Periodically Air-Filled Substrate Integrated Waveguide (SIW) Band-Pass Filters

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***Abstract*—In this paper, we describe the design of a periodically air-filled substrate integrated waveguide (SIW) band-pass filter in which part of the dielectric substrate is removed to reduce insertion losses. The unit cell parameters of the structure, which are directly related to the center frequency (f_c) and bandwidth (BW) of the first passband, and also to the first stopband or bandgap (BG) of the structure, have been appropriately selected for filtering purposes, thus providing some useful design rules. Furthermore, we apply the concept of glide symmetry for achieving a much larger fractional bandwidth (FBW). Additionally, a microstrip-to-SIW transition including a novel coupling iris is proposed. A prototype of the periodic SIW filter with glide symmetry has been manufactured and measured for validating purposes. The proposed filter proves to be a good candidate for millimeter wave applications.**

I. Introduction

Substrate integrated circuits (SICs) are good candidates for filtering applications, given their reduced sizes and weights with respect to the classical waveguide technology, and they exhibit higher quality factors than printed technology. Among the different SIC structures [1], SIWs are the most popular, due to an easy manufacturing process, lower costs, and ease of integration with other planar circuits, antennas, and passive and active devices on the same substrate [2]. Recently, several modified SIWs have been proposed, where the dielectric substrate has been partially or fully removed to improve the quality factor [3], [4], [5], due to the reduction of the dielectric losses. Different implementations of such modified SIWs can be found in the technical literature, known as hollow SIW (HSIW) [3], air-filled SIW (AFSIW) [4], and empty SIW (ESIW) [5], implemented as band-pass filters, showing narrow-band characteristics, with a fractional bandwidth around 3%. In [6], a higher symmetry called glide symmetry, which is created with a combination of a translation and mirroring over a plane, was applied to the design of a wide-band sub-wavelength CSRR-loaded SIW filter with $FBW = 26\%$, thus illustrating the potential of this technique to widen the passband of conventional SIW filters. However, a poor matching was observed in the lower passband edge when using conventional taper transitions from microstrip to SIW. Besides, such design did not exhibit the low insertion losses of AFSIWs.

In this contribution, we make use of the results obtained in a previous work of the authors [7], where, similarly, the dispersion characteristics of waves propagating in periodic SIWs with different periodic configurations (with and without glide symmetry) were used to achieve a significant broadening of the first passband when glide symmetry was considered

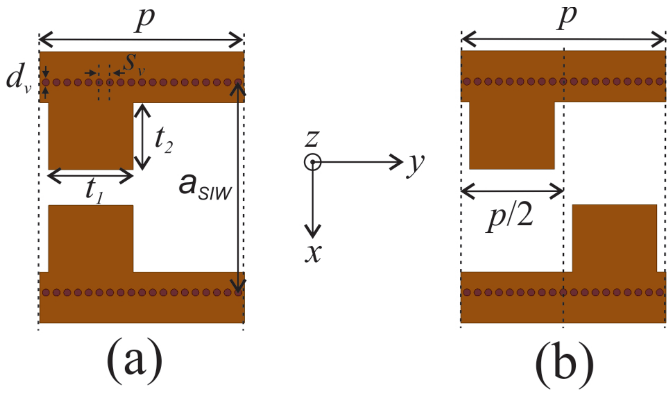

Fig. 1. Scheme of the proposed unit cells of the periodic SIW partially filled with air. (a) Unit cell of the initial periodic configuration (named non-glide configuration). (b) Unit cell of the same structure shown in case (a) when glide symmetry is applied.

in the structure. However, in the aforementioned work, less attention was paid to both the achieved matching level in the passband and to the obtained rejection bands. In this new contribution, we go a step further with the objective of achieving enhanced filtering electrical responses, by designing band-pass filters based on periodic air-filled SIWs with and without glide symmetry, in order to benefit from low insertion losses due to the removal of dielectric material. We will provide useful design guidelines that can be used to meet the prescribed filter electrical specifications based on the dispersion diagram properties of a periodic SIW. Additionally, some design curves are provided, from which appropriate unit cell parameters can be easily selected for achieving the desired filter center frequency and bandwidth.

