (b) S-parameters of one and two layers of both lattices for a normal incident wave with the E-field parallel to the strips. (c) Effective permittivities of the two layers with continuous (red curve) and discontinuous wires (blue curve).

4. SIMULATION OF THE CYLINDRICAL BASE STATION ANTENNA

The base station antenna is designed such that it respects a cylindrical shape as shown by the schematic structure in Figure 3. It is composed of the central isotropic conical broadband radiating element depicted in Figure 1(a), which is surrounded by the cylindrical metamaterial of Figure 2. In a first step, the reflector is made of only one metamaterial layer of copper strips printed on the thin dielectric film and curved on the outer face of a cylindrical shaped foam dielectric ($\varepsilon_r = 1.07$) of radius r. The metallic strips on the foam cylinder are continuous or discontinuous. The green region of Figure 3(a) corresponds to discontinuous strips and covers an angle α. This latter region is transparent for electromagnetic waves in the frequency band of interest, as detailed in the previous section. Conversely, the $(360 - \alpha)^\circ$ angular red region corresponds to continuous strips in order to reflect waves towards the transparent region. In a final step, a second metamaterial layer is placed around the first one separated by a distance $R - r$. The goal is to realize an antenna covering the UMTS (1.92–2.17 GHz) and WIFI (2.4–2.6 GHz) frequency bands. It must be able to emit a directive lobe with an angular width $\leq 60^\circ$ through 360° around the axis of the antenna and show overall dimensions lower than 20 cm.

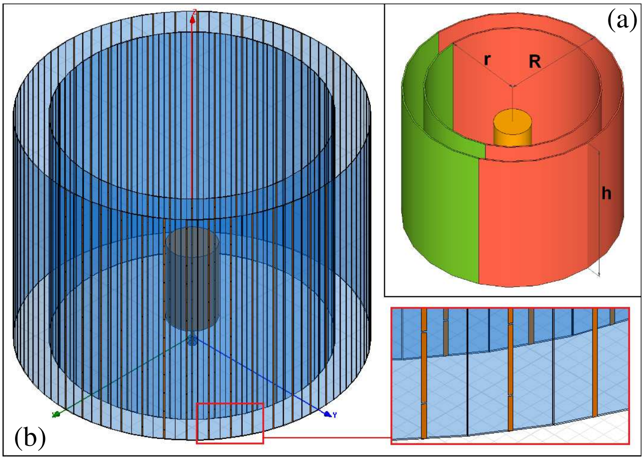

Figure 3. (a) Schematic view of the two metasurface-layer antenna with the discontinuous wires zone (green) and the continuous one (red). (b) Design incorporating continuous and discontinuous wires used in the simulation process. The inset shows the discontinuous wires in the design.

An optimization process is undertaken on the design parameters r, α and h in order to have the best tradeoff in return loss of the antenna comprising two metamaterial layers. As it can be observed from Figure 4(a), $r = 6.4\,\text{cm}$ for the metamaterial layer allows a very good impedance matching with vacuum. This matching is very sensitive to r. The angle α shows however less influence than r on the S_{11} coefficient of the antenna. Two frequency bands where the antenna is matched ($S_{11} \leq -10\,\text{dB}$) are clearly visible in Figure 4(b) for the three different values of α with an optimized result for $\alpha = 120°$. When h is increased from 6 cm to 12 cm, the antenna is better matched around 2.2 GHz for $h = 12\,\text{cm}$. For the sake of compactness, we assume the S_{11} to be reasonable even if better matching can be obtained for $h > 12\,\text{cm}$.

