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Glide-Symmetric SIH Unit Cells Implemented in Parallel-Plate Waveguides at mmWaves

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Abstract—This work studies the behaviours of unit cells based on substrate integrated holes (SIH) in parallel-plate waveguides (PPW). The basic SIH unit cell has been improved through the incorporation of a metallic patch. A comparison between the perfect dielectric hollow with patch unit cell and a SIH with patch unit cell has been carried out. The unit cell dimensions are used to study the different effective refractive indices. High order symmetries as a means to control dispersion and effective refractive indices are also introduced. By applying glide symmetry on different planes, we aim to enhance the effective refractive index and reduce dispersion across different frequency ranges. It is demonstrated that 1D glide-symmetric configurations reduce dispersion at higher frequencies, while 2D glide-symmetric configurations are able to reduce dispersion at high frequencies and also, to increase the effective refractive index simultaneously.

Index Terms—Glide symmetry, millimetre waves, parallel-plate waveguide, substrate integrated hole (SIH), unit cell.

I. INTRODUCTION

In the area of high-frequency wireless communications, millimetre waves (mmWaves) have emerged as a promising solution to meet the growing demand for bandwidth and faster transmission speeds. These high frequencies have numerous advantages, such as large available spectrum and the ability to transmit large amounts of data in a relatively short time [1]. However, realising the full potential of mmWaves requires the development of efficient and cost-effective devices and components at these frequencies.

Historically, gap waveguide technology [2] has been the benchmark technology for fulfilling the aforementioned requirements. Nevertheless, planar technologies, such as substrate integrated waveguide (SIW) [3], have recently garnered significant attention. SIW achieves shielded waveguide through the top and bottom metallizations of the dielectric laminates and through lateral rows of metallized vias. With a correct placement of the vias, negligible leakage is achieved [4]. This technology represents a compelling alternative to gap waveguide technology, addressing the cost-effectiveness requirement. Nonetheless, it is important to note that SIW exhibits noteworthy insertion losses attributable to the presence of dielectric material [5]. To address this limitation of SIW, a variant known as air-filled SIW (AF-SIW) [6] has been

developed in recent years. The fundamental concept behind AF-SIW revolves around reducing insertion losses by eliminating the part of the laminate from the propagation zone, both dielectric and metallization. Consequently, AF-SIW employs a multilayered configuration, with the upper and lower layers imposing perfect electric conductor (PEC) conditions to the vertical boundaries of the waveguide, while the middle layer comprises an air-filled area instead of dielectric material. The lateral boundaries of the waveguide remain as in basic SIW.

In the literature of the SIW technology at mmWaves, numerous devices have appeared in the area of antennas [7], related to the waveguide component design [8] and also, in the phase correction and lenses area [9]. AF-SIW technology has also been studied in these areas. In [10], this low-loss technology is used to increase efficiency in the antenna with respect to a SIW antenna. Other example is shown in [11], this work achieves a low-loss phase shifter. However, a very small part of the works uses the exposed propagation zone of the external layers of the multilayer configuration of this technology. In [12], a contactless AF-SIW (CLAF-SIW) unit cell with dielectric hollow in the aforementioned area is presented, achieving a phase shift regarding to reference CLAF-SIW unit cell. Nevertheless, this unit cell is theoretically and practically unfeasible in planar technology, being a developed option the one shown in [13]. The feasible phase-shifting elements are substrate integrated holes (SIH) and they generate undesirable effects such as the ones described in [14]. In this context, unit cells allow us to study the modification of the phase constant (β) within periodic structures. This environment could generate stopbands or dispersion behaviours which can be controlled by high-order symmetries [15], examples of this symmetries are twist symmetry [16] and glide symmetry [17].

In this work, the study of SIH unit cells based on parallel-plates waveguide (PPW) is shown at mmWaves. The interest in these unit cells lies in the use of integrated lenses. Glide symmetry takes on a special interest to enhance the achievable phase shift and avoid dispersion at working frequencies. The document is organised as follows. The Section II explains the behaviour of the unit cell in terms of effective refractive index of both the basic dielectric hollow unit cell and its counterpart unit cell with a patch over the hollow. Section

III introduces the SIH patch dielectric unit cell and examines its effect in relation to patch size. Subsequently, we explore the application of glide symmetry to this unit cell, analyzing the distinct behaviors that emerge when glide symmetry is employed. Conclusions are drawn in section IV.

