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Parallel Plate Waveguide Feeding Structure for Planar Connected Arrays

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***Abstract*—A novel approach for the practical realization of the feeding lines in connected array of slots is presented. The proposed feed concept is based on a Parallel Plate Waveguide (PPW) structure and allows to simplify the unit cell design. When compared to the typical integrated coaxial feed, the PPW-based feeding structure can reduce the cost and complexity of the array, by resulting in a lower number of metal layers and by allowing for large diameter vias. Two examples of unit cell design, based on this new feed concept, are presented: one consists in a single-polarized array of connected slot, covering the band from 70 GHz to 140 GHz; another example is referring to a single- and dual-polarized connected slot array covering the 2-8 GHz range.**

***Index Terms*—antenna arrays, antenna feed, dual-polarization, wideband arrays.**

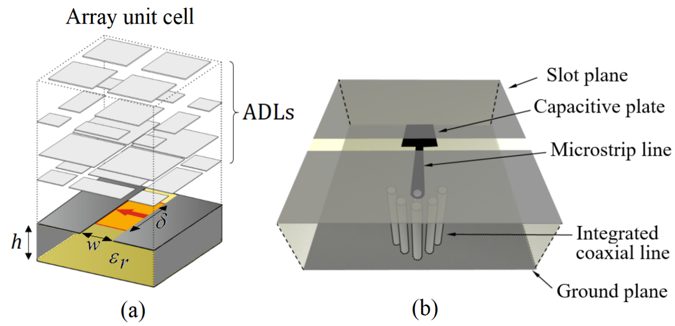

Fig. 1. (a) Sketch of the connected array unit cell with the ADL superstrates and (b) typical integrated coaxial feed.

I. Introduction

CONNECTED slot arrays have recently emerged as effective solutions to realize wide-scanning wideband phased arrays. These kinds of arrays find application not only in multifunction radars [1], [2], but recently also in wireless and satellite communications [3], [4].

Among the different existing wideband array concepts, connected slot arrays are particularly advantageous because of their low-profile and planar structure, that allows for manufacturing the array with a single multilayer printed circuit board at microwave frequencies. Several designs based on connected slots were presented in [5]–[9]. A connected slot array is an array of long slots, each fed at periodic locations, to achieve a uniform field distribution and in turn a wideband radiating aperture. For unidirectional radiation, a backing reflector is typically placed at a certain distance from the slot plane, which limits the operational bandwidth. A solution to increase the bandwidth and scan range of connected slot array with a backing reflector was proposed in [6] and consists of loading the array with artificial dielectric layers (ADLs). The array unit cell concept is shown in Fig.1(a), which depicts the connected slot array and an artificial dielectric superstrate. The ADLs are stack of metal layers made of periodic sub-wavelength patches, to synthesize an effective anisotropic material. ADLs can be designed to implement a wideband impedance transformer to free space without supporting surface wave. When the array is loaded with ADLs, the distance between the slots and the backing reflector can be largely reduced, enabling the implementation of the element feed with vias at microwave frequencies.

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In earlier connected array designs [6], [7], [10], the feeding concept depicted in Fig. 1(b) was used. The slots are fed by a microstrip line terminated in a capacitive patch. This patch acts as a series capacitance to compensate the inductive effect of the backing reflector. The microstrip is connected to an integrated coaxial line, which consists of a via to form the inner conductor and one or more vias for the outer shield. Although this strategy for the feed design was proven to be effective in [7], it is difficult to design due to its effects on the slot impedance performance and its large size compared to the unit cell.

In this work, an alternative strategy for the feed design is introduced that simplifies the unit cell. This is based on a parallel plate waveguide (PPW) feed the folds into a cavity and can be fed directly at the ground plane level. This approach allows to decouple the feed design from the array. Moreover the PPW can conveniently replace the ADLs in the purpose of impedance transformation, thus reducing the number of metal layers in the array.

