Reconfigurable Waveguides Using Glide-Symmetric Bed of Nails: Design of an All-Metal Switch at Millimetre-Wave Band

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Abstract—A reconfigurable millimeter-wave artificial waveguide using glide-symmetric pin-like contact-less metasurfaces is proposed in order to enable low loss and high-power-handling capability in switching operations. Thanks to the remarkable behaviour of glide symmetry, the meta-structures are used both as wide-band EBG material to confine the field in the guide and as low-dispersive guiding medium filling the guide itself. The reconfigurability is achieved by adjusting the displacement between the metasurfaces. A higher displacement enables propagation within the waveguide and a lower displacement suppresses it. A two-state reconfigurability is therefore designed, allowing the device to act as an on-off switch in the V-band. In particular, a dispersion analysis highlights the potential of such technology to achieve switching operating over a 55-66 GHz frequency range. A complete design including matching mechanism and WR15 feeding is also described and shown to exhibit a $S_{11} < -10$ dB bandwidth from 57.4 to 62.8 GHz. In the “off” state, the switch isolation is better than 65 dB and in the “on” state, the insertion losses are better than 0.7 dB within the entire operating frequency range. The isolation between two adjacent waveguides is also discussed to assess the integration of such a device within a switching network.

Index Terms—Waveguide, periodic structures, glide symmetry, electromagnetic bandgap material, substrate-integrated waveguide, gap-waveguide technology.

I. INTRODUCTION

FIFTH-GENERATION (5G) of mobile communication systems addresses the ever-growing need of higher throughput wireless connectivity in our society [1]–[3]. High data rate of the order of gigabits per second (Gb/s), a latency time in milliseconds, high traffic volume density, and improved spectral and energy efficiencies are the requirements for the new generation of wireless communications. Millimeter-wave (MMW) wireless systems are emerging as a promising technology for achieving these requirements [4]–[7]. This is due to the vast amount of underutilized spectrum in MMW frequencies along with the recent advances in designing low-cost high-performance integrated circuits (ICs) at such frequencies [8]–[10]. So, frequency bands such as 28 GHz and 40 GHz have been ratified for 5G use while the 3GPP release 17 is currently investigating the spectrum above 52.5 GHz, with a specific focus on the 60 GHz licence-free band [11]. MMW multibeam antennas (MBAs) are considered in the phase 2 of 5G deployment with suitable beamforming techniques to achieve massive multiple-input, multiple-output (MIMO) [12]–[14], thus significantly enhancing the spectral and energy efficiency while minimizing interference levels.

Radio frequency (RF) chains, digital-to-analog converters (DACs), and analog to digital converters (ADCs) are the most expensive parts of a wireless transceiver. In MMW massive MIMO wireless systems, due to the huge number of antennas to mitigate large free-space attenuation, employing one RF chain and one ADC or DAC for each antenna is not feasible as doing such also increases the energy consumption of the transceiver to an unacceptable level. Hybrid analog/digital beamforming architectures are proposed as a solution to this limitation [15]–[18]. In such architectures, the number of RF chains is typically much lower than the number of antennas and therefore, analog beamformers with phase shifters [19], Butler Matrices [20], or lenses [21], are considered to feed all antennas. While Butler-Matrix-based and lens-based hybrid arrays exhibit less complexity, they require a beam selector made of switches to map the few RF chains to the large number of analog beamformer inputs [21]. Recently, switching networks have also been suggested to replace phase shifters in analog beamformers in order to reduce complexity and increase power and spectral efficiencies [22]. Consequently, in this context, the design of power-efficient millimeter-wave switches is a key aspect in the implementation of hybrid analog/digital massive MIMO systems.

