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Tradeoff Between Impedance Bandwidth and Polarization Purity in Connected Slot Arrays

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***Abstract*—We present an approach to design wideband arrays of connected slots with artificial dielectric layers (ADLs) that allows to take into account both matching and polarization properties. The slots are fed by parallel plate waveguides (PPWs) that are co-designed with the ADLs to realize the desired matching bandwidth. An equivalent circuit model of the unit cell is derived, including both the feed and the ADLs, providing a fast and accurate estimation of both the active reflection coefficient and the cross-polarization level. Such model enables a tradeoff between matching and polarization efficiency already at the early stages of the design.**

***Index Terms*—artificial dielectrics, connected arrays, parallel plate waveguide, spectral domain method, wideband arrays.**

I. INTRODUCTION

Modern radar and telecommunication systems can benefit from wideband antenna arrays, to combine multiple antennas in a single aperture, and thus reduce the volume and weight of the system. Popular solutions for wideband antenna arrays are connected or tightly-coupled elements [1], [2], flared-notch [3] and Vivaldi antennas [4]. Tapered slot arrays have typically electrically large profile and complex assembly, due to multiple vertical printed circuit boards (PCBs) put together in an egg-crate configuration to realize dual polarization. On the contrary, connected arrays can be fabricated as a single, multi-layer, horizontal PCB.

To radiate in a single direction, connected array designs include a backing reflector, which limits the operational bandwidth. Artificial dielectric layers (ADLs) have been proposed [5] to overcome the frequency dependence of the reflector and enlarge the bandwidth. These are periodic arrangements of sub-wavelength metal patches to synthesize a desired effective refractive index. Unlike conventional dielectric slabs, ADLs are strongly anisotropic and do no support surface waves, allowing for wide scanning with stable input impedance.

Another benefit of connected arrays is that analytical solutions are available for the active input impedance of the array in the presence of ADLs [5]–[7]. These solutions allow simulating the unit cell with negligible computational resources, enabling the optimization of the design. The standard unit cell consists of a cavity backed connected slot loaded with ADLs. The feed is represented by a delta-gap source located at the slot plane.

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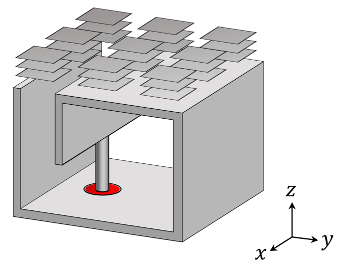

Fig. 1. Schematic drawing of the unit cell: a parallel plate waveguide fed connected slot array loaded with artificial dielectric layers.

In this paper, we investigate a connected array unit cell with a parallel plate waveguide (PPW) feeding structure that implements part of the impedance transformation, to decrease the number of metal layers in the ADL superstrate. An equivalent circuit model of the unit cell is derived, allowing for the calculation of the active reflection coefficient and the cross-polarization levels with negligible computational cost. The model enables the tradeoff between matching and polarization efficiency.

II. ARRAY UNIT CELL AND EQUIVALENT CIRCUIT

The unit cell under investigation is based on the concept introduced in [8] and is shown in Fig. 1. The radiating element consists of a connected parallel-plate waveguide (PPWs), fed by a via extruding from the ground plane, and located beside a metal cavity. Above the PPW openings, an ADL superstrate is placed to implement a wideband, wide-angle impedance matching structure.

