Broken glide-symmetric holey structures for bandgap selection in gap-waveguide technology

Pablo Padilla, Ángel Palomares-Caballero, Antonio Alex-Amor, Juan Valenzuela-Valdés, José M. Fernández-González and Oscar Quevedo-Teruel

Abstract—**In this letter, we propose a new technique to tune the bandgap in gap-waveguide technology based on broken glide-symmetric holey structures. We demonstrate that breaking the glide symmetry in a proper manner provokes the presence of a passband within the bandgap due to the frequency sweep of the second propagating mode. This passband generates field leakage in the gap that is translated into a filtering property. This filtering effect may be used to reduce or eliminate filters in large complex devices. In order to avoid undesired coupling due to the leakage from the airgap between the plates, an absorbing sheet is proposed to dissipate the undesired fields. This idea has been numerically studied and experimentally validated with a specific design, a WR15-size gap-waveguide prototype with glide-symmetric holes with filtering properties.**

Index Terms—**glide symmetry, gap-waveguide, periodic structures, higher symmetries, selected bandgap.**

I. Introduction

Gap-waveguide has become a popular technique for designing and manufacturing high frequency antennas and components in mm and sub-mm frequency bands [1-3]. In this technology, the electromagnetic propagation is only in air, reducing the losses. Additionally, the manufacturing can be done in two layers, without necessity of physical contact, reducing the cost of integration of complex microwave circuits [4]. To ensure field confinement in gap-waveguides, glide-symmetric holey structures have arisen as a robust and cost-effective alternative to metallic pins [5], mainly for mm and sub-mm wave systems.

Glide-symmetric periodic structures are composed of two mirrored periodic layers with a misalignment of half of the unit cell [6]. In a wide view, these structures have been proposed either for guiding surface waves with a low dispersion [7], or for field confinement [5,8]. The first case can be used to control the equivalent refractive index of field propagating in a surface, with more isotropy and lower dispersion in the propagation constant. The second case is employed to increase the rejected band by a holey periodic structure, which is the case of this work. Particularly, glide-symmetric holey structures have been proposed to produce cost-effective gap waveguide technology [5] and low-cost contactless flanges [8].

Up to now, glide-symmetric holey structures have been used as an alternative to bed-of-nails [5]. In this letter, we propose to go a step further with the use of partially broken glide-symmetric holes to produce a passband inside the main stopband, which is translated into a filtering effect in the gap waveguide. It is not possible to introduce partially broken glide symmetry in the original conception of gap waveguide with bed-of-nails [1]. In addition to the broken symmetry, we propose the insertion of a low-cost and high-loss material between layers, demonstrating that a common guiding line can be used not only to transmit at the frequencies of interest with low losses, but also to filter the waves at a given frequency range. The main aim of this work is to demonstrate the potential use of partially broken glide-symmetric structures for gap-waveguide propagation, leakage control and filtering capability.

II. Glide-symmetric Holey unit cell

A periodic structure possesses a bandgap when the field propagation is avoided in any direction within particular frequency range [5]. In particular, glide-symmetric holey structures, as represented in Fig. 1, are demonstrated to be able to produce a wide bandgap. The highest bandgap bandwidth can be obtained by properly choosing the relation between the size of the unit cell (a) and the radius of the holes (r). The frequency location of the optimal bandgap can be tuned by varying a and r as long as their ratio is maintained constant [9].

A. Unitary glide-symmetric holey cell

The unitary holey cell has a glide-symmetric configuration if a translation of half the periodicity, $a/2$, is introduced between the two holey layers of the gap. Additionally, the top and bottom side holes must have the same radii. This glide-symmetric holey structure, as illustrated in Fig. 1, is set as the reference model for the variations introduced in the rest of the studies in this work.

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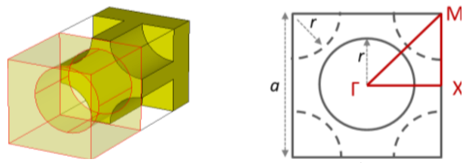

Fig. 1. Single glide-symmetric periodic unit cell: (left) 3D view, and (right) top view geometry (the continuous line refers to the upper layer of the gap while the dashed line refers to the lower one).

The bandgap of this periodic structure can be characterized through the irreducible Brillouin zone. In this work, we calculate this zone with the eigenmode analysis of *CST Microwave Studio*. The basic reference dimensions are: r=1.1 mm and a=2.83 mm, for an air gap of 50 µm. This r/a relation provides the largest bandgap [9], which covers almost the full range of both WR15 and WR10 standards. Figure 2.a shows the dispersion diagram of the reference cell, where the bandgap is outlined in grey.

