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A Glide-Symmetric Reconfigurable Metasurface in Substrate-Integrated-Waveguide Technology

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Abstract— We propose a unit cell of a holey metasurface parallel-plate waveguide having the capability to reconfigure its effective refractive index by acting on the depth of the holes. The waveguide is glide symmetric, which means that two identical metasurfaces are chosen as bottom and top plates, and are placed in an off-shifted configuration along the two periodicity direction, in order to maximize the operation al bandwidth. we discuss the choice of the shape of the hole, and propose an implementation in printed circuit board technology by replacing the metallic holes as substrate integrated holes.

Keywords— metasurfaces, glide symmetry, periodic structure, guided waves.

I. INTRODUCTION

Reconfigurability is an attractive feature for modern communication systems. As an alternative to lossy and unshielded microstrip delay-lines, many phase-shifter concepts in SIW technology have been developed: changing the width of the waveguide [1], adding inductive posts [2], integrating ferrite materials [3], or creating density changes [4], [5].

In the context of millimeter-wave radiating devices for modern communication standards, smart features require extreme configuration capabilities with reduced power dissipation, by granting a low-loss and wide bandwidth operation. However, at millimeter waves, dielectric losses limit the power handling of these designs. Partially air-filled phase-shifters have been presented [6]. But hollow metallic waveguides are the preferred alternative to drive the losses down [7]. Furthermore, gap-waveguide technology avoids the need for contact between upper and lower waveguide parts [8]. Therefore, it has been developed in many microwave applications due to its high power handling abilities [9]. Having two independent metallic layers facilitates the insertion of phase-shifting artefacts within the waveguide, such as ferrite slabs [10]. Additionally, the use of High-Impedance Surfaces (HIS) like bed of nails to guide the waves facilitates width variation to change the phase [11]. In [12], a 90°-phase-shifter in gap-waveguide technology is presented, combining the use of a dielectric slab and an increase of the waveguide width to change both the phase and the impedance.

Reduced losses and wide bandwidth can be achieved at millimeter waves with Glide-Symmetric (G-S) all-metal holey metasurfaces (see Fig. 1), which support modes propagating in the air between the metasurfaces having a stable refractive index over a ultra wideband. On one hand the absence

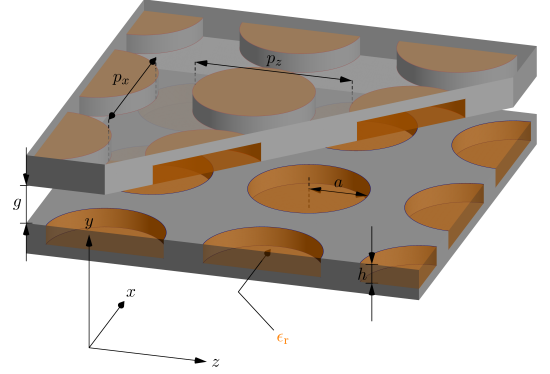


Fig. 1. GS holey PPW with circular holes. The two holey structures are off-shifted of half a period in the two periodicity directions (glide symmetry). The holes depth is h and a material having dielectric constant ϵ_{r2} fill them. The wave propagates in the gap between the metasurfaces, filled with air ($\epsilon_{r1} = 1$ not shown).

of dielectric drastically reduces losses, and the shape and depth of holes can be used to tune the required refractive index to be synthesized. On the other hand, Glide Symmetry (GS) is responsible for a large stopband blocking more effectively the propagation of waves with respect to non G-S structures. Previous reconfigurable devices have benefited from the stopband features of GS. A reconfigurable filter is designed in [13] by breaking the GS, which re-opens the stopband between the first and second modes. In [14] the giant stopband that is created between the second and third modes by GS is exploited: changing the gap between the metasurfaces shifts this stopband, such that the operating frequency finds itself either in a passband or in the stopband, creating a high-power-handling switch.

Here we propose a unit cell as the basic brick of a G-S metasurface-based reconfigurable phase shifter, with the refractive index being controlled by changing the depth of the holes in both metasurfaces. In future work we will replace the bottom metal of the hole with a contactless high-impedance metasurface with can be moved and will modify the effective length of the hole. This working principle needs a holey PPW that is sensitive to the hole depth. In Section II, this sensitivity is improved by studying the refractive index of G-S metasurfaces with different shaped holes with the homogenized closed-form results in [15]. In Section III we implement the metasurfaces in a printed circuit board (PCB) by choosing

a substrate-integrated technology, where the metallic hole is replaced by vertical metallic vias in a dielectric substrate. We find there that reproducing the holes directly in the substrate using metallic vias improves the impact of the hole depth on the refractive index. In Section IV we draw some conclusion and propose future work.