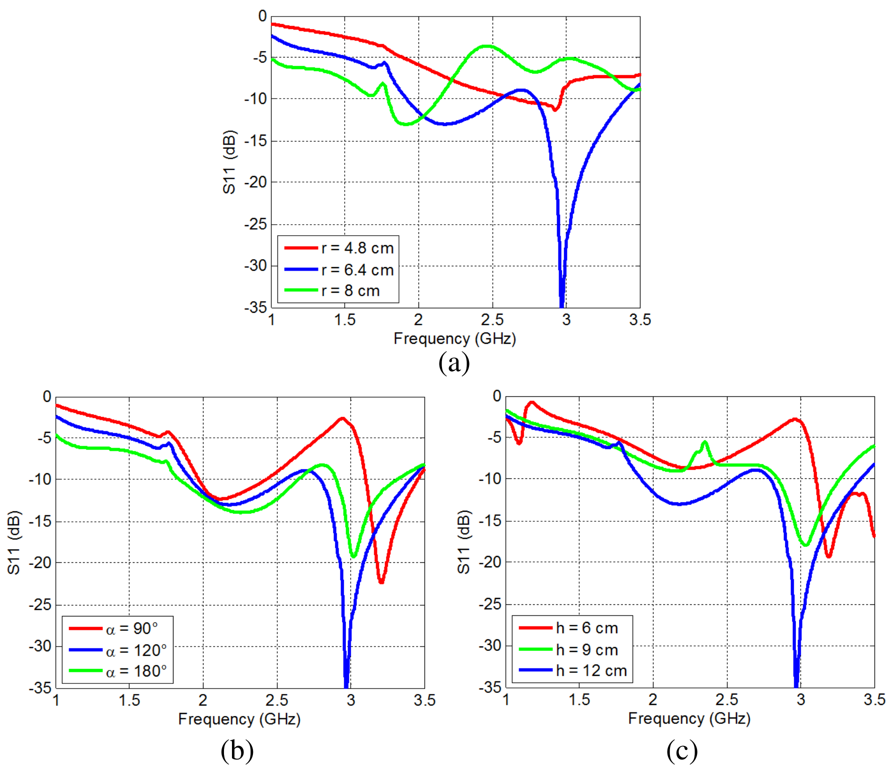

Figure 4. Optimization of the design parameters r, α and h for best tradeoff in impedance matching with $R - r = 1.6\,\text{cm}$. (a) r varying with $\alpha = 120°$ and $h = 12\,\text{cm}$. (b) α varying with $r = 6.4\,\text{cm}$ and $h = 12\,\text{cm}$. (c) h varying with $\alpha = 120°$ and $r = 6.4\,\text{cm}$.

After optimization, we obtain $h = 12\,\text{cm}$, $R = 8\,\text{cm}$, $r = 6.4\,\text{cm}$ and $\alpha = 120^\circ$. The calculated S_{11} parameter is shown in Figure 5(a) for one and two metamaterial layers. A good impedance matching can be observed between 1.9 GHz and 3.4 GHz. The calculated H-plane (plane containing H and k vectors) radiation patterns are presented in Figures 5(b) and 5(c). Compared to the monopole source alone which presents an omnidirectional pattern in the H-plane, the cylindrical metamaterial antenna presents a more directional pattern. The half-power beamwidth varies from 105° to 39° as frequency increases from 1.5 GHz to 2.5 GHz for the one-layer antenna and from 86° to 34° for the two-layer antenna. However, in both prototypes, a high level of backward radiation can be observed for frequencies above 2.3 GHz.

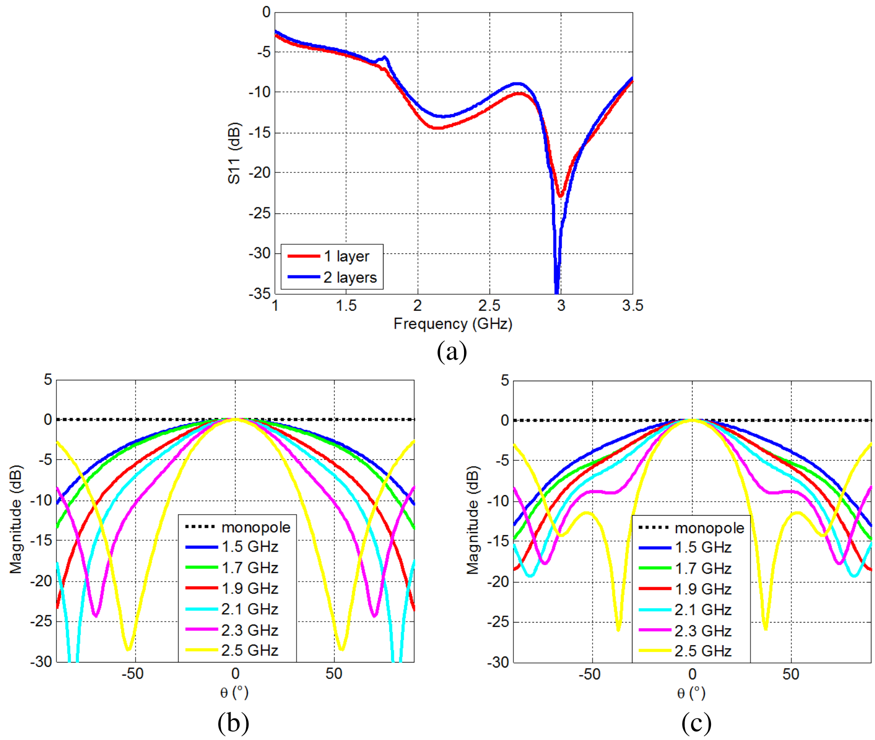

Figure 5. (a) Simulated S_{11} parameter of the base station antenna with a metamaterial made of one and two layers. (b)–(c) Simulated H-plane radiation patterns for respectively one layer and two metamaterial layers.