II. Non-glide air-filled periodic SIWs

Fig. 1(a) shows the unit cell of the air-filled periodic SIW in the proposed initial filter design, which consists of a SIW of width a_{SIW}, whose lateral waveguide walls are delimited by vias characterized by their diameter $d_v = 0.8$ mm and separation $s_v = 1.2$ mm, which have been appropriately chosen in order to avoid radiation losses. The propagation constant of this guide is determined by the width a_{SIW} of the SIW (see Fig. 1(a)), and also by the effective permittivity ϵ_{reff} obtained after periodically removing substrate material in the propagation area in order to create permitted and forbidden bands. The SIW parameters have been set to the following values (see Fig. 1): width $a_{SIW} = 23$ mm, and height $b = 0.63$ mm (corresponding to the height of the substrate employed

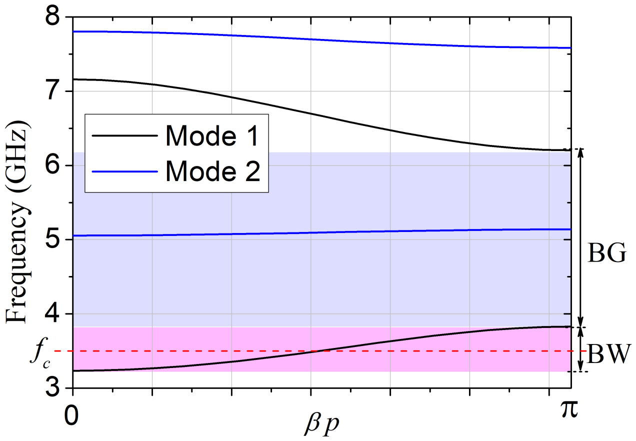

Fig. 2. Dispersion diagram of the first two modes of the periodic SIW shown in Fig. 1(a) with the following parameters: $p = 23$ mm, $t_1 = 9.5$ mm and $t_2 = 7.5$ mm (parameters corresponding to the so-called Reference Case).

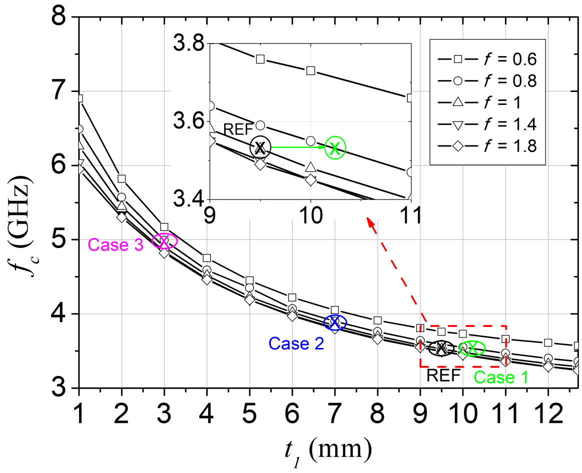

Fig. 3. Variation of the center frequency (f_c) of the first passband of mode 1 as a function of t_1 ($t_2 = t_{2ref} = 7.5$ mm), obtained from the analysis of the dispersion diagram of the periodic SIW shown in Fig. 1(a). Different values of the scale factor f have been considered (f represents a scale factor of the reference period $p_{ref} = 23$ mm used in Fig. 2, i.e., $p = f \cdot p_{ref}$).

