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Applications of Artificial Dielectric Layers for the Design of Planar Integrated Antennas

(Invited Paper)

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***Abstract*—In this paper, we present an overview of our recent works on artificial dielectric layers (ADLs), used to enhance the radiation efficiency of planar printed antennas and arrays. The artificial material is realized by introducing planar sub-resonant metallic inclusions in a host material. This allows to enhance the permittivity of the host medium, which is characterized by high anisotropy. An analytical method has been developed to model the ADLs, valid for arbitrary number of layers and generic illumination. After a general description of this method, two design examples are presented. The first utilizes a single ADL slab as a superstrate of an on-chip double slot antenna operating at 300 GHz. Simulated and measured results show an improvement of the antenna gain and overall efficiency of about 2 dB. The second example exploits the use of the ADLs for the design of wideband, wide-scan planar phased arrays. A connected-slot array is loaded with an ADL superstate, to achieve wide-scan capability, up to 50 degrees in all azimuth planes, over an octave bandwidth.**

I. Introduction

Planar integrated antenna technologies, due to their light weight, low profile, cost effectiveness and ease of connection with the active devices, are becoming an attractive solution for commercial applications, such as high-data rate communication [1] and automotive radars [2], [3]. The aforementioned applications not only require highly reliability, but also extreme integration to serve the purpose of compactness and low cost. Thus, the recent trend is to place planar antennas as close as possible to the radio front-end, possibly on the same semiconductor chip or printed circuit board as the electronic components, to facilitate the integration.

Although planar antennas show advantageous properties, there are two major challenges associated with their design, namely surface waves and front-to-back radiation ratio. An innovative planar methodology is presented here to solve the aforementioned bottlenecks. This solution consists of engineering anisotropic equivalent materials, referred to as artificial dielectric layers (ADLs), and using them to enhance the performance of planar antennas. The proposed technique can be used to obtain simultaneously high radiation efficiency (i.e., minimal surface wave excitation) and good front-to-back ratio.

Artificial dielectric were introduced in [4], and exploited for antenna design in [5], [6]. In this work we propose a novel approach to exploit ADL superstrates for enhancing the performance of integrated antennas. An overview of our recent research activities on ADLs is presented, covering both the theoretical development and the practical implementation.

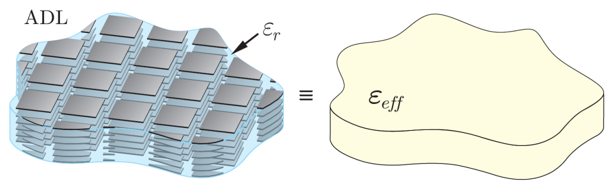


Fig. 1. Artificial dielectric layers embedded in a host medium with relative permittivity ε_r to realize an equivalent effective homogeneous medium. Each layer is composed by an array of electrically small patches.

II. Analysis Method

A planar realization of artificial dielectrics can be achieved by embedding a periodic array of sub-wavelength square metal patches inside the host dielectric, in a multilayer configuration as depicted in Fig. 1. An analytical method for the description of this three-dimensional structure was developed by the authors of this paper in [7], [8]. The method was first introduced for a single layer [7], aiming at describing the interaction between a generic plane wave and a square-mesh layer. The method leads to the derivation of an equivalent circuit that is useful to highlight the characteristic properties of the structure: anisotropy, decoupling of the transverse electric (TE)and transverse magnetic (TM) modes, independence from azimuth incidence.

The theoretical derivation proposed for the single layer was generalized to the cascade of multiple layers in [8]. The reactive coupling between adjacent layers is rigorously taken into account in analytical form, for arbitrarily small inter-layer separation. In Fig. 2, we show the equivalent circuits which were derived in [8] for a generic plane-wave incidence for TE and TM modes separately. In these equivalent circuits, each layer of ADLs is represented by a susceptance $B_{s\infty}$, whose closed-form expression is given in [8].