II. RECONFIGURABILITY OF METALLIC HOLEY CELLS

A reconfigurable holey PPW whose refractive index changes with the hole depth requires a unit cell as sensitive as possible to the depth of the holes. This is expected to be mostly related to the hole itself – its shape, size and filling. In a practical design, the PEC will be replaced by a movable HIS. When opening the holes and loading them capacitively with the HIS, the accurate value of the effective refractive index will probably change compared to holes closed with PEC. However, the sensitivity to the hole depth should be qualitatively preserved.

In order to accelerate this study, the closed-form formula in [15] for the quasi-static refractive index is used here. While the accuracy of this formula deteriorates with increasing frequency, it is sufficiently accurate to describe the variation of the index with the hole depth, as it will be confirmed in the following section by full-wave results obtained with CST Microwave Studio.

All the following structures have vacuum in the gap between metasurfaces in order to let the wave mainly propagating in a lossless medium. In Fig. 3, the quasi-static refractive index is computed as function of the hole depth h . As expected, the refractive index sensitivity to the hole depth is limited: beyond a certain depth, the refractive index saturates at a maximum value. This is due to the fact the hole can be considered as a waveguide whose modes are excited below their cut-off frequencies. Therefore the waves have a limited penetration in the holes. A better penetration is achieved when increasing the density of the hole filling, as shown in Fig. 3

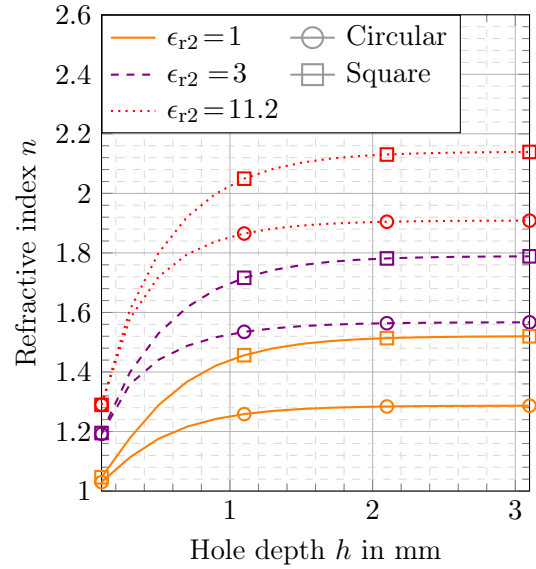


Fig. 3. Refractive index of GS unit cells having square periodicity $p = 4$ mm and a gap $g = 0.1$ mm. Circular holes have radius $a = 1.5$ mm, circular holes have side $a = 1.5$ mm. The gap is filled with air, while the hold is filled with a dielectric ϵ_{r2} .

for permittivities $\epsilon_{r2} = 1$, $\epsilon_{r2} = 3$ and $\epsilon_{r2} = 11.2$. A denser dielectric lowers the cut-off frequencies of the excited modes, and so the sensitivity to the hole depth is increased. Therefore, the convergence value of the refractive index is higher for a denser dielectric.

Increasing the maximum achievable refractive index as function of the hole depth is of foremost importance for the reconfigurable unit cell. Indeed, the higher the maximum index value, the larger the available range of reconfigurable indexes. Moreover, Fig. 3 shows that the refractive index is most sensitive when the hole depth is small, meaning that most of the index reconfiguration is only possible when the holes are shallow. This is an important limiting factor given that the unit cell can not be reconfigured starting at $h = 0$: the hole depth is lower-bounded by the thickness of the metallic plates that constitute the PPW. The hole depth can then only be increased by moving the hole bottom further away of the central PPW. This is illustrated in Fig. 4, which plots the index variation when changing the depth from $h = 0.5$ mm to $h = 2.5$ mm for different sizes of the holes. This variation is much smaller than the maximum refractive index that can be achieved by increasing the hole depth, given that the index variation is considered only starting at $h = 0.5$ mm, which is assumed to be the thickness of the PEC plate here.

On top of increasing the hole density, a significant improvement of the depth sensitivity can be achieved by changing the hole shape. Fig. 3 shows that square holes yield larger refractive indexes than circular holes with the same area – here, a square size $a = 2.7$ mm. Consequently, the possible index variation is larger as well, as illustrated in Fig. 4.

