Modeling and simulation of an antenna with optimized AMC reflecting layer for gain and front-to-back ratio enhancement for 5G applications

A Hocini¹,³, N Melouki¹ and T A Denidni²

¹Laboratoire d’Analyse des Signaux et Systèmes, Department of Electronics, University of M’Sila, B.P.166, Route Ichebilia, M’Sila, 28000, Algeria
²Institut National de la Recherche Scientifique (INRS), Université Laval, Montreal, Quebec, Canada

E-mail: abdesselam.hocini@univ-msila.dz

Abstract. A low-profiled microstrip patch antenna for application in the 5G wireless communication systems is backed by a reflecting layer based on an optimized artificial magnetic conductor (AMC) to enhance the gain and the front-to-back ratio. The design and analyses process were carried out using the full-wave commercial simulator CST Microwave Studio in parallel with Matlab, using the embedded CST to Matlab VBA-based interface to create an automated simulation environment and to design both a conventional antenna and the proposed one. A genetic algorithm (GA) is used to optimize the AMC reflecting layer to achieve maximum gain and front-to-back ratio around the frequency band of interest. The results yield an important enhancement in the peak gain and front-to-back ratio, alongside a low side-lobe level (SLL) due to the successful surface waves suppression, thus making this antenna design a good candidate for future wireless communication systems.

1. Introduction

Microstrip patch antennas play a vital role in today’s communication systems, as they are widely used to establish communication links between wireless devices due to their unique properties, such as low profile, compactness, low-cost and simple fabrication, and capability of integration with solid-state devices [1]. In spite of these remarkable advantages, microstrip patch antennas suffer from narrow bandwidth and low gain and efficiency.

The upcoming 5G wireless communication systems require high-performance antennas, namely, low-profile and compact antennas with high gain and efficiency and a broad bandwidth. Tackling the microstrip patch antennas disadvantages would make them perfect candidates to meet all such 5G networks’ requirements.

Increasing the substrate’s thickness can improve the bandwidth; however, using a thicker substrate would generate more and stronger surface waves. As a result, the radiation efficiency and gain would be degraded. In [2], the authors used a negative-index metamaterial with a modified split-ring resonator unit cell to improve the bandwidth while maintaining the degree of miniaturization; in [3], a synthesized photonic bandgap substrate was used to widen the bandwidth and improve the return loss at stable high gain.

³ To whom any correspondence should be addressed.
With the aim of solving the low gain and efficiency problem, electromagnetic band gap structures and artificial magnetic conductors (AMC) have been used to enhance and improve the performances of microstrip patch antennas. In [4], the authors used aperiodic photonic crystals with drilled air-gap holes in different configurations to achieve higher gain and efficiency. In [5], the gain and the front-to-back ratio were enhanced using a novel elliptical electromagnetic band gap structure; whereas in [6], such a structure was used as a reflector to suppress the surface waves at the operating frequency, which led to increased gain.

In this work, a probe-fed microstrip patch antenna is proposed for operation at 30 GHz; it is backed by an AMC structure that acts as a reflector thus improving the front-to-back ratio and the gain. To optimize and achieve the desired AMC unit cell parameters, a genetic algorithm is applied using the established VBA language interface between Matlab and CST Microwave Studio. The results yield an important improvement in terms of front-to-back ratio (low side-lobes level) and gain compared with the conventional design.

2. AMC unit cell and antenna design

2.1. AMC unit cell

As is known, upon reflection a perfect electric conductor (PEC) shifts by 180° the phase of a normally incident wave; whereas in the case of a perfect magnetic conductor (PMC), the phase shift is 0° An AMC mimics this property at a resonance frequency [7]. AMCs also exhibit a high surface-impedance property that can be used to suppress surface waves. As a result, the antenna’s gain and side lobe levels are increased and reduced, respectively [8], when an AMC structure is used as a reflector such as in the case discussed here.

We consider an AMC unit cell structure consisting of a simple square patch on a Rogers (RT5880) substrate with a relative permittivity ($\varepsilon_r$) of 2.2, a loss tangent ($\tan\delta$) of 0.0009 and a thickness of 0.787 mm. The dimensions of the unit cell (figure 1 (a)) are calculated using the equivalent LC model from [8] (figure 1 (c)), $w_{amc}$ and $g_{amc}$ being the patch width and the gap width, respectively. All above parameters where chosen carefully so that the AMC’s zero-reflection property should occur near the frequency of 30 GHz. Figure 1 (d) shows the CST Microwave Studio simulation model used [9].

Figure 2 shows the simulated reflection phase response of the initial AMC unit cell with $w_{amc} = 1.3428$ mm, $g_{amc} = 0.2$ mm, and $h_{amc} = 0.787$ mm. These parameters yield a resonance frequency of 28.77 GHz for the 0° reflection phase, with a ±90° reflection phase bandwidth of 13.44 GHz (22.77 – 36.21 GHz). Thus, the unit cell parameters need to be adjusted in accordance with the desired band.

Figure 1. AMC unit cell (a) front view; (b) side view; (c) equivalent circuit; (d) numerical simulation model

Figure 2. Simulated reflection phase of the initial AMC unit cell and of the optimized one.
To optimize the parameters of the unit cell, we used a genetic algorithm (GA) in combination with the full-wave simulation tool (CST MWS). As is known, genetic algorithm optimizers are robust, stochastic search methods modeled on the principles and concepts of the natural selection and evolution [10]. The flowchart of the proposed optimization process is shown in figure 3.