Once the propagation of a plane wave through the ADL slab is described, the radiation patterns and the input impedance of an antenna located in the close proximity of the ADLs can be calculated. The field of the antenna is expanded in a spectrum of plane waves, and for each of such plane waves a circuit model like the one in Fig. 2 can be applied. This

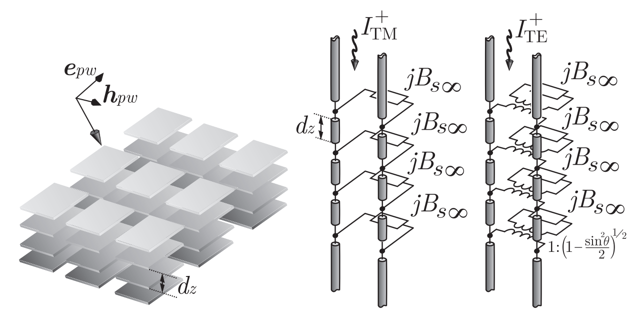
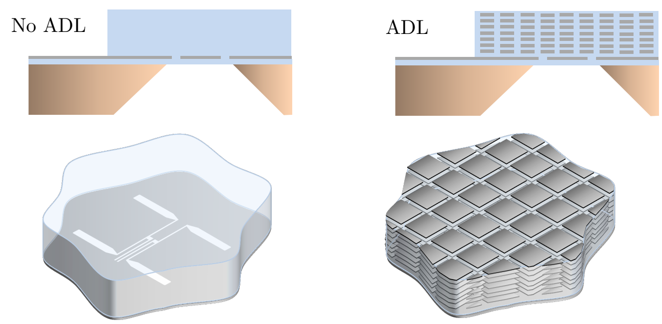
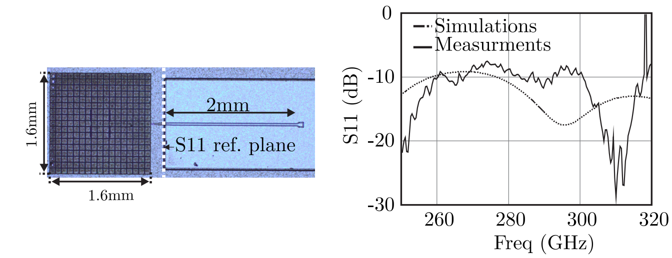


Fig. 2. Equivalent circuit of ADL for plane wave incidence.



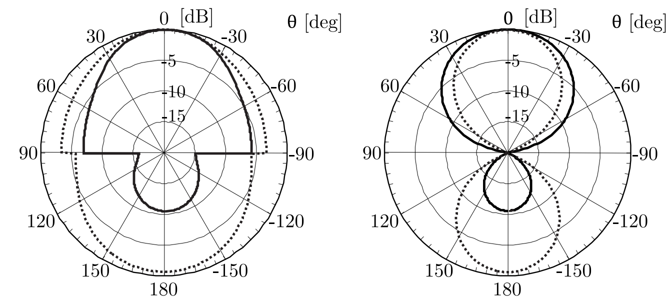
(a) (b)

Fig. 3. Two- and three-dimensional view of a double slot antenna (a) without and (b) with the ADL superstrate.



(a) (b)

Fig. 4. (a) Micrograph of the fabricated chip and (b) simulated and measured reflection coefficient.



(a) (b)

Fig. 5. Normalized simulated radiation patterns in dB at 305 GHz. The solid and the dashed line represent the antenna with and without the ADL, respectively.

method, described in detail in [8], allows the simulation of complex geometries including several layers using minimal computation resources.

III. 0.3 THz On-chip Antenna Design

The realization of a 0.3 THz on-chip double-slot antenna enhanced by an ADL superstrate was shown in [9]. In this work the advantage of using ADLs in terms of front-to-back ratio and surface-wave loss reduction was demonstrated. A double slot antenna at 300 GHz was considered as a radiating element, as shown in Fig. 3(a). The antenna was realized using an in-house integrated circuit process. The silicon on the back side of the antenna has been etched off. To demonstrated the enhancement due to the ADL, a similar antenna has been fabricated, including 7 ADLs, each separated by 5μm along the z-axis (see Fig. 3(b)).

