Gap Waveguide Topology With Reduced Height Pins for Millimeter-Wave Components

David Santiago, Miguel A. G. Laso, Txema Lopetegi, and Ivan Arregui

Abstract – A new topology for groove gap waveguide (GGW) technology is proposed to ease its manufacturing process by computer numerical control (CNC) milling. GGW technology consists of two metal plates, where one of them presents a $\lambda/4$ height pin bed that avoids contact with the other plate, making it an ideal alternative to other waveguides for millimeter-wave applications. However, the manufacture of the pins by CNC milling may be troublesome due to the large pin height required. A GGW with reduced height pins will be proposed, maintaining the standard dimensions of the equivalent rectangular waveguide ports and the operation bandwidth. The performance of this new topology will be compared with other proposals by means of simulations and measurements, and a bandpass filter will be also implemented and manufactured in this technology to validate its usefulness.

1. Introduction

Groove gap waveguide (GGW) technology was proposed as an alternative to conventional waveguides, especially for high-frequency applications [1, 2]. The topology is based on two parallel plates, with a pin bed structure in one of the plates (see Figure 1). This pin bed structure introduces a high impedance condition over this plate that avoids the electrical contact requirement between the top plate and the pins of the bottom plate, if they are separated a distance (gap) less than $\lambda/4$ [3, 4]. Moreover, the pin height should have a value similar to $\lambda/4$, as explained in [5, 6].

Taking into account previous considerations, the frequency performance achieved by the GGW is similar to the rectangular waveguide [7, 8] but with manufacturing advantages. As previously mentioned, it avoids the contact and also the alignment between the different parts of the device. However, the use of computer numerical control (CNC) milling for fabrication of these structures can still be troublesome. Recently, several alternatives to the conventional GGW topology were proposed to simplify it [8−13]. For example, different pin shapes can be used: circular [8]; square [1]; pyramidal [9]; conical [10]; and even half-height pins [12, 13]. As in the conventional topology, a pin height similar to $\lambda/4$ is used in [8−11]. The large pin height causes different manufacturing problems. Therefore, this issue is alleviated in the latest proposals [12, 13] by using pins with a reduced height but with the disadvantage of having a pin bed structure in both plates of the GGW technology.

In this work, a GGW topology with reduced height pins, placed in only one of the plates, is proposed, with the other plate free of the pin bed to facilitate the manufacturing process. This also allows the use of standard rectangular waveguide ports in the devices, making easier its integration into waveguide systems. The bandwidth operation of the proposed structure was analyzed and its performance was compared with some alternatives previously published. Finally, a bandpass filter using the proposed GGW topology was designed and manufactured to validate its usefulness for the design of millimeter-wave components.

2. Proposed Topology

Figure 2 shows a schematic of the conventional GGW topology (pin height $h_c = \lambda/4$), where a base below the pins with height b_c was included. This modification allows us the use of the classical pin height ($\lambda/4$) and the use of WR22 standard ports ($W = 5.69$ mm, $H = 2.845$ mm). Moreover, the other geometrical parameters of the topology are also shown in Figure 2: p (pin separation); r (pin size); and g (gap or separation between plates). This topology presents the same operation bandwidth as the equivalent WR22 rectangular waveguide (33 GHz to 50 GHz), while preserving all the previously mentioned manufacturing advantages provided by the GGW technology.

To ease the manufacturing process, the reduction of the pin height is one of the most important parameters in the CNC milling workshop because, using this process, the longer the milling cutter needed, the thicker it has to be for a stable fabrication. If the height of the milling cutter is reduced while maintaining its thickness, as it is done in this article, not only the machining time would considerably decrease but also the manufacturing cost. Therefore, the previously mentioned GGW

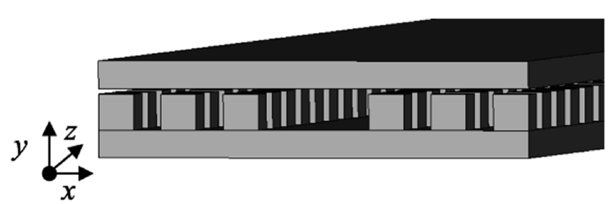

Figure 1. GGW technology.