The AMC patch size $w_{amc}$ and the gap $g_{amc}$ were selected as state variables. The relative permittivity $\varepsilon_r$ and the height $h_{amc}$ of the AMC substrate are considered constant and equal to 2.2 and 0.787 mm, respectively. The zero-phase frequency is set at $f_{amc}=30$ GHz.

The optimization objective was formulated as a two-criterion function with respect to both the zero-phase frequency position and the maximum bandwidth. Thus, the fitness function was defined and minimized as:

$$F = \left(\frac{f_{amc_{max}} + f_{amc_{min}}}{2} - f_{amc}\right)^2 - \left(\frac{f_{amc_{max}} - f_{amc_{min}}}{f_{amc}}\right),$$

where $f_{amc_{max}}$ and $f_{amc_{min}}$ are the upper and lower limit of the $\pm90^\circ$ reflection phase bandwidth.

The minimum and the maximum value of the patch size $W_{amc}$ were set to 1 mm and 2 mm, respectively; the gap $g_{amc}$ was defined within the range $0.1 - 0.5$ mm. The initial population consisted of 50 random individuals undergoing the selection process (roulette); the probability of crossover was 100%, the probability of the mutation was set at 1%, and the number of generations was set to be 50.

After reaching the maximum number of iterations, the final optimized parameters for our designing scenario were:

$w_{amc} = 1.2477 \text{ mm}, g_{amc} = 0.2 \text{ mm}, h_{amc} = 0.787 \text{ mm};$

the reflection phase diagram for the best optimized individual is shown in figure 2.

2.2. The proposed design

The AMC unit cell optimized above was used as a reflector to enhance the performances of a probe-fed microstrip patch antenna with a rectangular radiator of $3.53 \times 2.55 \text{ mm}^2$ printed on top of a Rogers RO3003 dielectric slab with a relative permittivity of 3, a loss tangent of 0.001 and dimensions of $7.06 \times 5.11 \times 0.254 \text{ mm}^3$, width, length and thickness respectively. The characteristic impedance of the coaxial feed line was 50 ohm; the line passed through a hole in the AMC reflector to feed the patch. These parameters were calculated [11] so as the designed antenna would have a resonance frequency of
30 GHz. The proposed antenna is suspended at a height $h_z$ above the AMC surface, which is an array of $12 \times 12$ unit cells ($17.37 \times 17.37$ mm$^2$). Figure 4 shows the geometry of the proposed antenna.

The distance, $h_z$, needs to be chosen carefully to enhance the antenna’s performances in terms of the back-reflected radiation. Therefore, a parametric study with different spacing $h_z$ needs to be conducted to illustrate the performance enhancement.

3. Simulation results and discussion
The simulated return loss $S_{11}$ for both the conventional antenna and the AMC-backed one is shown in figure 5. By varying the distance $h_z (0 – 10$ mm), different return loss values are obtained, the best one being $-52.72$ dB at a distance of $h_z = 4.6$ mm, with a resonance frequency of 30.37 GHz, compared with the conventional antenna, where the return loss is $-30.6$ dB at a resonance frequency of 30 GHz. Thus, a frequency shift is introduced by the AMC surface due to its electromagnetic properties. Both antennas’ impedance bandwidth is around 3.53 % (1.06 GHz). A significant improvement of about 72.29 % in the return loss is achieved.

Figure 6 illustrates the gain and the SLL of the proposed antenna as a function of the spacing between the antenna and the AMC surface. The maximum peak gain achieved is 9.28 dB at a distance of 0.5 mm with an SSL of $-18.9$ dB, while the peak gain of the conventional antenna is 7.34 dB with an SSL of $-15$ dB. Thus, improvement is seen of 26.43 % (1.94 dB) in the peak gain and 26 % ($-3.9$ dB) in the SLL.

The lowest SLL value is $-24.6$ dB for a distance of 9.4 mm with a gain of 8.55 dB, or an improvement of 63.8 % ($-9.57$ dB) in the SLL and an increase of 16.49 % in the peak gain. The necessity thus becomes obvious of a trade-off between a higher peak gain or a lower SLL. The above findings also indicate that the maximum front-to-back performance is achieved at a spacing $h_z$ of 9.4 mm (see figure 6), due to the effectiveness of back-radiation suppression (surface waves) when incorporating an AMC-based reflector in the antenna. Also, the antenna’s gain may be further enhanced by increasing the number of cells on the AMC surface.

4. Conclusions
In this work, a probe-fed microstrip patch antenna suspended over an AMC based reflector was simulated and investigated. A parametric study was conducted by varying the spacing between the AMC reflector and the suspended microstrip antenna. Most importantly, the proposed design effectively improved the antenna’s gain up to 9.28 dB; the side lobe level was also improved down to $-24.57$ dB due to the successful suppression of the surface waves. Therefore, the compact overall
size of the structure (17.4 × 17.4 mm) and the relatively high gain make the proposed design an extremely attractive candidate for the next generation (5G) of mobile communication systems.

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