The non-resonant patches composing the ADL, as depicted in Fig. 3(b), are hosted by an electrically thin silicon dioxide slab with relative permittivity $\varepsilon_{\text{host}} = 4$. Such value is increased by the presence of the ADLs to an equivalent relative dielectric constant $\varepsilon_{\text{eff}} = 32$, for normally incident waves. The ADL superstrate does not suffer from surface-wave losses. This is due to the fact that, in virtue of the anisotropy, the waves incident at angles towards the grazing do not feel the larger effective dielectric constant, which would otherwise induce surface-wave modes.

The micrograph of the fabricated chip is shown in Fig. 4(a). The geometrical parameters have been selected so that the antenna is matched around the frequency of 300 GHz, as depicted in Fig. 4(b). Note that there is a frequency shift of 3% between the measured and the simulated results which is mainly due to the fabrication tolerances.

The simulated normalized radiation patterns of the antenna, with and without ADL, are reported in Fig. 5, at 305 GHz. It can be observed that the antenna with the ADL has a front-to-back ratio greater than 10 dB. On the contrary, the antenna in absence of the ADL, loaded only by an electrically thin slab of the same height of the total ADL slab, exhibits a front-to-back ratio lower than 1 dB. This is because almost equal power is radiated in the two half spaces above and below the slot ground plane. The value of front-to-back ratio for the ADL loaded antenna is higher than 10 dB over the whole matching bandwidth (not shown here). Instead, the reference antenna has an almost frequency independent front-to-back ratio of about 0.7 dB.

Figure 6 shows the measured far-field patterns for the antenna with ADLs. The radiation patterns are obtained using a near to far field transformation after acquisition of near-field data on a planar scan. The patterns in the H-plane show an excellent agreement with the simulations. The E-plane patterns are asymmetric and oscillatory. The reason for the fluctuation is the presence of the probe, which interferes with the antenna and limits the near-field scanning area. Also the

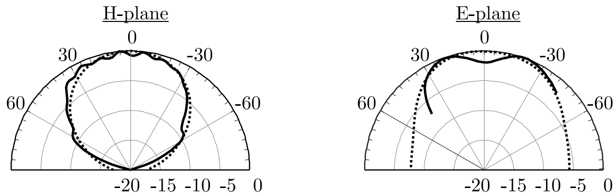


Fig. 6. Simulated and measured radiation patterns.

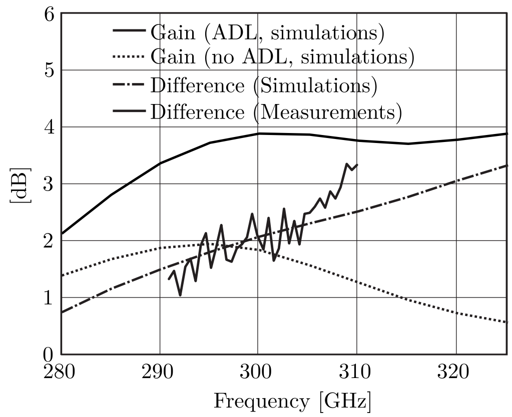


Fig. 7. Simulated gain of the two antennas, with and without the ADL loading; the relative gain difference is also reported and compared with the measured one.

reference antenna without the ADL was measured in the same manner. The relative difference between the broadside gain of the two antennas, with and without ADL, is shown in Fig. 7. An improvement of about 2 dB is observed for the ADL loaded antenna with respect to the reference one.

IV. Artificial Dielectrics for Wideband and Wide-Scan Arrays

Another application of ADLs deals with a novel concept of planar wideband phased arrays with wide-scan capability. The proposed solution combines combines the concepts of ADLs and connected arrays.

