PROJECT III.5 PHOTONIC CRYSTALS, METAMORPHIC MATERIALS AND NOVEL RF SYSTEMS

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Objectives

To design, optimize and fabricate photonic crystals and frequency-agile metamaterials (metamorphic materials) to be used as electromagnetically active filters and substrates/superstrates for novel embedded antenna architectures and other systems (filters, waveguides and resonators) operating in the microwave/mm-wave region, for applications in novel RF transceivers.

MAIN RESULTS IN 2011

On-Package integration of Planar Spiral Artificial Magnetic Conductors and Dipole Antennas for single-chip 60 GHz Radio Transceivers

The new generation of integrated radio transceivers operating in the 60-GHz range, opens up a wealth of future applications with communication bandwidths up to 9 GHz offering great speed for data transmission, unmatched by current devices. These transceivers require antenna elements and arrays optimally designed and integrated in close proximity to transceiver dies, preferably embedded on-package. Even though 60-GHz radios allow for the first time direct integration of antennas on die packages, integration and coupling problems become significant due to the high frequencies involved and the macroscopic design rules and low manufacturing tolerances of packaging technologies. Studying novel robust design approaches maximizing antenna element performance for these future mobile terminals becomes an area of great scientific and commercial interest, given the very stringent package technology constraints and performance requirements fundamental for 60-GHz radios:

(1) Large bandwidths of 15% or more, covering the 57-66 GHz spectrum plus extra band-edge to allow for detuning due to coupling. (2) Directional radiation with high element gain and minimal back radiation on the die side. This is very important since high propagation loss at these frequencies demands the radiated energy into tightly focused beams. (3) Small areas and thickness fitting package integration resulting in antenna profiles a fraction of the wavelength, even at 60 GHz. (4) Adherence to packaging layout rules allowing prescribed values of permittivities, metal layer positions, large via diameters relative to antenna design features, and package metal trace constraints. (5) As inexpensive a fabrication method as possible.

In this work we present novel design rules for integration of dipole antennas on appropriate metallodielectric materials based on printed spirals and operating as Artificial Magnetic Conductors (AMC), that are very thin and suitable for on-package integration. We also present novel designs of package-integrated antennas and arrays on spiral AMCs, satisfying all the above technology and performance requirements. Several researchers have studied antennas and other structures coupled to AMCs. However, very little exists on applications of these concepts for 60-GHz radio transceivers, a subject which is quite challenging and where existing designs are narrowband and occupy large areas.

SINGLE-LAYER SPIRAL AMC ON PACKAGE AND SURFACE PLASMONS

The objective here is to have as thin a substrate material as possible, creating on its physical surface as good a broadband magnetic conductor as possible. We use only 3 Cu metallization layers, of 15μm thickness each, separated by dielectrics of constrained thicknesses T1=60μm, T2=190μm and complex permittivity $\varepsilon = 4(1\text{-}j0.01)$. Fig. 1a shows the 3 metallization layers of the package: M1 is the top layer reserved for the final antenna printing. M2 is the AMC metallization layer. We will place it at the minimum distance from M1 (which in packaging language will be layer L2). Finally, M3 is reserved in our approach for a backing conductor and we will place it two layers underneath M2 (on layer L4). The die lies underneath M3 where further metallization layers may exist but are reserved for other functions such as signal routings, bump pads etc. Fig. 1b shows the design of our AMC, within one lateral Unit Cell (UC). It consists of a metal spiral, of adjustable length, edge-to-edge distance and trace width. For simplicity we will consider the UC to be a square of side A and the spiral outer contour to be a square centered within the U.C. The backing conductor is shown behind the spiral, printed on M3.

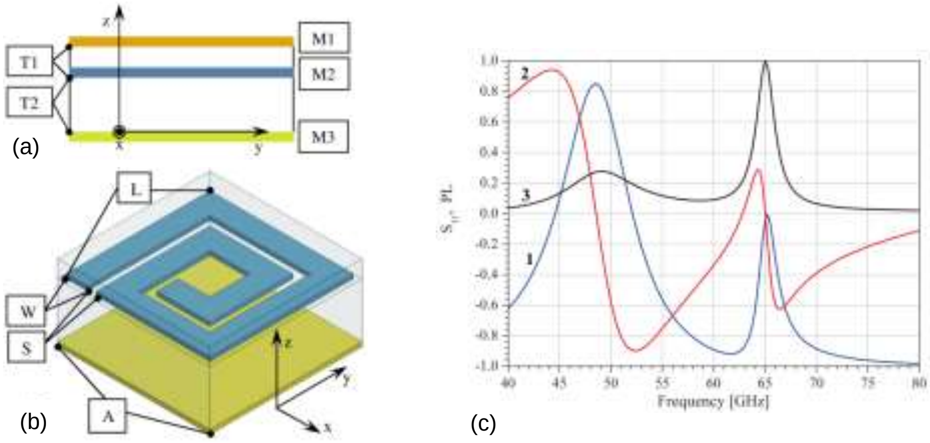
(a)
(b)
(c)