Therefore, these preliminary studies motivate the use of holey PPW with square holes filled with a dense dielectric,

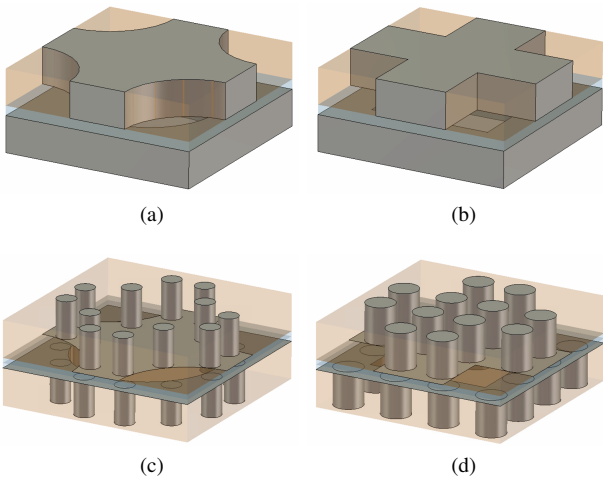


Fig. 2. Holey G-S unit cells: (a) all-metal circular hole, (b) all-metal squared hole, (c) Substrate Integrated Holes (SIH) circular hole, (d) SIH squared hole.

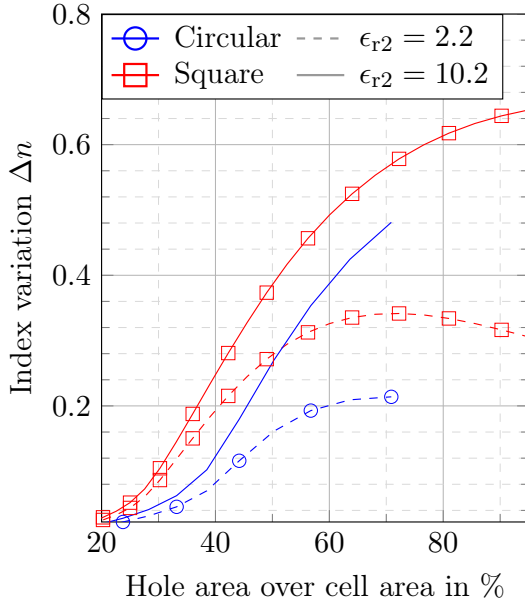


Fig. 4. Refractive index absolute variation when changing the hole depth from 0.5 mm to 2.5 mm.

which yield a good sensitivity of the refractive index to the hole depth. Moreover, the thinner the PEC plates of the PPW, the larger the available index variation.

Unfortunately, holey metasurface with square holes are difficult to manufacture, and filling each hole with the dielectric is particularly challenging. That is why in the next paragraphs, an alternative is sought to facilitate the manufacturing of the reconfigurable unit cell.

III. RECONFIGURATION OF SIH UNIT CELL

In this section we propose to facilitate the manufacturing of the holey metasurface of the previous section by using metallized dielectric layers instead of fully metallic plates. The resulting waveguide is made of SIH, first introduced in [16]. The idea is to recreate the holes in the dielectric substrate layer by etching the copper on top and bottom metallization away in the desired hole shape, and then by adding metallic vias around the hole. The resulting unit cells are pictured in Figs. 2c and 2d for circular and square holes.

In Fig. 5, the comparison between PEC-based holes and SIH is shown, with focus on the achievable refractive index variation for both hole shapes. These results are obtained with the CST Microwave Studio eigensolver tool, computing the phase constant of a wave propagating along the x direction of the 2-D lattice of GS SIHs, and therefore its effective refractive index. The refractive index is plotted as function of the frequency, and each curve corresponds to the index variation when changing the hole depth from $h = 0.5$ mm to $h = 2.5$ mm. The largest variation is obtained again with square holes also in SIH technology, and this variation is increased at expense of stronger frequency dispersion.

As a conclusion, we can state that the use of dielectrics enables higher refractive indexes, thus making possible a larger