–Taconic CER-10–, with $\epsilon_r = 10$). The different parameters of the periodic structure (the period p and the parameters t_1 and t_2 in the studied periodic configuration) will determine the bandwidth and location of the different permitted and forbidden bands. In Fig. 2 it is represented the dispersion diagram of the first two modes (the first mode with black line and the second mode with blue line) of the periodic SIW shown in Fig. 1(a) with parameters: $p = 23$ mm, $t_1 = 9.5$ mm and $t_2 = 7.5$ mm. This initial configuration will be referred in the following as Reference Case.

The first passband of this initial periodic structure (corresponding to mode 1) extends from $f_1 = 3.23$ to $f_2 = 3.83$ GHz, being the center frequency $f_c = 3.53$ GHz, and its bandwidth $BW = 0.6$ GHz, providing a significantly high $FBW = 17\%$ and a first stopband for mode 1 (marked with light blue color in Fig. 2) extending up to 6.2 GHz. Thus, this periodic SIW will have an effective rejection bandwidth (or bandgap, BG) of $BG = 2.37$ GHz. These will be the filter parameters obtained when using such unit cell in a filter design.

Next, going a step further, and with the purpose of providing some design rules for filtering applications, we have represented in Fig. 3 the center frequency f_c of the first passband of mode 1 of this periodic SIW obtained from the analysis of the dispersion diagram with $t_2 = t_{2ref} = 7.5$ mm as a function of t_1, and for different values of the period p. Each period is expressed in terms of a scale factor f relative to the value of the reference period $p = p_{ref} = 23$ mm used in Fig. 2, i.e., $p = f \cdot p_{ref}$. In the same way, Figs. 4 and 5 show the BW and BG of this periodic SIW, obtained from its dispersion diagram with $t_2 = t_{2ref} = 7.5$ mm as a function of t_1 for different values of the period factor f. In these figures (Fig. 3, Fig. 4 and Fig. 5), the obtained filter parameters for the Reference Case defined in Fig. 2 have been highlighted with a black circle and named as REF. Thus, these three figures can be conveniently used as practical tools to search the appropriate periodic SIW parameters for achieving a desired filter response in terms of f_c, BW and BG.

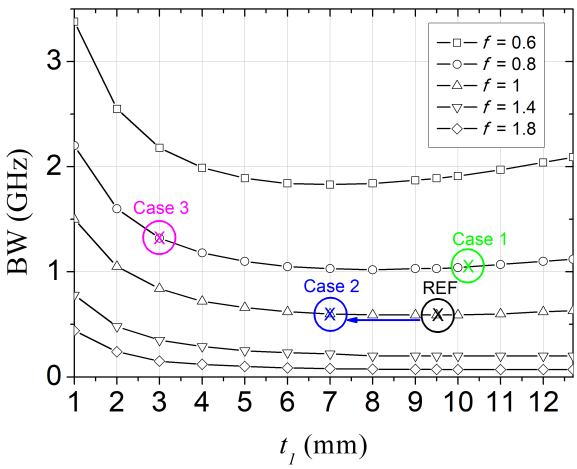

Fig. 4. Variation of the bandwidth (BW) of the first passband of mode 1 of the periodic SIW shown in Fig. 1(a) as a function of t_1 ($t_2 = t_{2ref} = 7.5$ mm), and for different values of the period factor f.

Three additional examples of filter design parameters based on this periodic structure have been highlighted in Figs. 3-5 in order to show how to use the information provided in such figures. In the first one, labelled as Case 1, f_c has been fixed but a higher BW has been obtained, for which we have moved along an horizontal line of constant f_c in Fig. 3, from the initial point (REF) to the right until the point marked with a green circle named Case 1 (see the zoom in the figure inset), cutting the curve with period factor $f = 0.8$ at $t_1 = 10.23$ mm. With these new values of f and t_1, we can read in Fig. 4 a new (higher in this case) $\mathrm{BW} = 1.05$ GHz (marked again as Case 1 with a green circle in this figure). These modified parameters will provide a lower $\mathrm{BG} = 1.85$ GHz in Case 1, marked in Fig. 5 with a green circle. Unlike Case 1, in Case 2 we have maintained the BW of the Reference Case, but we have chosen a different f_c (higher in this case), following