II. Drawbacks of Integrated Coaxial Feed

In connected slot array designs, the first step is to optimize the preliminary unit cell shown in Fig. 2(a), which includes the ADLs, an infinitely thin slot plane and a cavity below. In this preliminary unit cell, the feed is assumed to be a delta-gap generator in the slot and is characterized by a certain active input impedance Z_a. A realistic implementation of the feed requires to transfer the feed from the slot plane to the backing reflector, under which the coaxial connectors or the corporate feeding network are located. The typical implementation of this transition, used in all previous designs, is obtained by

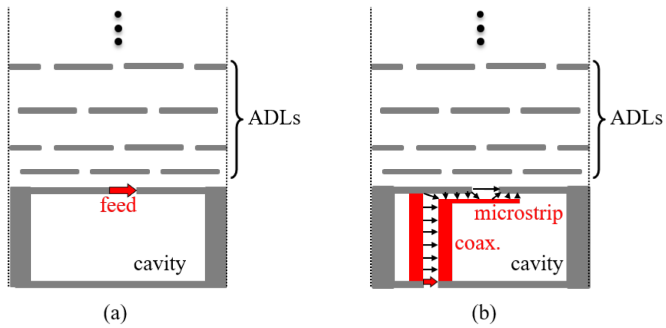

Fig. 2. (a) Connected array unit cell with delta-gap feed at the slot plane and with (b)integrated coaxial and microstrip lines. Black arrows represent electric field distribution in the feeding lines.

combining an integrated coaxial line and a microstrip, as shown in Fig. 2(b). The feed is now located at the ground plane and excites the vertical coaxial line and the microstrip crossing the slot and terminating with a capacitive stub. The electric field distribution in the feeding line is represented by the black arrows in the figure, to highlight that the electric field propagating in the feeding lines reaches the slot to realize an approximation of the ideal delta-gap generator.

Although this strategy for the feed design was proven to be effective in [7], it has some disadvantages:

- The coaxial line is designed to be matched to Z_a, but when adding this line to the unit cell, the presence of the additional vias changes the cavity size and in turn Z_a. Thus, it is not possible to design the slot element and the coaxial line independently, and typically a lengthy iterative optimization of the unit cell performance is required when the feed is included.
- To avoid too large coaxial lines that occupy most of the cavity, the aspect ratio of vias needs to be as large as possible. However, this approach limits the maximum achievable distance from the ground plane and the scalability to higher frequency.
- Electrically long coaxial lines can introduce common-mode resonances [6]. Thus, the line length and the distance from the ground plane must be small enough to keep the resonances outside the operative band.

III. Novel Feed Concept

An alternative strategy for the feed design is introduced here that can overcome the above mentioned limitation and can simplify the unit cell. The different logical steps that lead to the feed concept are described in Fig. 3. The initial structure is the same ideal unit cell as considered early, shown again in Fig. 3(a). To explain the concept, it is assumed that the ADL superstrate is composed of two quarter wave slabs, with effective medium impedances equal to Z_1 and Z_2, respectively. The two ADL slabs implement a transformer between the free-space impedance and a lower impedance Z_L, so that the slot input impedance is well matched to Z_L. One can imagine to place a PPW section between the cavity and the ADL, with a characteristic impedance $Z_0 = Z_L$ (Fig. 3(b)). In this