A connected array consists of an array of either slots or dipoles which are electrically connected [10]. They have the advantage of being broadband and, at the same time, they exhibit low cross polarization. Practically the bandwidth of a connected array is limited by the distance from the backing reflector, which is needed to ensure unidirectional radiation. A connected array of slots in presence of a backing reflector is depicted in Fig. 8, with the relative geometrical parameters. Here, we propose to load these arrays with ADL superstrates.

As an example, Fig. 9(a) shows a unit cell of the connected array loaded with a 3-slab ADL superstrate. The ADL slab is characterized by a high effective relative permittivity, thus increasing the radiation towards the positive z-direction. Consequently, the array 'feels' less the presence of the backing reflector, which can be located closer to it without strongly degrading the impedance matching properties.

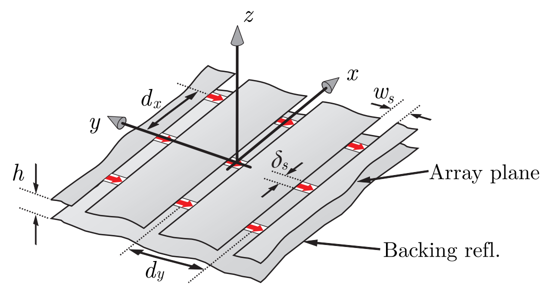


Fig. 8. Doubly periodic connected array of slots radiating in the presence of backing reflector.

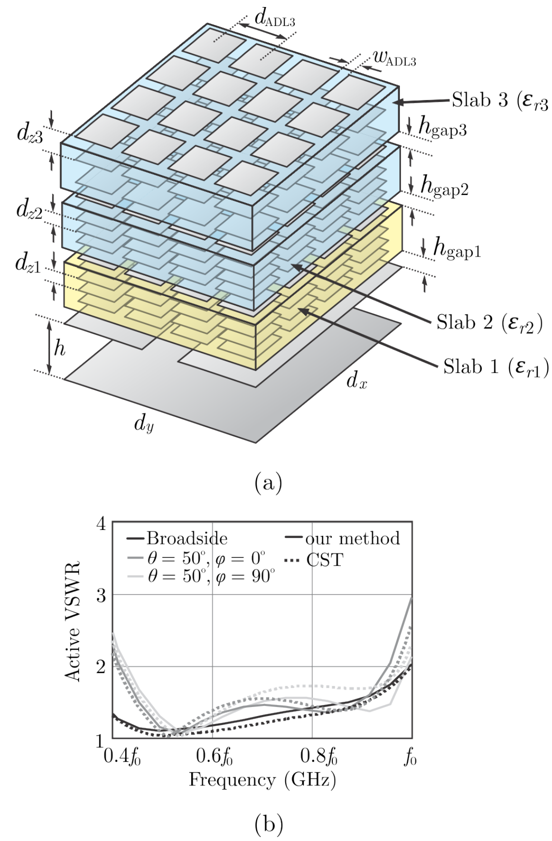


Fig. 9. (a) A unit cell of the connected array radiating in the presence of multi-layer ADL stack and (b) active VSWR for broadside and scanning to 50 degrees in E- and H- plane.

Simulating a structure like the one in Fig. 9(a) requires heavy computational resources. Therefore, the analytical tool described in Sec. II is used to estimate the performance of the connected array of slots loaded with ADL. With our method, the calculation of the active input impedance, for 15 frequency points and 3 scan angles, can be completed in 0.2 seconds, while it requires about 180 minutes with a commercial EM solver [11], on the same computer.

Based on this concept, a design example is shown, for a single-polarized array. Simulated results are presented to investigate the effectiveness of the proposed array concept, targeting the frequency range of one octave, and scanning up to 50 degrees in all azimuth planes. The active reflection coefficient of the array is shown in Fig. 9(b), for broadside and scanning to 50 degrees in E- and in the H-plane. The VSWR is less than 2 over more than one octave bandwidth. A good comparison is obtained for all the scanning angles between the simulated results obtained with our analytical model and CST.