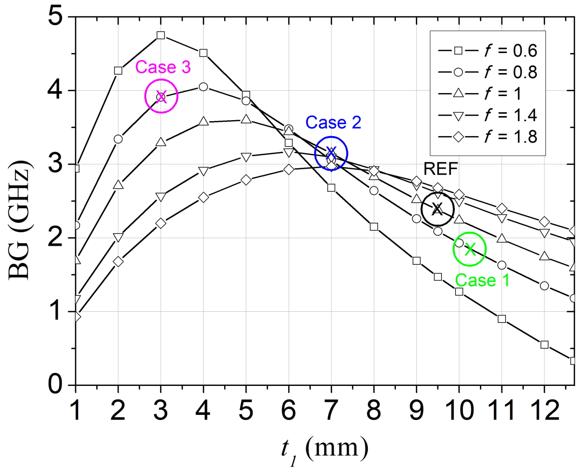

Fig. 5. Variation of the first bandgap (BG) of mode 1 of the periodic SIW shown in Fig. 1(a) as a function of t_1 ($t_2 = t_{2ref} = 7.5$ mm), and for different values of the period factor f.

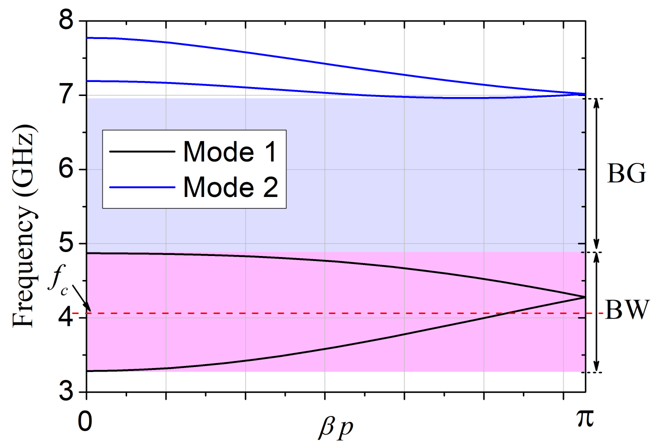

Fig. 6. Dispersion diagram of the first two modes of the periodic SIW with glide symmetry shown in Fig. 1(b), with parameters $p = 23$ mm, $t_1 = 9.5$ mm and $t_2 = 7.5$ mm (Reference Case for the glide configuration).

this design process: we have moved along an horizontal line of constant BW in Fig. 4 from the initial point (REF) to the left until the point marked with a blue circle labelled as Case 2, which is placed on the curve of the same period factor $f = 1$ but at a new value of $t_1 = 7$ mm, which yields a higher $f_c = 3.84$ GHz, at the sight of Fig. 3. Similarly to the previous case, the new parameter t_1 provides a different value of BG, as can be seen in Fig. 5, which has moved from the initial value of 2.37 GHz (black circle, REF case) to a higher value of 3.15 GHz (blue circle, Case 2).