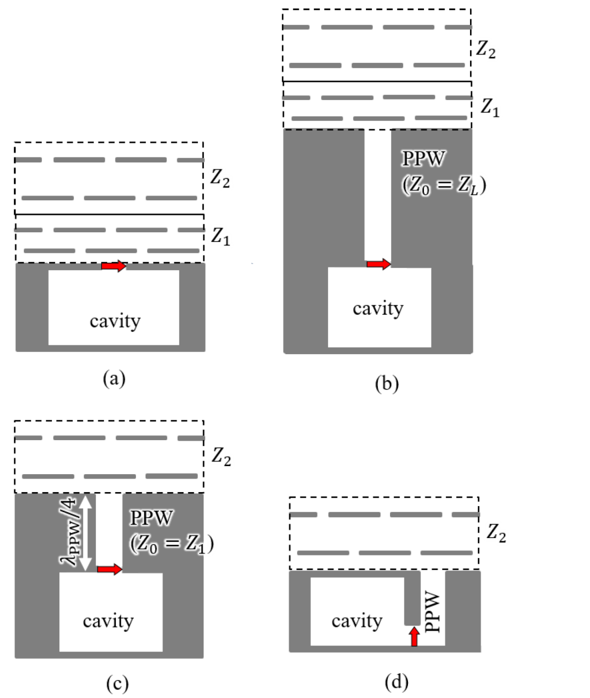

Fig. 3. (a) Initial unit cell, with two ADL slabs; (b) PPW section included above the slot with characteristic impedance $Z_0 = Z_L$; (c) PPW section with characteristic impedance $Z_0 = Z_1$ replacing one ADL slab; (d) Folded PPW with cavity on the side and vertical feed above the ground plane.

configuration, the slot is no longer present and the feed is located at the bottom of the PPW. The next step is to replace the lower ADL slab, with effective medium impedance Z_1, with the PPW section, whose characteristic impedance is now $Z_0 = Z_1$. The resulting unit cell is shown in Fig. 3(c). The impedance transformer that before was implemented by the two ADL slabs is now realized by the ADL and the PPW. The final step consists of folding the structure as depicted in Fig. 3(d), so that the cavity is beside the PPW and the feed is now vertically oriented.

The considered PPW only supports the fundamental transverse electro-magnetic (TEM) mode. Higher order modes are not supported since the distance between the plates of PPW is assumed to be smaller than a quarter wavelength.

By comparing the structure in Fig. 3(d) with the previous one in Fig. 2(b), a number of advantages can be pointed out:

- Unlike the coaxial line, the PPW is separated from the cavity, which allows to decouple the effects of the cavity and the feed lines on the impedance of the slot.
- Since part of the ADL transformer is implemented in the PPW, the number of ADL layers is reduced, which is beneficial for cost and complexity of manufacturing. Although one could in principle implement the same impedance matching function also in the coaxial line, in practice coaxial lines with length of about quarter wavelength and characteristic impedances above 100Ω would be very large and occupy most of the cavity, causing impedance mismatch. On the contrary, a PPW with characteristic impedance $> 100\Omega$ can be made

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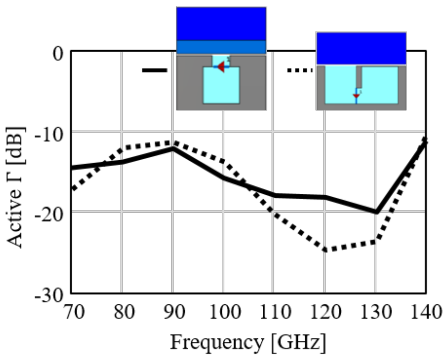

Fig. 4. Active reflection coefficient for the unit cell design with two ADL sections and for the same unit cell with a PPW replacing the lower ADL section and a folded cavity.

compact even with large diameter vias, while leaving enough space for the cavity.

- The PPW structure allows the realization of the vertical walls by means of vias with larger aspect ratio, allowing for larger distances from the ground plane, and in turn better matching at the low end of the frequency band. This also facilitates the scalability of connected array designs to millimeter wave frequencies.
- Common-mode resonances are avoided for the PPW, since the length of the feed line is very short compared to the wavelength.

IV. Unit Cell Design Examples

To assess the effectiveness of the proposed feeding structure, two design examples are presented. The first example is a 2:1 linearly polarized connected array suitable for millimeter wave applications, covering the bandwidth between 70 and 140 GHz. A second example targets the same 4:1 bandwidth as the connected array, from 2 to 8 GHz.

A. 70-140 GHz Single-Polarized Array

This example considers a single-polarized connected slot array with ADL superstrate and PPW feed, operating from 70 to 140 GHz, which covers simultaneously two frequency bands for automotive radars [11], [12].