V. Conclusion

In this paper, we proposed to use artificial dielectric layers to improve the performance of integrated antennas and antenna arrays. For the analysis of antennas in the presence of ADLs, we developed a model based on spectral Green's functions, which allows to describe with closed-form expressions the propagation of an arbitrary plane wave through the artificial material. This method can be combined with an expansion of the field from a near source in a spectrum of plane waves, to obtain the input impedance and the radiation patterns of an antenna loaded with ADLs.

We presented two examples that exploit ADLs. The first considered an on-chip double slot antenna loaded with ADL to enhance the front-to-back ratio. While the same effect can be realize with real high-permittivity dielectrics, these latter would reduce the efficiency due to the excitation of surface waves. ADLs do not have this problem, thanks to the anisotropic characteristics. The second example showed a wideband connected array of slots, loaded with 3-slab artificial dielectric superstrate to improve matching and scanning performance. Also in this case, the anisotropy of the ADLs is beneficial, avoiding the occurrence of scan blindness for scanning up to 50 degrees.

Acknowledgment

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References

[1] S. K. Reynolds, B. A. Floyd, U. R. Pfeiffer, T. Beukema, J. Grzyb, C. Haymes, B. Gaucher, and M. Soyuer, "A silicon 60-GHz receiver and transmitter chipset for broadband communications," *IEEE J. Solid-State Circuits*, vol. 41, no. 12, pp. 2820–2831, Dec. 2006.

[2] H. Li, H.-M. Rein, T. Suttorp, and J. Bock, "Fully integrated SiGe VCOs with powerful output buffer for 77-GHz automotive radar systems and applications around 100 GHz," *IEEE J. Solid-State Circuits*, vol. 39, no. 10, pp. 1650–1658, Oct. 2004.

[3] B. Schoenlinner, X. Wu, J. P. Ebling, G. V. Eleftheriades, and G. M. Rebeiz, "Wide-scan spherical-lens antennas for automotive radars," *IEEE Trans. Microwave Theory Techn.*, vol. 50, no. 9, pp. 2166–2175, Sep. 2002.

[4] W. E. Kock, "Metallic delay lenses," *Bell System Technical Journal*, vol. 27, no. 1, pp. 58–82, 1948.

[5] K. Takahagi and E. Sano, "High-gain silicon on-chip antenna with artificial dielectric layer," *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3624–3629, Oct. 2011.

[6] H. Attia, L. Yousefi, M. M. B. Suwailam, M. S. Boybay, and Omar M. Ramahi, "Enhanced-gain microstrip antenna using engineered magnetic superstrates," *IEEE Antennas Wireless Propag. Letters*, vol. 8, pp. 1198–1201, Nov. 2009.

[7] D. Cavallo, W. H. Syed, and A. Neto, "Closed-form analysis of artificial dielectric layers—Part I: Properties of a single layer under plane-wave incidence," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 6256–6264, Dec. 2014.

[8] D. Cavallo, W. H. Syed, and A. Neto, "Closed-form analysis of artificial dielectric layers—Part II: Extension to multiple layers and arbitrary illumination," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 6265–6273, Dec. 2014.

[9] W. H. Syed, G. Fiorentino, D. Cavallo, M. Spirito, P. M. Sarro, and A. Neto, "Design, fabrication, and measurements of a 0.3 thz on-chip double slot antenna enhanced by artificial dielectrics," *IEEE Trans. THz Sci. and Tech.*, vol. 5, no. 2, pp. 288–298, Mar. 2015.

[10] D. Cavallo, A. Neto, G. Gerini, A. Micco, and V. Galdi, "A 3- to 5-GHz wideband array of connected dipoles with low cross polarization and wide-scan capability," *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1148–1154, Mar. 2013.

[11] "CST Microwave Studio 2012," Available: http://www.cst.com.