II. DIELECTRIC HOLLOW WITH PATCH

In this section a perfect dielectric hollow unit cell is compared to its counterpart, a dielectric hollow with a patch. Figs. 1(a) and 1(b) illustrate a conventional dielectric hollow unit cell along with its patch dielectric hollow counterpart, respectively. Both unit cells share a common periodicity denoted as L and both units cells are composed with two layers separated by a gap (g) that represents the distance due to middle layer in the AF-SIW structure. The outer layers have a slot in the metallization which exposes the square dielectric blocks with a side length of W . The dielectric hollow have a height (h) and is confined with a metallic wall, the patch assumes a metallic square shape with a side length of l . The dielectric used in depicted unit cells has a relative permittivity of 3.55.

Fig. 1(c) compares the performance of the conventional dielectric hollow unit cell with the dielectric hollow with patch

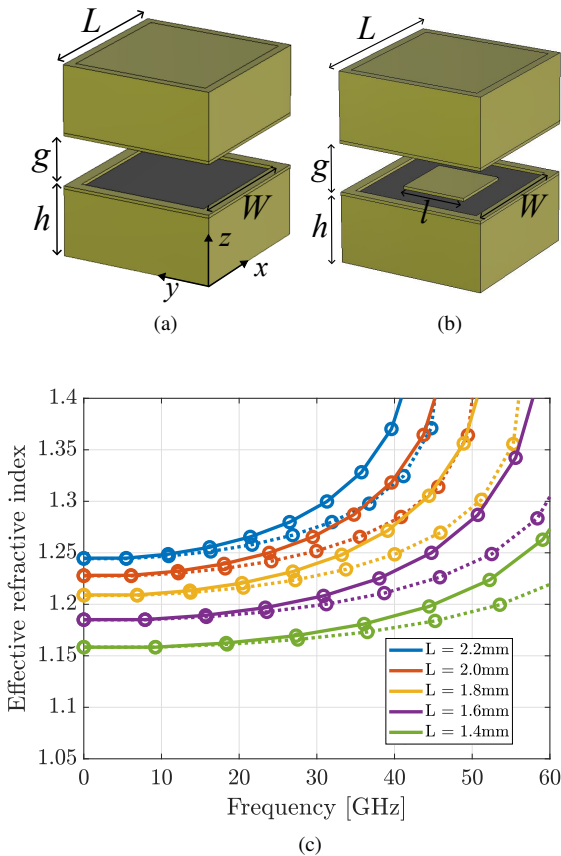


Fig. 1. Design of dielectric hollow unit cell: (a) Conventional dielectric hollow and, (b) Configuration with a patch over the slot. (c) Effective refractive indices of both unit cells by varying the parameter L . The solid lines depict the patch dielectric hollow unit cell, while the dotted lines represent the conventional dielectric hollow unit cell.

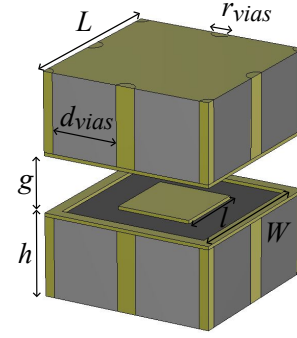


Fig. 2. Unit cell illustrating a SIH unit cell with patch. It consists of a hollow with a side length of W , a metallic patch in the shape of a square with a side of length l , a gap g between laminates, and a depth of size h . Additionally, it features a distance between metallic via d_{vias} and a metallic via radius r_{vias} .

unit cell. In order to obtain this study, a sweep of L with specific dimensions: a gap (g) of 0.508 mm, a height (h) of 0.813 mm, a hollow width (W) of 1.56 mm, and a metallic patch length set at 50% of the width of the hollow width has been performed. This analysis in the propagation direction along the X-axis was carried out using the eigenmode solver of CST Microwave Studio. The results illustrate that incorporating a metallic patch leads to higher effective refractive indices within the high ranges of bandwidths, for example between 30 GHz and 40 GHz. However, this improvement comes at the cost of increased dispersion at higher frequencies. Additionally, as shown in Fig.1(c), an increase in L results in a reduction in the maximum operating frequency while simultaneously raising the effective refractive index. This phenomenon occurs because lower modes begin to entering into the hollows, introducing dispersion at lower frequencies. Consequently, this limits the maximum achievable operating frequency for potential designs.