The first step is the ADL design, which can be performed with the aid of standard multi-section impedance transformer theory. In the present example, the ADL transforms the characteristic impedance of free space ζ_0 = 377 Ω to the impedance Z_L = 50 Ω at the slot feed, with a good reflection coefficient for a 2:1 frequency band. For this purpose, a 2-order Chebyshev transformer can be considered. Fore the sake of simplicity, the ADL slabs are first considered as homogeneous dielectrics. Using the available ADL analytical tool [13], one can later synthesize real metal ADLs that approximates the homogeneous materials.

Once the ADL slabs are designed, the unit cell of the array is included, made by a short PPW and a square cavity below, with height of about $\lambda_d/4$ (λ_d is the wavelength in the dielectric at center frequency of 105 GHz). It is assumed that both the PPW and the cavity are filled with a dielectric with relative permittivity ε_r = 2.2, and the period of the array $d_x = d_y$ =1.1mm, i.e. about half wavelength at highest frequency of operation (140 GHz). The active reflection coefficient in Fig. 4 is obtained, which is lower than -10 dB over the entire band of interest. If the impedance of the PPW is chosen as the same as the impedance of the first section of the superstrate transformer, one can replace the dielectric slab with the PPW. In this case, the characteristic impedance of the PPW $Z_0 = Z_1 = 89.3\Omega$. The length of the PPW is selected as $\lambda_d/4$ = 0.48 mm to behave as a section of the transformer. Finally, the cavity and the PPW are placed next to each other with the feed oriented vertically in between. The resulting unit cell side view together with the active reflection coefficient are also shown in shown in Fig. 4. Values below -10 dB are achieved over the entire band, for scanning to broadside.

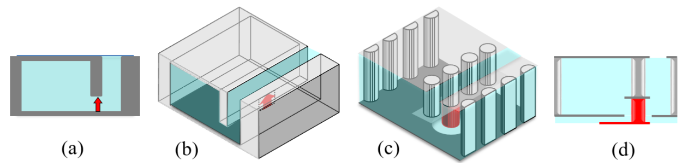

Fig. 5. (a) Side-view and (b) 3-D view of the array element, with metal blocks and ideal lumped feed; (c) 3-D view and (d) side-view of the array element, with vias replacing the metal walls and the feed. The feeding via crosses the ground plane through a hole to connect with a microstrip line.

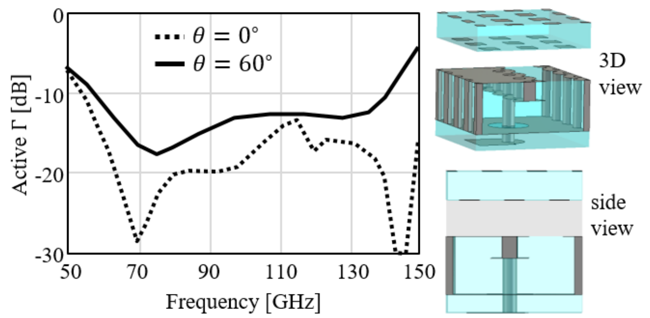

Fig. 6. Active reflection coefficient for broadside and scanning to 60° in the E-plane for the unit cell in the inset.

In the current unit cell, all the vertical metal walls are composed by solid metal blocks. To make it compatible with PCB manufacturing, the metal walls can be replaced by vias. The side and three-dimensional (3-D) views of the slot structure with solid metal and with vias are shown in Fig. 5. The side walls of the unit cell are realized with vias connecting the slot plane with the backing reflector. The other wall of the PPW is obtained with vias that start from the slot plane but stop at an intermediate layer, without reaching the ground plane. Only one of such vias acts as the feed and is made longer to cross the ground plane through a circular opening and reach a microstrip line underneath the ground plane.