This unit cell can be modeled with the equivalent circuit shown in Fig. 2. The ADLs are represented by two transmission lines, for the transverse electric (TE) and the transverse magnetic (TM) modes, respectively, where each layer is modeled as shunt impedances ($Z_{\mathrm{TE}}^{\mathrm{ADL}}$ and $Z_{\mathrm{TM}}^{\mathrm{ADL}}$). The spaces between the patch layers are associated with transmission line sections, with characteristic impedance Z_{TE} and Z_{TM}, which

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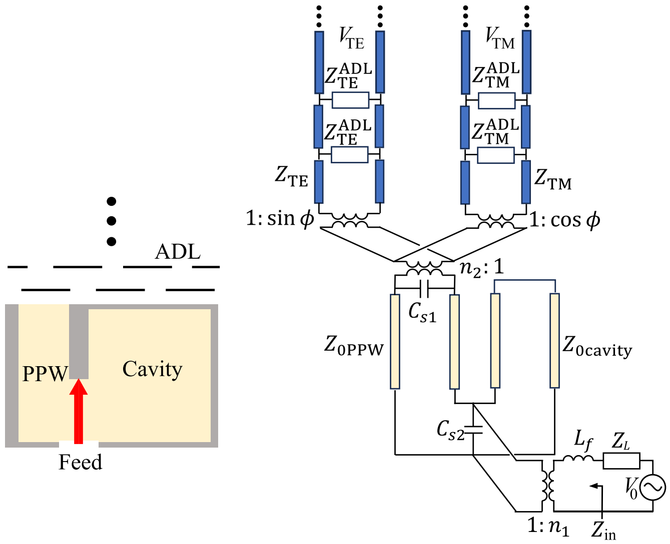

Fig. 2. Equivalent circuit representation of the connected slot array loaded with ADLs, the PPW, and the cavity.

are customarily used to define the spectral Green's function in stratified media. Transformers with turn ration $1 : \sin\phi$ and $1 : \cos\phi$ are considered, to account for the projection of the TE and TM field components onto the slot axis. Another transformer with turn ratio $n_2 : 1$ accounts for the scan angle in the E-plane and depends on the width of the PPW. Two capacitors C_{s1} and C_{s2} are included at the two ends of the PPW and are associated with the reactance of the PPW edges. These capacitive terms include all the higher order Floquet modes due to the periodicity along y, while the Floquet modes along x are included in the series feed inductance L_f. At the feed, a transformer with turn ratio $1 : n_1$ accounts for the size of the feeding gap. Finally, the PPW is modeled as a transmission line section, and the cavity as a shorted stub.

It is important to note that all the components of this circuit are known in closed form and depend on the geometrical parameters and the materials of the unit cell. The derivation of the circuit components will be described in a separate publication. In this paper, the focus is on the use of the circuit for co-optimization of matching and polarization performance.

III. Tradeoff Between Matching and Polarization

By solving the equivalent circuit in Fig. 2, one can find the active input impedance of the unit cell Z_{in} for different scanning conditions, as well as the correspondent active reflection coefficient with respect to the reference feed impedance Z_L.

From the same circuit, the voltage V_{TE} and V_{TM} on the transmission lines above the ADLs can be found. These quantities are proportional to the the TE- and TM-components of the radiated electric field. Projecting these components onto the co-polar and cross-polar unit vectors defined according to the third Ludwig's definition [9], the cross- to co-polarization ratio can be written as

$$\mathrm{Xpol}(\theta,\phi) = \frac{\frac{\sin 2\phi}{2}\left(V_{\mathrm{TM}}(\theta,\phi)\sec\theta - V_{\mathrm{TE}}(\theta,\phi)\right)}{V_{\mathrm{TM}}(\theta,\phi)\sin^2\phi\sec\theta + V_{\mathrm{TE}}(\theta,\phi)\cos^2\phi}. \quad (1)$$

where θ and ϕ are the elevation and azimuth scan angles, respectively.

A. Design Example

A 5:1 design example is considered that can scan to 60° in both the E- and H-plane. A 4-section Chebyshev transformer is implemented in the artificial dielectric layers. The geometrical parameters of the ADLs are found by a synthesis procedure that exploits the equivalent transmission line models of ADLs [10]. The ADL structure is then combined with the connected PPW element and the cavity, and the dimensions are optimized using the equivalent circuit in Fig. 2 to minimize the active reflection coefficient.