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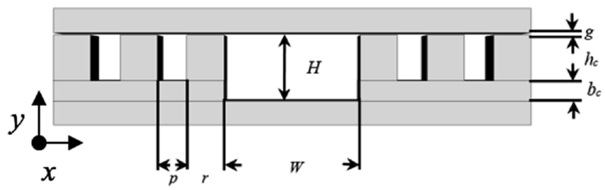

Figure 2. Front view of the conventional GGW topology (h_c = 1.9 mm).

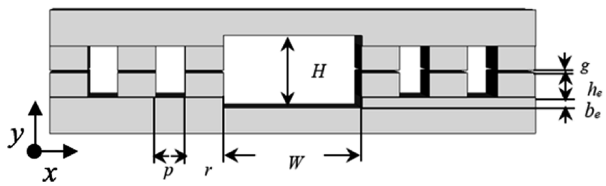

Figure 3. Front view of the GGW topology with reduced height pins in both plates (h_e = 0.95 mm).

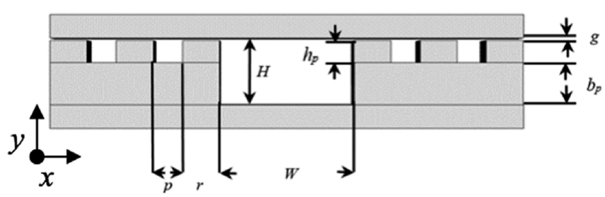

Figure 4. Front view of the proposed GGW topology (h_p = 0.95 mm).

topology presented in [13] with reduced pin height was analyzed (see Figure 3). This GGW topology operates in the desired bandwidth and has the advantages of the conventional GGW topology, but with an easier manufacturing process due to the lower pin height h_e. However, this topology increases the complexity of the structure because the pin bed must be included in both plates. Therefore, the manufacture is easier, but it is necessary to mechanize both plates.

With the aim of avoiding the pin bed in both plates of the device and also the manufacturing problems of the large $\lambda/4$ height pins, an analysis comparing the behavior of the GGW technology with different pin heights was performed. Although reducing the pin height affects the operation bandwidth of the technology, it is possible to reduce this height, while maintaining the desired operation bandwidth, if appropriate dimensions for the other geometrical parameters are used. As a result, the topology proposed in this work is shown in Figure 4. In this structure, the pin height h_p can even be reduced to the half using pins in only one of the plates, while the rest of the parameters (gap g; pin size r; and pin periodicity p) have the same values as in the conventional GGW topology. To modify this parameter (h_p) without changing the gap or the standard port height H, the base height (b_p) was increased to compensate for this modification. For WR22 standard ports, the final dimensions are the following: W = 5.69 mm; H = 2.845 mm; h_p = 0.95 mm; g = 0.1 mm;

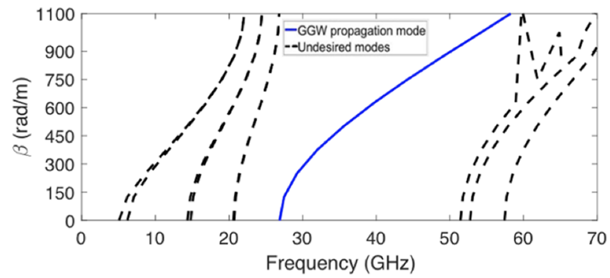

Figure 5. Dispersion diagram of the proposed GGW topology (W = 5.69 mm; H = 2.845 mm; g = 0.1 mm; r = 1.56 mm; and p = 1.23 mm) using the reduced height h_p = 0.95 mm and b_p = 1.795 mm.

b_p = 1.795 mm; r = 1.56 mm; and p = 1.23 mm. This allow us to work between 26.87 GHz and 51.43 GHz in a single-mode configuration (see Figure 5).

To evaluate the behavior of the proposed GGW topology, its performance has been compared with the conventional GGW structure and the topology with reduced pin height in both plates [13], using the electrical conductivity of aluminum (3.56e07 S/m). A simulation of the structures in the Q band (33 GHz to 50 GHz) was conducted with CST Microwave Studio (version 2022; see Figure 6). The three topologies have a similar performance over the desired bandwidth, obtaining even a better insertion loss value for the proposed GGW topology. To confirm these simulation results, the conventional and the proposed GGW topologies were manufactured by CNC milling (see Figures 7a and 7b). As seen in Figure 8, the measurements confirm the simulation results previously obtained.