The last step to complete the design is replacing the homogeneous anisotropic slab with real ADL patches. Using the ADL Analytical Tool [13], the ADL is designed. It is a two-layer ADL with dielectric with relative ε_r = 2.2 between the layers. Once the geometrical parameters of the patch layers

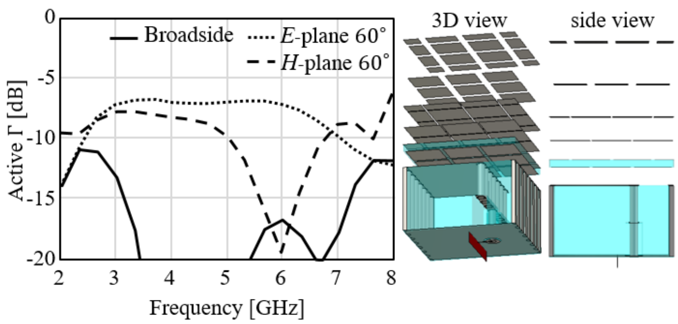

Fig. 7. Active reflection coefficient for broadside and scanning to 60° in the E-plane for the single-polarized unit cell in the inset.

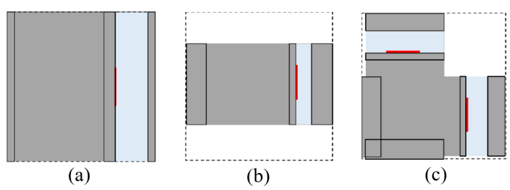

Fig. 8. (a) Top view of the single polarized connected PPW array; (b) Reduction of the PPW size; (c) Dual-polarized configuration.

are determined, the overall unit cell is simulated with CST. The model is depicted in Fig. 6, which also shows the active reflection coefficient for broadside and for E-plane scanning to 60°. This design has potential for application in dual-band automotive radar covering simultaneously the bands around 79 GHz and 140 GHz with 1-D scanning capabilities.

B. 2-8 GHz Single- and Dual-Polarized Array

As a second example, the same design procedures can be applied for an array operating at 2-8 GHz. The ADL is designed to transform the free-space impedance $\zeta_0 = 377\Omega$ to $Z_L = 50\Omega$. To cover a 4:1 frequency band, a 4-order Chebyshev transformer is used. The ADL is then combined with the connected array unit cell. A PPW section is included, to replace the lowest dielectric slab of the transformer. The walls are replaced with vias, and a central pin crosses the ground plane through a hole and is connected to a microstrip line below the ground plane. The active reflection coefficients are reported in Fig. 7, which shows values lower than -10 dB for broadside, and lower than -7 dB for scanning to 60° in the E- and H-planes.

The PPW-based structure is also compatible with dual polarization. To achieve two polarizations, the single-polarized unit cell in Fig. 8(a) can be first modified as in Fig. 8(b), with the size of the PPW reduced by about half. The narrower structure can be duplicated for the orthogonal element to achieve double polarizations, as in Fig. 8(c). The final model of the unit cell shown in Fig. 9 exhibits an active reflection coefficient lower than -6 dB in the range 2.1 to 8 GHz, for broadside and for scanning to 60° in both main planes.

V. Conclusions

A novel approach to feed connected arrays was presented. Compared with the typically used integrated coaxial, this

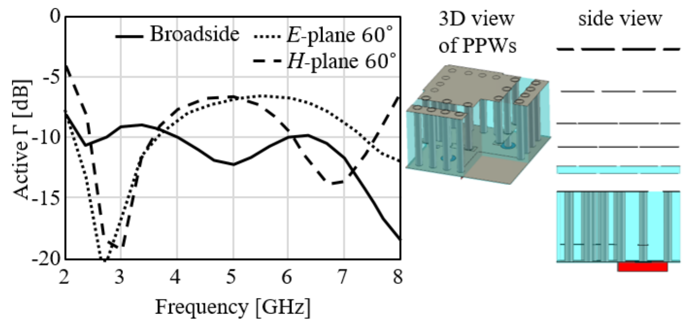

Fig. 9. Active reflection coefficient for broadside and scanning to 60° in the E-plane for the dual-polarized unit cell in the inset.

new PPW feed concept is easier to design and can reduce the number of ADL layers, because part of the impedance transformation is implemented in the PPW.

Two design examples were shown in simulation to verify the effectiveness of the concept, for both single and dual-polarization. Two unit cells were shown, at mm-wave and microwave frequencies, with one and two octave bandwidth, respectively.

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