Integrated circuits at microwave and millimeter-wave frequencies can be conveniently realized with gap-waveguide technology [23]. In this technology, the electromagnetic wave is guided in an air region rather than in a dielectric, resulting in reduced losses compared e.g. to substrate-integrated waveguides. Moreover, the metallic top and bottom plates of gap waveguides are contactless. This facilitates the manufacturing process which can be performed in two separate parts. Gap waveguides are designed by mimicking a perfect magnetic conductor (PMC) boundary condition on the two sides of the waveguide by means of an electromagnetic band-gap (EBG) material [24]–[26]. Bed-of-nail metasurface is among the most widely used configurations for this purpose [27], [28].
Recently, new EBG designs for gap waveguides have been proposed in order to enhance their confinement properties without adding significant complexity to the design [29], [30]. These solutions are based on the use of two metasurfaces on both plates of the waveguide, having a mutual shift of half period in both periodicity directions. This symmetry configuration is commonly called glide symmetry. It is a higher-order symmetry of periodic structures [31]–[34] which has recently gained interest thanks to discovering new interesting dispersive behaviour [35]. On one hand, they are less frequency-dispersive than their non-glide-symmetric counterparts in their first pass-band, leading to their adoption in design of ultrawideband lenses [36]–[38]. On the other hand, they have wider and stronger stop-bands compared to non-glide-symmetric periodic structures [39], [40], explaining why they are used in EBGs for gap waveguides. These two properties, together with the contactless nature of the metasurfaces, make glide-symmetric metasurfaces particularly interesting to embed reconfigurable properties in gap waveguides. The impact of some geometric parameters on the transmission properties of glide-symmetric waveguides was studied in recent work [41]. A phase-shifter has been proposed in glide-symmetric gap waveguide technology where the phase shift is adjusted by changing the height of a dielectric slab that is inserted inside the waveguide [42]. In [43] different kinds of pin-like structures inside a waveguide lead to different phase shifts.

In this paper, we propose an integrated waveguide presenting a two-state functioning. An “on-state” allows the propagation through the guide, while an “off-state” stops the propagation. This reconfiguration is done by mechanically adjusting the distance between the top and bottom plates, which is made possible thanks to their contact-less configuration. Glide-symmetric EBGs offer strong stop-band characteristics, and glide-symmetric pins inside the waveguide ensure nearly dispersion-less wave propagation.

The paper is organized as follows. In Sec. II we first present the design concept of the two-state waveguide by choosing the proper EBG and guiding pin configurations. We then introduce the feeding and the impedance matching networks in the proposed waveguide. In Sec. III we discuss the simulation results of the designed waveguide. First, we investigate the results in a single waveguide. Then, we consider two coupled lines and validate the “on” and “off” states in these waveguides. We also show the good isolation between the two lines using the simulation results.

II. RECONFIGURABLE ARTIFICIAL WAVEGUIDE

In this section, we propose a structure to implement a reconfigurable artificial waveguide that can alternate between “on” and “off” states. It lets the wave propagate in its “on” state, whereas it attenuates the wave while in the “off” state.

The artificial waveguide employs EBG structures at its lateral boundaries to confine the field inside the guide, which is filled with an artificial medium. Fig. 1 shows a perspective view of the artificial waveguide with its different medium regions, where the propagation direction is shown with an arrow. The EBG medium confines the field within the guiding medium. We discuss the design of different parts of the waveguide, including the guiding medium, the EBG, and a matching section.

A. Design of Guiding Medium and EBG

In order to implement the EBG regions, we use two parallel plates loaded with pins as our waveguide structure. The EBG performance (namely, a high attenuation in the operating frequency range of interest) should ensure that the wave is well confined in the guiding region. We use a glide symmetric configuration of pins in the EBGs to achieve a stronger and wider stopband compared to a single metasurface as suggested in [29]. The guiding medium of the waveguide is also realized with a pin-like pair of metasurfaces whose geometric parameters are different from those used for the EBG. The unit cells of both EBG and guiding media are shown in Fig. 2. Different geometrical parameters lead to different electromagnetic characteristics in the two regions. It is important to note that the only parameter which is kept the same for EBG and guiding medium is the gap $g$ between the tip of a pin and the opposite plate.

For an “on” state in the waveguide, we design the periodic structure in the guiding region to be in its pass-band, hence able to propagate an electromagnetic wave. We also make certain that the periodic structure in the EBG medium is in its stop-band, thus attenuating the fields outside the guiding medium. Fig. 3 plots the full dispersion diagrams of the unit cells shown in Fig. 2. The eigenmode solver of CST Microwave Studio is used to find the dispersion diagrams [44]. The geometrical parameters of the unit cell of guiding medium are $p_{\text{guide}} = 1.5$ mm, $h_{\text{guide}} = 0.2$ mm, $d_{\text{guide}} = 0.4$ mm and $g = 0.9$ mm. The parameters for EBG unit cell are $p_{\text{EBG}} = 3$ mm, $h_{\text{EBG}} = 1.2$ mm, $d_{\text{EBG}} = 0.8$ mm, and $g = 0.9$ mm. The potential operating frequency range is highlighted by a gray rectangle in Fig. 3 and covers the 55–66 GHz bandwidth. Indeed, within this range, the guiding medium exhibits a linear-frequency-dependent propagation constant and the EBG medium exhibits a bandgap. The field can therefore propagate while being confined with no dispersion.