A third example of filter design can be followed making use of the information provided through the parameter sweep of t_1 shown in Figs. 3-5, labelled as Case 3 and marked with a pink circle. In this example, different values of f_c and BW have been obtained from those derived in the Reference Case (both higher in this case), which have been obtained in this example by selecting the parameters $f = 0.8$ and $t_1 = 3$ mm. Such higher values of f_c and BW can be explained as follows. On the one hand, a lower value of $f = 0.8$ (lower period) instead of the value $f = 1$ for the Reference Case, implies a lower consecutive distance between the high dielectric permittivity regions in the periodic waveguide, resulting in a higher BW of the passband. On the other hand, a lower value of $t_1 = 3$ mm (instead of $t_1 = 9.5$ mm) results in a lower mean value of the effective permittivity in the unit cell, resulting in a higher passband of mode 1 and, consequently, in a higher center frequency f_c of such passband. At the sight of Fig. 3, the new f_c is equal to 5.0 GHz (instead of 3.53 GHz), while Fig. 4 shows that the new BW is of 1.32 GHz (instead of 0.6 GHz), being the resulting BG equal to 3.91 GHz instead of 2.37 GHz (see the pink circle labelled as Case 3 in Fig. 5). Thus, we can conclude that Figs. 3-5 can be easily employed to get the desired filter design specifications in terms of f_c, BW and BG, which will be somehow restricted by the possible values of the waveguide parameters (f, t_1 and t_2). In particular, t_1 must be always lower than the period $p = f{\cdot}p_{ref}$, and t_2 must be lower than $a_{SIW}/2$. Previously, in Figs. 3-5, the parameter t_2 has been fixed to 7.5 mm, while t_1 has been swept from 1 to 12.7 mm. Alternatively, an additional degree of freedom can be achieved in the filter design previously described when using the periodic SIW shown in Fig. 1(a) if the parameter t_2 is varied.

III. Glide-symmetric air-filled periodic SIWs

If we want to achieve a band-pass filter response with higher FBW, without reducing the rejection band with this same topology of periodic SIW, we can take advantage of the glide symmetry, by applying such symmetry over the periodic SIW shown in Fig. 1(a), as it can be seen in Fig. 1(b). The dispersion diagram of the first two modes of this new structure is represented in Fig. 6 for the Reference Case in the glide configuration (with parameters $p = 23$ mm, $t_1 = 9.5$ mm and $t_2 = 7.5$ mm). The first passband of this glide-symmetric periodic structure (corresponding to mode 1) extends from 3.28 to 4.87 GHz, being the center frequency $f_c = 4.08$ GHz (see Fig. 6). In this way, as already shown in previous works [6], [7], the obtained glide-symmetric unit cell (with exactly the same parameters of the non-glide Reference Case) has nearly the same cutoff frequency (3.28 GHz instead of 3.23 GHz), but a much wider BW, that changes from 0.6 GHz to 1.59 GHz in this case. Although the f_c has also moved from 3.53 GHz to 4.08 GHz, the resulting FBW increases from 17% to 39%, a much higher value compared to other AFSIW filters presented in the technical literature, to the knowledge of the authors. Besides, it is also interesting to note that, in this case, the resulting rejection band is still quite high (BG = 2.09 GHz). These will be the filter parameters obtained when using such glide-symmetric unit cell in a filter design, as will be shown in Section IV.

IV. Finite implementation of an air-filled periodic SIW acting as band-pass filter

As a proof of concept, a periodic band-pass filter with the glide-symmetric configuration unit cell depicted in Fig. 1(b) has been designed and fabricated, by using 3 unit cells of the glide-symmetric air-filled periodic SIW named as Reference Case studied in Section III. The scheme of this filter is shown

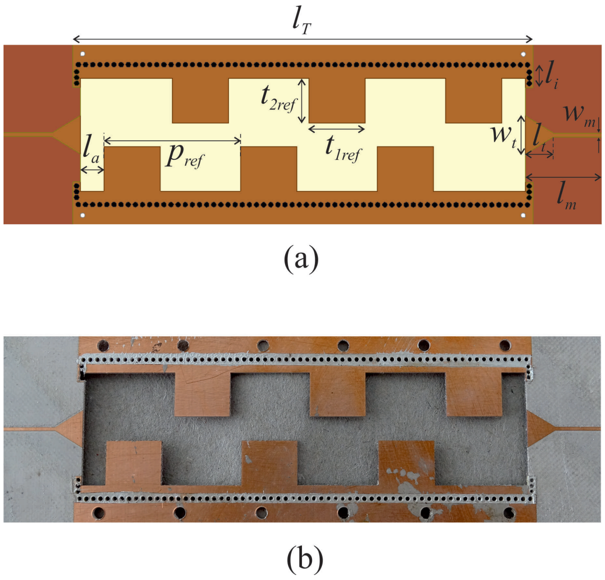

Fig. 7. Band-pass filter based on the unit cell depicted in Fig. 1(b) consisting of a glide-symmetric air-filled periodic SIW named as Reference Case in Section II. (a) Scheme of the filter. (b) Photograph of the fabricated filter.