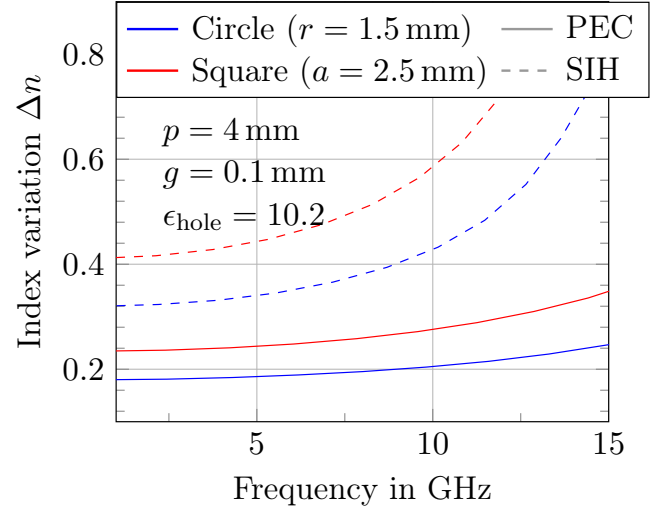


Fig. 5. Absolute refractive index variation in the four structures of Fig. 2. All the considered structures have periodicities $p = 4$ mm and a metasurface gap $g = 0.1$ mm. Square holes of size $a = 2.5$ mm are compared to circular holes of radius $a = 1.5$ mm. PEC-based holes are compared to SIH, where hole shapes are created with 12 vias of radius $r = 0.2$ mm. The hole is filled with a dielectric $\epsilon_{r2} = 10.2$.

range of variation. Dielectric-filled holes is in the nature of SIH, as the dielectric in the holes is the same as the substrate layer. In all-metal structures, sufficiently high indexes would require a very small gap between the metasurfaces. The increase of refractive index with SIH releases this constraint, which facilitates the assembling of prototypes.

A. SIH Hole with Central Via

In [17], [18], it is highlighted that an increased refractive index can be achieved by adding a metallic pin inside the holes, because then a TEM mode can penetrate further in the holes. Nevertheless, one of the downsides of this idea is its manufacturing cost, because it demands milling the holes around the central pin. With SIH technology, adding a central pin does not add any manufacturing complexity to the design, because an additional metallic via is simply added in the middle of the holes. Therefore, it is of interest to see if even more refractive index sensitivity to the hole depth can be achieved with this central via. In Fig. 6, the refractive index of G-S PPW with square SIH is plotted as a function of frequency, for different hole depths h . The case with an additional central via, enabling the propagation of a TEM mode, is compared to the case without this via.

The ultra-wideband nature of the GS waveguides is confirmed in this figure as the index is stable from 0 to 20 GHz for several choices of parameters. This is already well known in literature when dealing with this symmetry configuration and motivates our choice of GS waveguides. Without the central via, the refractive index variation from $h = 0.5$ mm to $h = 2.5$ mm is approximately 0.33 at low frequencies. When adding the central pin, it rises up to 0.45. This confirms that a larger index variation can be obtained by enabling the propagation of TEM modes in the

holes. However, this design is not selected for future work, due to its increased frequency dispersion. SIH are already responsible for a rise of the dispersive behavior, limiting the bandwidth in which the refractive index variation is stable. In Fig. 6 this phenomenon is accentuated by the central pin. The trade-off between dispersion and index variation favors the design without the central pin as the selected unit cell capable to work around 20 GHz, at the expense of a slightly limited available index range of variation.

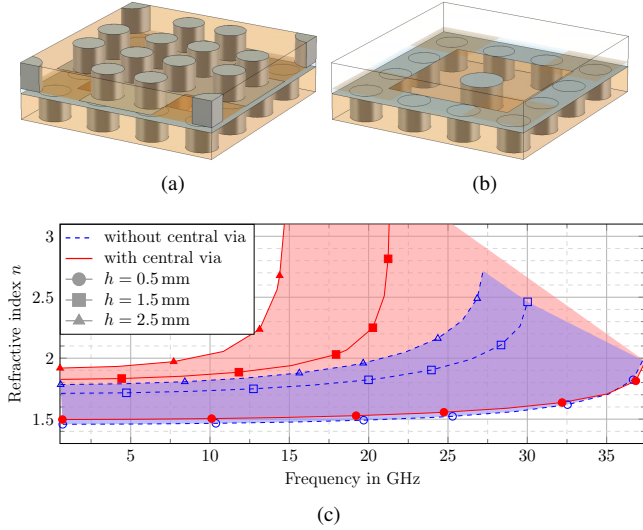


Fig. 6. G-S SIH unit cell with central pin: (a) complete unit cell, (b) view of the lower substrate, (c) Refractive index as a function of frequency, for different hole depths. The structures have $p = 4$ mm, $g = 0.1$ mm, and SIH of size $a = 2.5$ mm with $\epsilon_{r2} = 2.2$, and 12 vias of radius $r = 0.2$ mm. The central pin has a radius of 0.4mm.

IV. CONCLUSION

We have proposed a unit cell based on a GS holey metasurface which can be reconfigured by varying the depth of the holes. Different shapes have been studied and a realization in PCB technology has been given, keeping the main features of the structure (propagation in the air to reduce losses, wideband operation) and reaching higher reconfigurability and larger tolerances on geometric parameters. future work will aim at replacing the fixed metallic bottom of holes with a contactless HIS which can be moved by mechanical actuators.

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