Fig. 1 *a) Package metal stack. b) Spiral AMC Unit Cell c) Material response for normal plane-wave incidence: Complex reflection coefficient S_{11} = (1) + j(2) and power loss (3).*

In Fig. 1c we plot the complex reflection coefficient S_{11} of the structure composed of the UC of Fig. 1b, under normal plane-wave incidence. We note that we have AMC behavior, i.e., $S_{11} \approx +1$, at 48 GHz, which is sufficiently broadband (8GHz). This shows that spiral metallodielectric arrays are promising thin AMC metamaterials on-package. We also plot in Fig. 1c the total power absorption of the material. While at the AMC resonance we notice modest (but non-negligible) absorption, we also observe a Surface Plasmon Polariton (SPP) resonance at 65 GHz, within the radio operation band. At that region of the spectrum, the electromagnetic waves are completely transformed into surface modes, absorbing 100% of the incident power. Surface plasmons are detrimental to antenna operation, therefore the spiral AMC design has to be optimized so that not only the AMC functionality be properly tuned within the operation band, but also in such a way that SPPs completely disappear.

OPTIMIZED ON-PACKAGE SPIRAL AMC ANTENNA AND ARRAYS

A spiral AMC without SPPs and integrated antenna is shown in the package layout of Fig. 2a, optimized according to general design principles developed in [1]. We have chosen a minimum area package of 3×5 U.C., just enough to contain the dipole and leave a perimeter of only 1 U.C. The total package size is 1.44×2.40 mm^2 containing an AMC of truly small size of $0.28\lambda \times 0.48\lambda$ at 60 GHz, with λ the free-space wavelength.

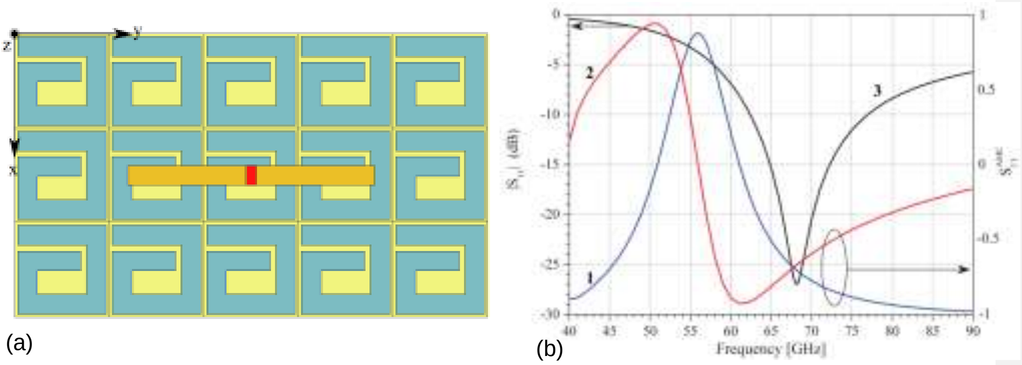
(a)
(b)

***Fig. 2** a) Optimized on-package spiral AMC antenna: Package dimensions $1.44 \times 2.4 \times 0.25$ mm^3. b) Complex reflection coefficient S_{11}^{AMC} = (1) + j(2) (right scale) and return loss $|S_{11}|$ (3) of dipole printed on-package without any other metallization.*

In Fig. 2b we show the response S_{11}^{AMC} of the optimized spiral AMC package, without the antenna, with the AMC functionality projected on M1 tuned appropriately in order to accept the dipole integration, according to the design rules in [1]. We also show the return loss $|S_{11}|$ of the dipole antenna, without the AMC, also tuned appropriately for integration.

Fig. 3a shows the return loss of the integrated spiral AMC antenna of Fig. 2a. The -10dB band extends from 56 GHz up to 76 GHz, easily containing the operation band. In fact, the system's bandwidth is 30%, twice the bandwidth required for the 60-GHz radio applications. In Fig. 3b we plot the gain in the two principal cuts (in dBi), for 60 and 70 GHz. The maximum gain is 6dBi, while the total radiation efficiency is 85%-88% flat within the band. The front-to-back ratio is more than 10 dB, making this a very directive element, with minimal back-side radiation, precisely due to the presence of the AMC.