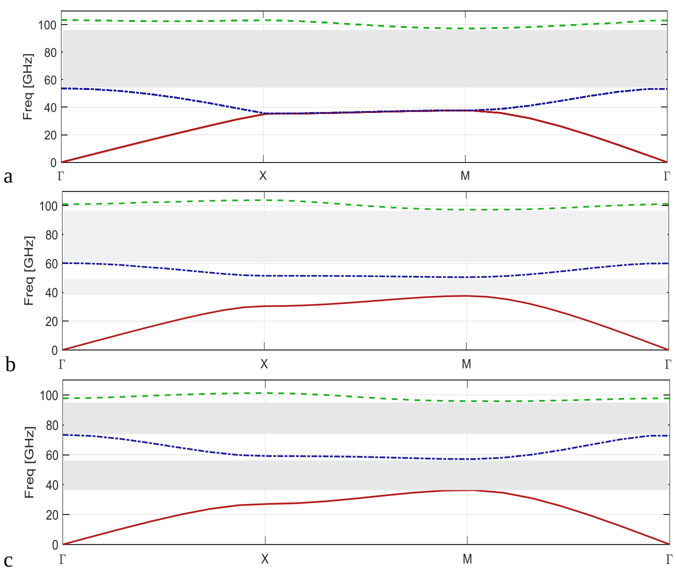

Fig. 2. Example of dispersion diagram for a=2.83 mm: a) Glide-symmetric holey structure, with dimensions: r=r_1=r_2=1.1 mm; b) symmetry breakage, for radii values: r=r_1=r_2=1.1 mm, and separation offset d_x=d_y=0.2 mm, c) symmetry breakage, for r_1=1.1 mm and r_2=1.2 mm, and d_x=d_y=0.5 mm.

B. Breaking the symmetry

In previous studies, it was introduced that the bandgap can be split into two separated ones when the glide symmetry is broken. This means that, by breaking this symmetry, the second mode is shifted up in frequency, introducing a passband within the original bandgap. For this unit cell, there are three possible ways for breaking the symmetry. The first one implies varying independently the radius values of the glide-symmetric holes for the top and bottom surfaces of the gap. The second one consists of introducing a misalignment different than a/2 between the top and bottom layers. The third option is to define different holes depths at each layer. These three possibilities are illustrated in Fig. 3. In this work, we will focus our analyses only in the first two.

The effect of the first option is mainly linked to the size of the passband bandwidth, while the second one mainly tunes the passband. Both effects, properly combined, permit an accurate definition of the bandwidth and frequency location within the bandgap. Figures 2.b and 2.c exemplify how breaking the symmetry can split the bandgap in two sections. These results, which can be tuned with the physical dimensions, show two examples of passband located within the original stopband between 50-60 GHz and 60-70 GHz.

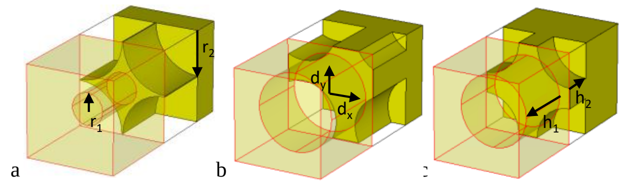

Fig. 3. Symmetry breakage of the periodic unit cell: a) radius change, b) layer misplacement, c) hole depth variation.

This pass/stop effect can also be studied in transmission by using a parallel plate structure with a gap height of microns, and glide-symmetric holes within the gap. Figure 4 presents the electric field distribution (amplitude) in the gap, of 50 µm, inside the periodic structures previously studied in Fig. 2.b. In this case, the matching is not relevant since the structure is only designed to verify whether the electric field is propagating through or not. The first one, Fig. 4.a, is for the glide-symmetric configuration, while the second one, Fig. 4.b, corresponds to having broken the glide symmetry. As predicted, the broken glide-symmetric configuration provides a passband frequency range.

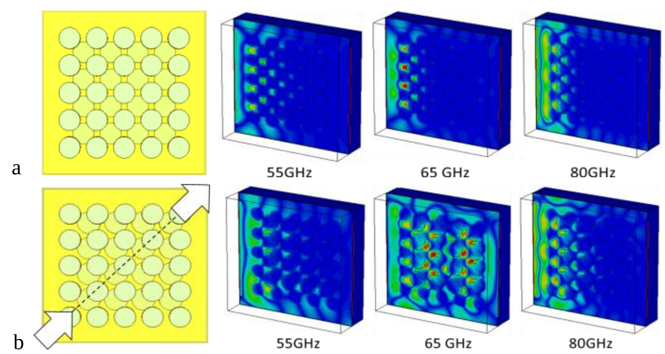

Fig. 4. Electric field distribution (normalized amplitude) inside parallel plates with a gap height of 50 µm: a) glide-symmetric holey structure, b) breaking the glide-symmetry of the holey structure. Excitation goes from left to right.

C. Filtering properties of breaking the symmetry

The presence of a middle passband inside the bandgap can be used in gap-waveguide technology for filtering purposes, simplifying the overall circuitry. However, the effect of the passband is that the electric field leaks through the gap, and may produce coupling in other parts of the gap-waveguide structure. For instance, this coupling can be of importance between near gap-waveguide lines. This undesired coupling can be avoided if the leaked fields are fast dissipated. The most suitable strategy for that is to introduce an absorbing material in the gap. We propose the use of commercial copy-carbon paper, which has to be properly characterized in advance (permittivity, permeability and loss tangent).