B. Two-State Reconfigurability

Thus far, we have properly chosen a guiding medium that can let wave propagate and an EBG medium that can effectively prevent any wave leakage from the guiding region. Now, we realize a transition from the “on” (or propagating) state to
Fig. 2. Unit cells of the glide-symmetric pin-like mediums used in the artificial waveguide. The unit cell on the left hand side is for the guiding medium and the one on the right hand side is for the EBG. The unit cells are shown with the correct ratio to highlight the differences in their geometrical parameters.

Fig. 3. Full dispersion diagram of the structure with the unit cells shown in Fig. 2 in the “on” state. Geometrical parameters of the guiding medium: \( p_{\text{guide}} = 1.5 \text{ mm}, d_{\text{guide}} = 0.4 \text{ mm}, h_{\text{guide}} = 0.2 \text{ mm} \) and \( g = 0.9 \text{ mm} \). Geometrical parameters of the EBG medium: \( p_{\text{EBG}} = 3 \text{ mm}, d_{\text{EBG}} = 0.8 \text{ mm}, h_{\text{EBG}} = 1.2 \text{ mm} \) and \( g = 0.9 \text{ mm} \).

Fig. 4. Full dispersion diagram of the unit cell shown in Fig. 2 (a) for two values of \( g = 0.005 \text{ mm} \) (off state) and \( g = 0.9 \text{ mm} \) (on state) in the guiding medium with geometrical parameters \( d_{\text{guide}} = 0.4 \text{ mm}, h_{\text{guide}} = 0.2 \text{ mm} \) and \( p_{\text{guide}} = 1.5 \text{ mm} \) (b) for two values of \( g = 0.005 \text{ mm} \) (off state) and \( g = 0.9 \text{ mm} \) (on state) in the EBG medium with geometrical parameters \( d_{\text{EBG}} = 0.8 \text{ mm}, h_{\text{EBG}} = 1.2 \text{ mm} \) and \( p_{\text{EBG}} = 3 \text{ mm} \).

an “off” (or attenuating) state. In the “off” state, the EBG medium should still attenuate the fields, thus avoiding wave propagation in the cross-sectional directions like previously. Moreover, the guiding region should become an EBG material itself, within the waveguide operating frequency range, to prevent any wave propagation in the longitudinal direction of the waveguide.

The possibility to switch from the “on” to the “off” state is offered by the contactless configuration, which allows for adjusting the distance between the two plates. We investigate the effect of the same variation in the parameter \( g \) of the unit cells shown in Fig. 2 i.e. the distance between the top of a pin and the opposite metallic plate. This can be easily controlled by moving the two metallic plates either closer to or further away from each other.

Fig. 4 (a) depicts the full dispersion diagrams of the guiding medium when varying the gap \( g \) of \( \Delta g = 0.895 \text{ mm} \). The two different gaps are \( g_{\text{off}} = 0.005 \text{ mm} \) and \( g_{\text{on}} = 0.9 \text{ mm} \). We notice that by decreasing the gap, the frequency region highlighted with a gray rectangle (55-66 GHz) passes from an “on” state (pass-band) to an “off” state (stop-band). More precisely, we can remark that decreasing the gap \( g \), the previous pass-band is transformed into a stop-band between the second and third Bloch modes. Any value of \( g \) less than 0.007 mm is sufficient to ensure a bandgap in the guiding medium in the “off” state.

Next, we investigate the same gap variation \( \Delta g = 0.895 \text{ mm} \) on the EBG (varying the gap from \( g_{\text{on}} = 0.9 \text{ mm} \) to \( g_{\text{off}} = 0.005 \text{ mm} \)). Fig. 4 (b) displays the full dispersion diagrams of the EBG medium for the two aforementioned gap sizes. As expected, the smaller the gap gets, the wider the stop-band becomes and the material still behaves as an EBG in the gray-shaded frequency range: the stop-band width is increased for a smaller gap and the EBG medium provides a stop-band in the gray region with both gaps \( g_{\text{off}} = 0.005 \text{ mm} \) and \( g_{\text{on}} = 0.9 \text{ mm} \). Therefore, the design of the “off” state is complete.