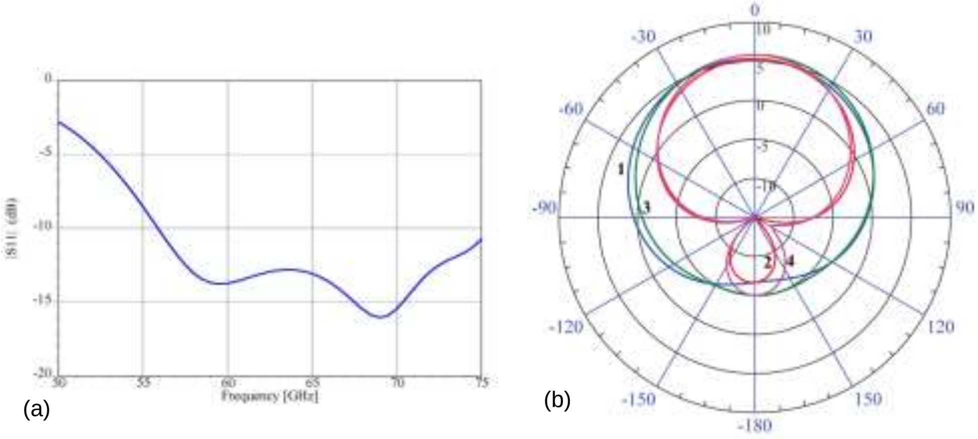

***Fig. 3** a) Return loss of the system of Fig. 2a. b) Realized gain G (θ) (dB) of the system of Fig. 2a at 60 GHz, for $\phi = 0$ (1) and $\phi = 90^o$ (2) and at 70 GHz, for $\phi = 0$ (3) and $\phi = 90^o$ (4).*

Comment [n1]: Wrong sympol

Let us now present results of an array of antennas integrated on optimized AMC's on-package. We construct a 3×4 array of these antenna elements using as a cell the layout of Fig. 2a, where the 3 cells along the x-direction have an extra spacing of 1 row of unit cells each (without spirals), while the 4 cells along the y directions are in tandem, as shown in Fig. 4a. The total package size is 7.2×9.6 mm^2. We performed a 12-port HFSS simulation (1 million tetrahedra, 31GB RAM), accounting for all couplings, with ideal in-phase 50-Ohm lumped ports.

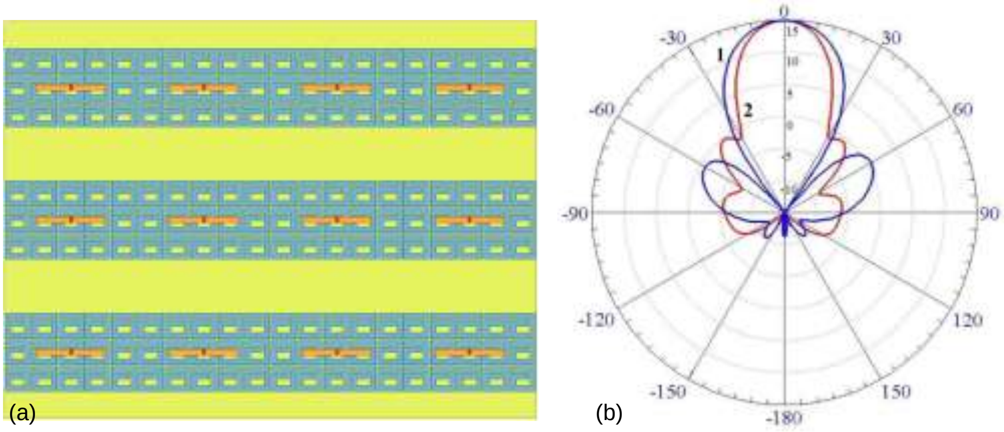

***Fig. 4** a) A 3×4 spiral AMC center-fed antenna array. b) Realized gain G (θ) (dB) of the array at 66 GHz, for $\phi = 0$ (1) and $\phi = 90^o$ (2).*

Comment [n2]: Wrong sympol

The realized gain at 66 GHz is shown in Fig. 4b and reaches a maximum of 15dBi broadside, almost constant within the operation band, with excellent front-to-back ratio of >20 dB and very suppressed sidelobes. This is a very directive broadband array integrated on a truly small package area of 69 mm^2, ideal for 60-GHz radio transceiver applications. We have fabricated a variety of prototypes of these antennas and arrays, which are currently being measured and characterized.

PROJECT OUTPUT IN 2011

Publications in International Journals

1. "Space-Frequency projection of Planar AMCs on integrated antennas for 60 GHz radios", C. Kyriazidou, H. Contopanagos and N. Alexopoulos, IEEE Transactions on Antennas and Propagation, Vol. 60, No. 4 (April 2012), pp. 1899-1909.