The effect of introducing a material sheet in the gap implies an increase in the permittivity value. This forces to redesign the dimensions and periodicity of the glide-symmetric holes. The effect of the increment in the permittivity is translated into a reduction in the dimensions of the unit cell. For example, for having the same results of Fig. 2.b, the new dimensions are: r_1=0.6 mm, r_2=0.65 mm, a=1.55 mm, separation offset d_x=d_y=0.45 mm and 30 µm gap, for an absorbing sheet of ε_r=3.68 and loss tangent (tanδ) = 0.15. The following section (experimental validation) is referred to these dimensions and values.

III. Experimental Validation

Our study of the gap-waveguide with broken glide symmetry holes has been verified through an experimental demonstration. For that, we design a WR15-size gap-waveguide with glide-symmetric holes whose symmetry has been broken in order to obtain a passband. As a consequence, there is field leakage at this pass-band through the glide-symmetric holes. This leakage is neutralized by the absorbing sheets placed in the gap, over the holes. This technique is evaluated with the mutual coupling between two waveguides, as illustrated in Fig. 5.a. The structure is a two-pieces aluminum block, with a separation gap of 30 µm, with two gap-waveguides milled on it, half in each piece (prototype in Fig. 5.b).

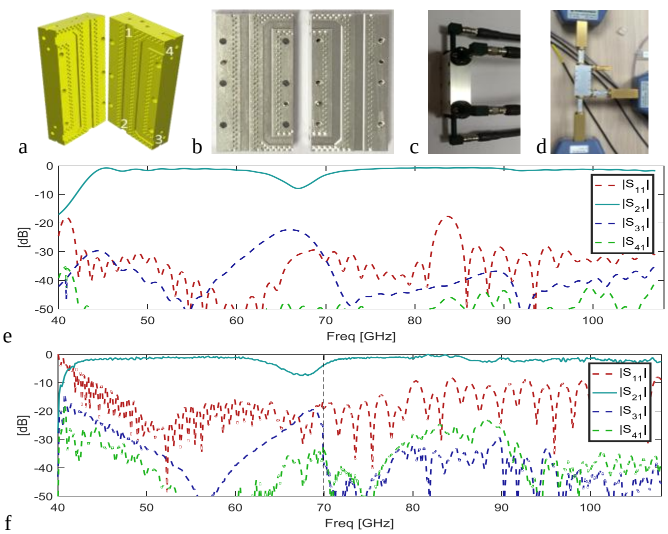

Fig. 5. Experimental demonstration for validation: a) prototype model, b) prototype, c) set-up for 40-70 GHz range, d) set-up for 70-110 GHz range, e) simulation results, and f) measurement results.

Figure 5.e and 5.f show the simulated and measured results, which are in excellent agreement in the transmission coefficient. There are only discrepancies with the S_{11}. These differences are due to the alignment since the tolerances are of the order of microns. Therefore, measurements have a higher level of reflections. The measurements were made with two separate set-ups: from 40 to 70 GHz directly with an R&S®ZVA67 VNA (Fig. 5.c), and from 70 to 110GHz with R&S®ZVA-Z110 heads (Fig. 5.d). In the first range (40-70 GHz), the calibration is made in the V-connectors and the effect of the V-to-WR15 transition cannot be avoided in the measurements. Similarly, in the second range (70-110 GHz), the calibration is made in the WR10 heads, so the effect of the WR10-to-WR15 transition affects to the measurements. Differently, the S_{21}, which is the most relevant parameter for this study, since it demonstrates the bandpass/stopband behaviour of the broken glide-symmetric structure, has a good agreement with simulations. Notice that the filtering effect around [65-70] GHz is not translated into a coupling between waveguides since the gap leakage is attenuated in the lossy material.

The practical use of this structure lays in its filtering nature, completely integrated in the structure at practically no extra cost. This filtering effect can be used to enhance the suppression of a particular frequency range in large and complex circuits. Our proposed technique, based on breaking the symmetry does not let to define accurately a strict filter in terms of band rejection, i.e. number of poles/zeros. Therefore, its application is limited to structures in which a filtering cavity structure cannot easily be integrated into the available space of the overall system, or an extra filtering is needed at some given bands.

IV. Conclusion

In this work, we have demonstrated that a gap-waveguide with glide-symmetric holes can benefit from introducing controlled variations in the periodic structure. In particular, we have studied how by breaking the glide symmetry affects the resulting bandgap. Those variations, properly introduced, produce a bandwidth splitting and the presence of a tunable passband. This passband is of interest for gap-waveguide technologies, since it can be used for filtering purposes at chosen frequency ranges without requiring additional circuitry. We have demonstrated these filtering properties through the design and measurement of a short prototype. The prototype consists of two gap-waveguides with broken glide-symmetry in the gap holes so that, depending on the chosen frequency, the guide is able to either permit or progressively stop the field propagation along the gap-waveguide without coupling with other surrounding gap-waveguides.

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