C. Feeding Mechanism and Impedance Matching

Fig. 5 (a) shows the complete proposed waveguide, including the feeding accesses. Two slots of dimensions of \( 3.7592 \text{ mm} \times 1.8796 \text{ mm} \) are etched in the bottom plate to enable exciting the structure by WR15 standard accesses (V band), normally placed below the waveguide and indicated by...
the black arrows in the figure. Fig. 5 (b) displays a top view of the waveguide with the upper plate removed for a clear visualisation of the pins. Gray squares are pins on the bottom plate, and white squares are the pins locations on the upper plate, removed from the picture. The waveguide is divided into three sections: the guiding section in the middle and two matching sections at both ends of the longitudinal direction. Each matching section includes the feeding slot at a distance \( l \) from the EBG at one end of the structure. With a proper choice of \( l \), the EBG medium reflects the wave from the feed towards the waveguide.

III. SIMULATION RESULTS

A. Single Waveguide

In this subsection, we discuss the simulation results of the waveguide designed in the previous section. The simulations are performed with the frequency solver of CST Microwave Studio. We have chosen 7 rows of pins in the guiding medium. This corresponds to a width of \( 3.5 \times p_{\text{guide}} \) which equals 5.25 mm and is slightly wider than the length of the rectangular waveguide feed. We have used a width of \( 1.5 \times p_{\text{EBG}} = 4.5 \) mm for the EBG regions surrounding the waveguide. The length of the structure is 25.5 mm. Furthermore, we empirically found that the distance \( l \) providing the best matching bandwidth is 3.4 mm. The metal is modeled as copper.

Fig. 6 plots the simulated scattering parameters for the designed waveguide with the aforementioned geometrical parameters and the gap \( g = g_{\text{on}} = 0.9 \) mm (the “on” state discussed in the previous section). The \( S_{11} \) curve displays a −10 dB impedance matching bandwidth of 5.7 GHz between the frequencies \( f_{\text{min}} = 56.8 \) GHz and \( f_{\text{max}} = 62.5 \) GHz. The \( S_{21} \) curve confirms the full transmission from the first waveguide port at one end to the waveguide port at the other end of the guide. \( S_{21} \) levels are above -4 dB in the entire −10 dB impedance matching bandwidth. If \( S_{21} \) levels of higher than −0.7 dB are required, the bandwidth reduces to 4.9 GHz between \( f_{\text{min}} = 56.8 \) GHz and \( f_{\text{max}} = 61.7 \) GHz. Fig. 7 plots the phase of \( S_{21} \) versus frequency. It is observed that the phase is linear in the aforementioned bandwidth, which is typical of waveguides realized with glide-symmetric geometries.

Fig. 8 displays the \( S \) parameter results of the structure in Fig. 5 when the gap \( g = g_{\text{off}} = 0.005 \) mm is considered (the “off” state discussed in the previous section). The result shows an insertion loss higher than 68 dB. Therefore, this waveguide can implement a switch with satisfactorily high isolation levels.

An important factor in the designed technology is the
precision of the mechanical adjustments needed to achieve reconfigurability. This precision can be known by studying the sensitivity of the design to changes in the gap $g$. Fig. 9 (a) depicts $S_{11}$ results for the structure shown in Fig. 5 with $g = 0.9$ mm in the “on” state and compares it to the two cases for which there is a $\Delta g = \pm 0.05$ mm difference. The results show that such a change does not deteriorate the bandwidth by much and it only moves the $-10$ dB bandwidth to slightly higher or lower frequencies in each case. Fig. 9 (b) plots $S_{21}$ results for the same structure with $g = 0.005$ mm in the “off” state and compares it to $g = 0.008$ mm and $g = 0.009$ mm. Here, we observe that the gap change of $\Delta g = +0.003$ mm does not jeopardize the design since the $S_{21}$ levels are kept below $-40$ dB after this change. The gap change of $\Delta g = +0.004$ mm provides $S_{21}$ levels that are lower than $-20$ dB.