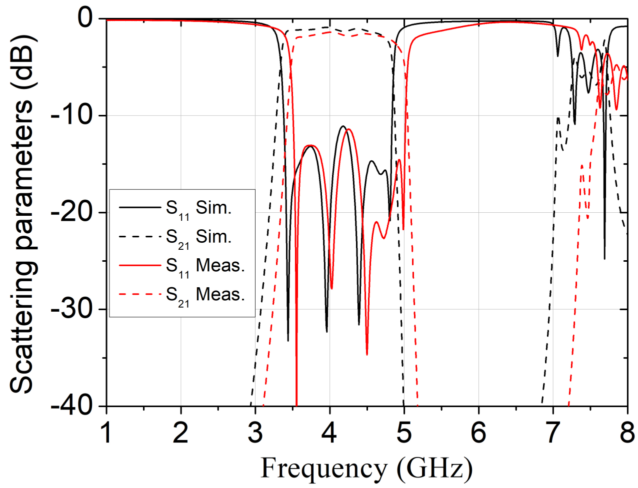

Fig. 8. Simulated and measured S-parameters of the glide-symmetric air-filled periodic SIW filter of Fig. 7.

in Fig. 7(a). With the aim of achieving a good return loss level in the passband, the modal impedance of the periodic air-filled SIW needs to be matched to that of the excitation microstrip line trough a taper transition, and a novel coupling iris has been introduced in the transition plane between the taper and the periodic SIW, as was already proposed in ESIW technology [5].

After a final optimization process (using Ansys HFSS) on the taper and iris dimensions, the obtained values for this filter with glide symmetry are $w_t = 6.41$ mm, $l_t = 4.73$ mm, and $l_i = 3.53$ mm (see Fig. 7(a)). The simulated electrical response of this filter is represented in Fig. 8 using black lines. Regarding the obtained passband (which is defined at a 10 dB input matching level), it can be observed that it extends from 3.37 to 4.83 GHz (the analysis of the dispersion diagram predicted a passband from 3.28 to 4.87 GHz), and a deep rejection band which extends up to 7.0 GHz (6.96 GHz from the dispersion diagram), despite only 3 periods have been used. The obtained insertion losses are lower than 2 dB from 3.35 GHz to 4.76 GHz, being the insertion loss of 1.18 dB at the center frequency $f_c = 4.1$ GHz. The simulated electrical response of this filter fits perfectly the predicted one by the analysis of the dispersion diagram of the unit cell. This glide-symmetric filter has been fabricated as shown in Fig. 7(b), and the measured response is represented in Fig. 8 with red lines, showing a very good agreement with HFSS simulations.

V. Conclusions

In this work, a very simple and efficient filter design procedure is proposed to design band-pass filters based on air-filled periodic SIWs, both with and without glide symmetry. The proposed method is based on the analysis of the dispersion properties of the periodic structure, which are directly related to the dimensions defining the unit cell. Such dimensions can, therefore, be appropriately selected to meet the prescribed electrical specifications, so that several design curves can be readily obtained for filtering purposes. A prototype of a glide-symmetric band-pass filter with a high FBW has been fabricated, fully validating the proposed design procedure. Finally, it has been demonstrated the potential of this technique to obtain large FBWs (even higher than 40%) that have not been achieved in conventional air-filled SIW filters. As a future work, these filters can be designed at millimeter wave frequencies following the described design procedure, at which the removal of dielectric material will be more relevant.

Acknowledgements

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