The resulting unit cell is shown in Fig. 3(a). The active reflection coefficient for scanning to broadside and to 60° in the E- and H-plane is reported in Fig. 3(b), calculated with the equivalent circuit and with CST. Good agreement is obtained between the two methods, which validates the equivalent circuit. The cross-polarization levels of this unit cell when scanning to 60° in the diagonal planes are plotted in Fig. 3(c), again using the equivalent circuit and CST. The cross-polarization ratio is observed to increase with frequency and to reach nearly 0 dB at the maximum frequency of operation f_0. This is a typical behavior of wideband ADL superstrates, whose anisotropy yields high cross-polarization due to different effective constitutive parameters for TE and TM modes.

However, the equivalent circuit allows to optimize the unit cell considering also the cross-polarized levels in the cost function to minimize, besides the active reflection coefficient. This allows the designer to make a tradeoff between polarization and matching efficiency. Typically, less dense metallic patches, will result in lower cross-polarization levels, at the cost of worse matching.

As an example of this tradeoff, the unit cell in Fig. 4(a) is designed. The active reflection coefficient for scanning to broadside and to 60° in the E- and H-plane is reported in Fig. 4(b), showing some degradation with respect to the previous example of Fig. 3, especially at the edges of the frequency band for scanning in the H-plane. On the other hand, the cross-polarization levels of this unit cell when scanning to 60° in the diagonal planes are lower than -8 dB until f_0, as shown in Fig. 4(c).

IV. Conclusions

An approach to design wideband connected slots arrays loaded with artificial dielectric layers (ADLs) was presented. This approach takes into account both matching and polarization properties. An equivalent circuit model of the unit cell is derived, including both the feed and the ADLs, providing a fast and accurate estimation of both the active reflection coefficient and the cross-polarization level. As an example,

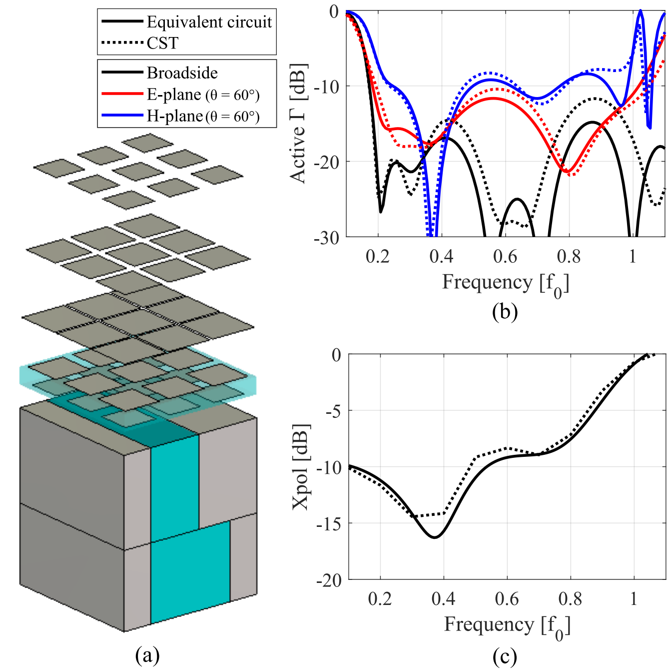

Fig. 3. (a) Drawing of unit cell optimized for impedance matching. (b) Active reflection coefficient for different scan angles. (c) Cross-polarization levels in the diagonal plane for $\theta = 60°$.