III. SIH WITH PATCH

A. Aspect Ratio in the Patch

In the previous section, we discussed about effective refractive indices in terms of the dispersion properties of two different units cells designs. This section shifts its focus towards evaluating the influence of the aspect ratio of the metallic patch on dispersion properties of the unit cells. However, the unit cells previously presented are unfeasible to design using planar technologies. As shown in [14], SIH structures offer a cost-effective solution while maintaining similar dispersion characteristics to conventional holey structures. Therefore, the unit cells proposed in this and the following sections are SIH-based, as depicted in Fig. 2. This unit cell replaces the perfect metallic walls by metallic vias to confine the dielectric hollow. The aspect ratio is defined as the ratio between the patch size (l) and the hollow width (W). To investigate the impact of the aspect ratio, three different values are evaluated $A_r = [20, 50, 80]\%$.

Fig. 3 depicts a comparison of the effective refractive indices of the SIH unit cell with patch. To carry out this

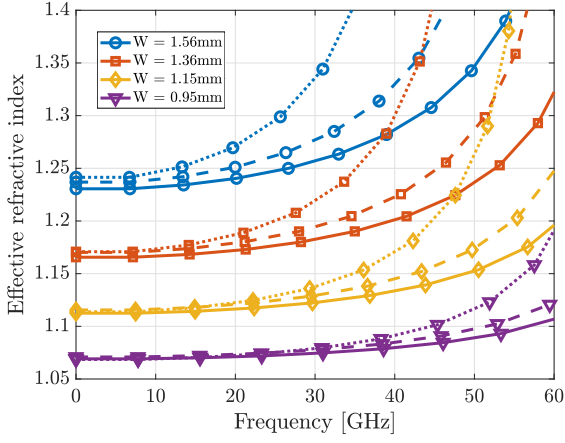


Fig. 3. Comparison of the effective refractive indices by varying the parameter W considering different aspect ratios. The solid lines correspond $A_{r1} = 20\%$, the dashed lines to $A_{r2} = 50\%$ and the dotted lines to $A_{r3} = 80\%$.

analysis, a sweep of the hollow width (W) has been performed with specific dimensions: a gap (g) of 0.508 mm, a height (h) of 0.813 mm, a distances between vias of 0.62 mm, a via radius of 0.14 mm, a unit cell period (L) of 1.8 mm, and the three different aspect ratios (A_r) mentioned previously.

The simulated results reveal that employing a higher aspect ratio can lead to a greater values of effective refractive index. Nonetheless, this enhancement comes at the cost of the appearance of noticeable dispersion at intermediate frequencies. Smaller size of patches exhibit behavior akin to patch-less cavities, while larger sizes tend to introduce greater dispersion effects. As shown in Fig. 3, if we compare the blue and yellow lines, it becomes evident that higher values of W are notably impacted by variations in the aspect ratio.

B. Glide symmetry

High-order symmetries have proven to be useful for controlling the dispersion in periodic structures, among many others applications. Therefore, in this subsection, we use this type of symmetry to address the drawback of increasing the refractive index at the expense of dispersion occurring at higher frequencies. Fig. 4(a) and Fig. 4(b) show the 1D and 2D glide-symmetric transformation of the SIH unit cell with patch for an A_r of 50%, respectively. The 1D glide symmetry is done by shifting $L/2$ the lower part of the unit cell in the X-direction, while the 2D glide symmetry is applied in the XY plane. During this analysis, a sweep of the hollow width (W) has been conducted, maintaining the values of the remaining parameters consistent with previous configurations. The comparison between the behaviour of the 1D glide-symmetric configuration and the SIH with patch [see Fig. 2] is presented in Fig. 4(c). The 1D glide-symmetric configuration provides a slight mitigation of the dispersion at higher frequencies. Nonetheless, in Fig. 4(d), a comparison between the 1D and 2D glide-symmetric configurations is illustrated. Here, a compelling advantage of the 2D glide-symmetric configuration becomes evident: it does not only