**B. Adjacent Waveguides**

In this subsection, we study two adjacent waveguides to evaluate the coupling between the two waveguides, both in the “on” and “off” states, to provide some insights regarding the use of such technology in a switching network. Fig. 10 (a) displays the top view of the two adjacent waveguides with the top plate removed to better visualize their inner structure. The waveguide ports are numbered in the figure. We compute the power flow inside the two waveguides by exciting waveguide port 1. The waveguides are considered to be made of copper in the simulations. The distance between the two waveguides is 7.5 mm ($1.5\lambda_0$) and the length of the simulated waveguides is 25.5 mm (approximately $5\lambda_0$) where $\lambda_0$ is the wavelength of the electromagnetic wave in free space at 60 GHz. Fig. 10 (b) displays the power flow inside the waveguides at 60 GHz when the structure is in the “on” state. It is clearly seen from the picture that there is a power flow along the longitudinal direction of the excited waveguide from port 1 towards port 2. It is also clearly visible that there is a good isolation between the two waveguides and that the EBG is confining the fields inside the upper waveguide. In contrast, Fig. 10 (c) shows the power flow at 60 GHz when the structure is in the “off” state. We observe that there is no power flow along the length of the top excited waveguide. The waveguide is attenuating the wave in both cross-sectional and longitudinal directions, therefore preventing propagation of the wave in any direction.

Fig. 11 plots the scattering parameters of the structure in Fig. 10 (b) by exciting the upper waveguide through waveguide port 1. $S_{11}$ and $S_{21}$ curves are similar to those shown in Fig. 6 and show that the waveguide is still functioning correctly in its bandwidth. The -10 dB $S_{11}$ bandwidth is 57.4-62.8 GHz. The insertion loss of less than 0.7 dB is achieved for most of the $S_{11}$ bandwidth (57.4-62.2 GHz). In a small portion of the $S_{11}$ bandwidth (62.2-62.8 GHz) the insertion loss goes beyond 0.7 dB and increases to a maximum of 3.3 dB at the end of the $S_{11} < -10$ dB bandwidth. In addition to these two curves, $S_{31}$ and $S_{41}$ results are also plotted to provide the coupling levels between ports of different waveguides. We observe that there is a good isolation between the waveguides and that the coupling is below -22 dB over the whole operational bandwidth.

The coupling is studied in more detail in Fig. 12 (a), which displays $S_{31}$ for different values of lateral spacing $s$.
between the two adjacent waveguides shown in Fig. 10 (a). It is observed that the $S_{31}$ decreases as the distance between the two waveguides is increased. With an increased distance, the wave is more attenuated across the EBG region between the two waveguides. An $s = 1.5 \, \text{mm}$ results in $S_{31}$ of below $-40$ dB in the first 4 GHz of the $S_{11}$ bandwidth previously discussed. But it increases up to $-13.5$ dB at one point in the $S_{11}$ bandwidth. Distances of $s = 2.5 \, \text{mm}$ and $s = 3.5 \, \text{mm}$ provide better isolation as their $S_{31}$ is below $-40$ dB for a larger part of the $S_{11}$ bandwidth. $S_{31}$ levels for $s = 2.5 \, \text{mm}$ and $s = 3.5 \, \text{mm}$ are respectively below $-22$ dB and $-32$ dB over the whole bandwidth. The case $s = 4.5 \, \text{mm}$ has $S_{31}$ levels below $-37$ dB in the entire $S_{11}$ bandwidth. Here $\lambda_0 = 5 \, \text{mm}$ at 60 GHz. Fig. 12 (b) plots $S_{41}$ for the same four values of spacing $s$ to study the effect of $s$ on this result. The findings are similar to those from $S_{31}$. An increase of $s$ leads to a decrease of $S_{41}$. Again, $s = 4.5 \, \text{mm}$ achieves the lowest $S_{41}$ levels which is lower than $-44$ dB in all the -10 dB $S_{11}$ bandwidth.

IV. CONCLUSION

An artificial waveguide technology using glide symmetry is introduced. The use of this symmetry in the guiding medium in addition to the EBG material provides a dispersionless propagation of the electromagnetic wave. Furthermore, the periodicity in the guiding region allows for the transition from the passband to a stopband in the 57.4-62.2 GHz frequency band. This transition can be achieved by a mechanical reconfiguration of the structure, namely readjusting the displacement between the two metallic plates. This mechanical reconfiguration of the glide-symmetric waveguide has been shown to
be an effective way to achieve a two-state on-off structure exhibiting in the off-state, an isolation better than 65 dB and in the on-state, insertion losses less than 0.7 dB. This technology may find applications in the design of low-loss RF switches.

As an important feature of the proposed technology, the signal propagates through air and not through any semi-conductor or dielectric material. So, the only losses are the ohmic losses of the metallic structure and the proposed approach is therefore able to handle high power. This makes glide-symmetric waveguides proper candidates to switch between multiple input ports of MMW multibeam antennas for instance.

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