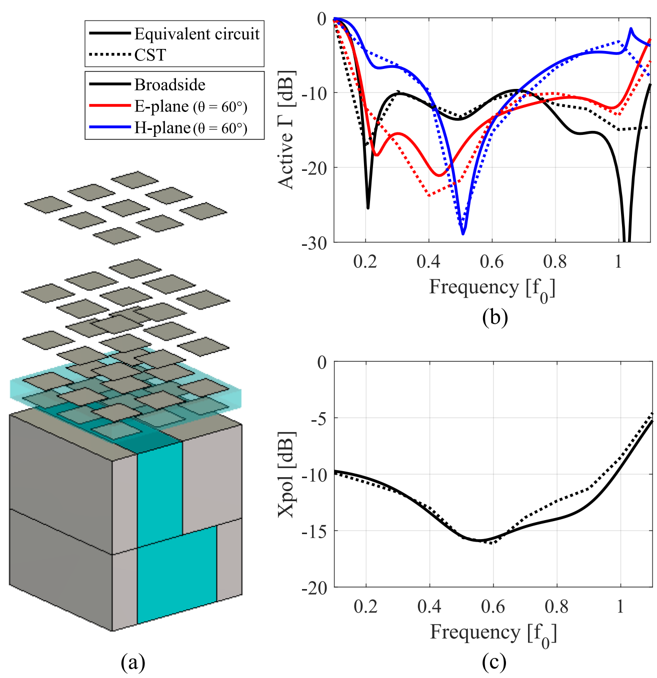

Fig. 4. (a) Drawing of unit cell optimized for cross-polarization levels. (b) Active reflection coefficient for different scan angles. (c) Cross-polarization levels in the diagonal plane for $\theta = 60°$.

the equivalent circuit was used to design an array optimized for low active reflection coefficient, without accounting for the cross-polarization levels, and compared to a design where the cross-polarization was also considered in the optimization. This allows the tradeoff between matching performance and cross polarization efficiency in such wideband connected slot arrays to be made in early stages of the design.

REFERENCES

[1] J. J. Lee, S. Livingston, R. Koenig, D. Nagata, and L. L. Lai, "Compact light weight UHF arrays using long slot apertures," *IEEE Trans. Antennas Propag.*, vol. 54, no. 7, pp. 2009-2015, Jul. 2006.

[2] S. S. Holland and M. N. Vouvakis, "The planar ultrawideband modular antenna (puma) array," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp 130-140, Jan. 2012.

[3] R. W. Kindt and W. R. Pickles, "Ultrawideband all-metal flared notch array radiator," *IEEE Trans. Antennas Propag.*, vol. 58, no. 11, pp 3568-3575, Nov. 2010.

[4] D. H. Schaubert, S. Kasturi, A. O. Boryssenko, and W. M. Elsallal, "Vivaldi antenna arrays for wide bandwidth and electronic scanning," in *Proc. Eur. Conf. Antennas and Propag.*, Edinburgh, U.K., Nov. 2007, pp. 1-6.

[5] W. H. Syed, D. Cavallo, H. Thippur Shivamurthy, and A. Neto, "Wideband, wide-scan planar array of connected slots loaded with artificial dielectric superstrates," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp 543-553, Nov. 2010.

[6] D. Cavallo, W. H. Syed, and A. Neto, "Connected slot array with artificial dielectrics: a 6-15 GHz dual-pol wide-scan prototype," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 3201-3206, Jun. 2018.

[7] D. Cavallo and R. M. van Schelven, "Closed-form analysis of artificial dielectric layers with non-periodic characteristics," in *Proc. Eur. Conf. Antennas Propag.*, Krakow, Poland, Apr. 2019, pp. 1-5.

[8] D. Cavallo "Parallel-plate waveguide-feeding structure for planar connected arrays," *IEEE Antennas Propag. Lett.*, vol. 21, no. 4, pp. 765-768, Apr. 2022.

[9] A. Ludwig, "The definition of cross polarization," *IEEE Trans. Antennas Propag.*, vol. 21, no. 1, pp. 116-119, Jan. 1973.

[10] A. J. v. Katwijk, A. Neto, G. Toso and D. Cavallo, "Design of wideband wide-scanning dual-polarized phased array covering simultaneously both the Ku- and the Ka-satcom bands," in *Proc. Eur. Conf. Antennas and Propag.*, Copenhagen, Denmark, Mar. 2020, pp. 1-3.