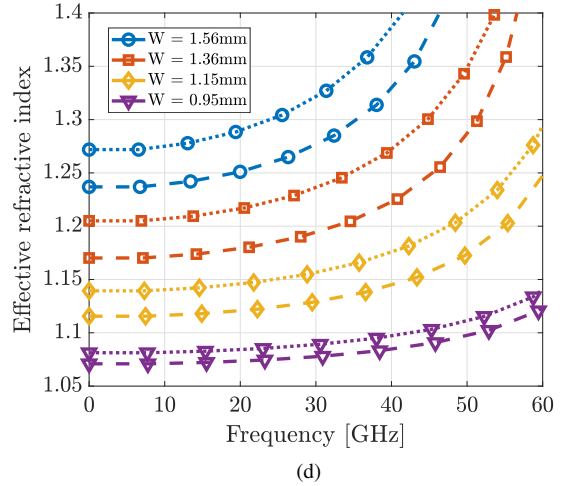
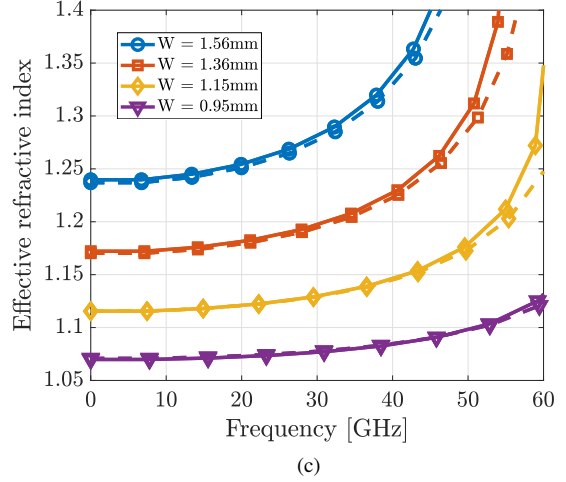
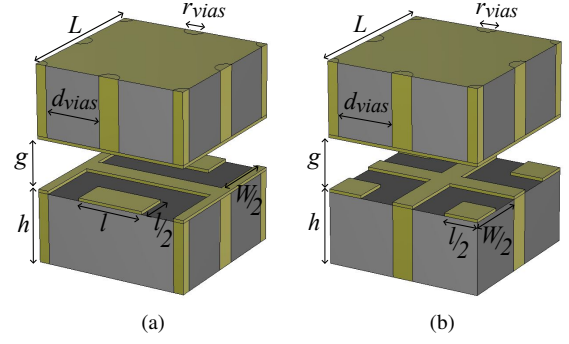


Fig. 4. SIH unit cells with patch and glide-symmetric configuration: (a) Design of 1D glide-symmetric SIH with patch unit cell, (b) Design of the 2D glide-symmetric SIH unit cell with patch, (c) effective refractive index comparison between the SIH with patch and its 1D glide-symmetric counterpart, and (d) comparison of the effective refractive indices between the 1D and 2D glide-symmetric designs, both obtained by varying the parameter L . The solid lines correspond to unit cell shown in Fig. 2 and, the dashed lines and dotted lines correspond to 1D and 2-D glide-symmetric unit cells, respectively.

effectively reduces dispersion compared to the 1-D glide-symmetric unit cell but also simultaneously increases the effective refractive index.

IV. CONCLUSION

This work has introduced an innovation in the SIH unit cell leveraging a metallic patch over the slot to enhance the effective refractive index. The use of glide symmetry has been applied in the SIH unit cell with patch in the two periodic direction. The 1D and 2D glide-symmetric configurations of this unit cell offer a precise control over dispersion properties and in the effective refractive index. By using glide symmetry, it has been demonstrated the potential to balance higher refractive indices with effective dispersion control. Future work will involve prototyping to validate these findings, with results to be presented at the conference.

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