5. EXPERIMENTAL VALIDATION OF THE CYLINDRICAL BASE STATION ANTENNA

A prototype of the base station antenna comprising the metamaterial has been fabricated and measured (Figure 6(a)). The measured S_{11} parameter shows that the base station is well matched in the [2 GHz–3 GHz] frequency band (Figure 6(b)) and agrees very well with simulations. The far-field radiation patterns of the antenna have been measured in a full anechoic chamber from 1.5 GHz to 2.5 GHz. The fabricated prototype is used as emitter and a horn antenna is used as the receiver to measure the radiated power level of the emitter. The measured far-field radiation patterns in the H-plane are presented

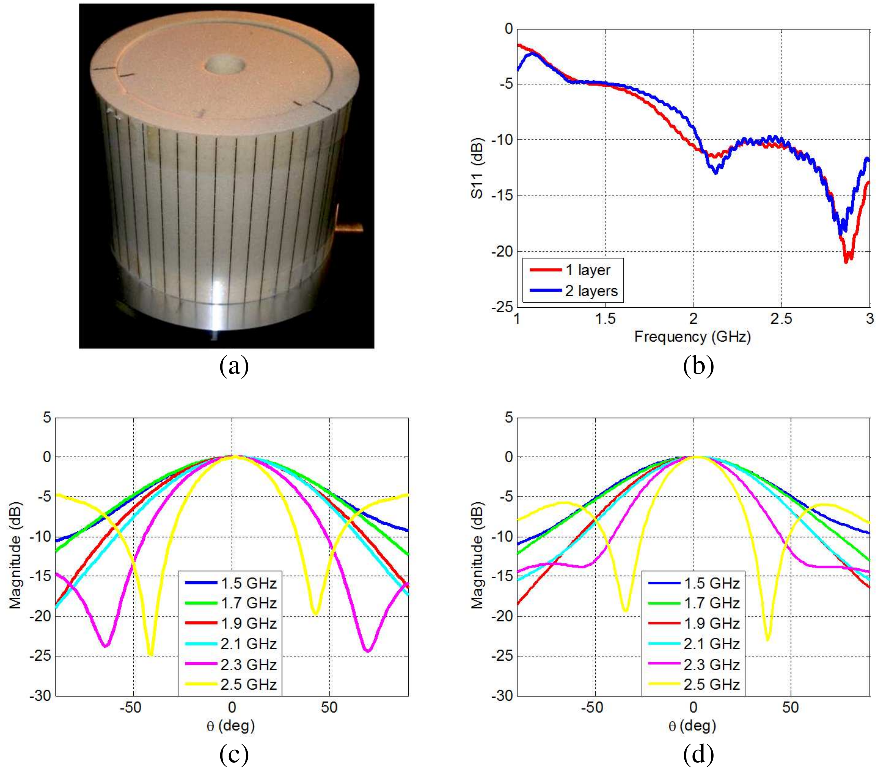

Figure 6. (a) Photography of the fabricated antenna. (b) Measured S_{11} parameter of the base station antenna with a metamaterial composed of one and two layers. (c)–(d) Measured H-plane radiation patterns for metamaterial with respectively one layer and two layers.

in Figures 6(c) and 6(d) for the prototype with the metamaterial composed of respectively one and two layers. We can observe that the -3 dB beamwidth of the radiated lobe varies from 76° at 1.5 GHz to 35° at 2.5 GHz for the one-layer antenna. For the antenna incorporating two layers, the half-power beamwidth varies from 74° to 30° in the [1.5 GHz–2.5 GHz] frequency range. Similarly to simulations, high sidelobe level appears in the measured radiation patterns as from 2.3 GHz.

6. CONCLUSION

A compact ($20 \times 20 \times 12\,\mathrm{cm}^3$) directional broadband antenna in the UMTS and WIFI bands controllable through 360° has been proposed. It is composed of a central omnidirectional broadband monopole feed surrounded by a metamaterial made of one or two metamaterial layers of metallic continuous and discontinuous strips. The emission of the antenna is studied for both structures of metamaterial. Equivalent effective permittivity of this metamaterial calculated by a retrieval procedure shows that the material made of continuous metallic wires presents a negative permittivity and is reflective, while the same material composed of discontinuous wires presents a positive permittivity and therefore becomes transparent. By controlling spatially the distribution of reflective and transparent zones of this metamaterial around the central feed, the emitted radiation is rendered directional with a -3 dB beamwidth $\leq 60°$ and controllable through 360°. It is shown that the use of a metamaterial composed of two layers allows to reduce the beamwidth by 10%. Even with two layers this antenna is more compact by a factor of 3 than those proposed in Refs. [4, 5]. This study constitutes a first step towards an agile antenna made of an active metamaterial composed of copper strips incorporating switching elements such as PIN diodes or MEMS.

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