3. Bandpass Filter Using Reduced Height Pins

Once the good behavior of the novel proposed GGW topology was validated, a bandpass filter implemented in this topology was designed. In this section, the design methodology and the manufactured results are presented.

3.1 Design Method

Following the approach explained in [14], the design method use resonant cavities coupled by cylindrical posts. To obtain a bandpass frequency response, the first step is to calculate the coupling between the resonant cavities ($k_{i,\ i+1}$) and the external quality factor (Q_{ext}), as detailed in [15]:

$$k_{i,i+1} = \frac{\text{BW}}{\sqrt{g_i \cdot g_{i+1}}}, \qquad i = 1, \ldots, N-1 \tag{1}$$

$$Q_{\text{ext}} = \frac{g_i \cdot g_{i+1}}{\text{BW}}, \qquad i = 0, N \tag{2}$$

where BW corresponds to the fractional bandwidth of the device, N is the order of the filter, and g_i is the equivalent low-pass filter coefficients. The resonators

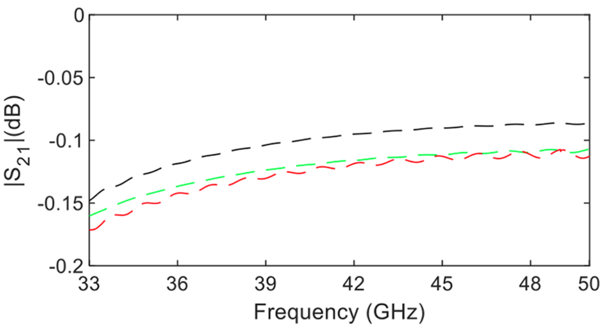

Figure 6. Insertion loss parameter of the GGW topologies ($W = 5.69$ mm; $H = 2.845$ mm; $g = 0.1$ mm; $b = 1.795$ mm; $r = 1.56$ mm; and $p = 1.23$ mm) using conventional pin height $h_c = 1.9$ mm and $b_c = 0.845$ mm (green line), reduced pin height in both plates $h_e = 0.95$ mm and $b_e = 0.4225$ mm (red line), and novel GGW topology introduced in this article $h_p = 0.95$ mm and $b_p = 1.795$ mm (black line).

used are implemented with the proposed GGW topology (see Figure 9). As explained before, the couplings between the cavities were achieved by cylindrical posts, all of them with the same diameter d. To achieve the desired couplings, the post heights h_{ij} have been varied. As seen in Figure 9, these cylindrical posts were placed in the top plate of the structure to facilitate the manufacturing process.

3.2 Design Example

A Chebyshev bandpass filter using the proposed GGW topology was designed with the following specifications: 1) central frequency $f_0 = 39$ GHz;

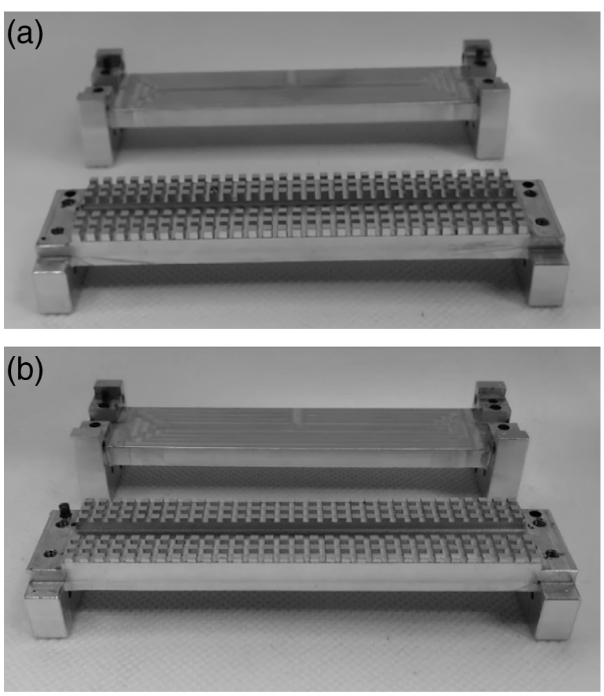

Figure 7. Manufactured GGW prototypes: (a) conventional topology and (b) proposed topology.

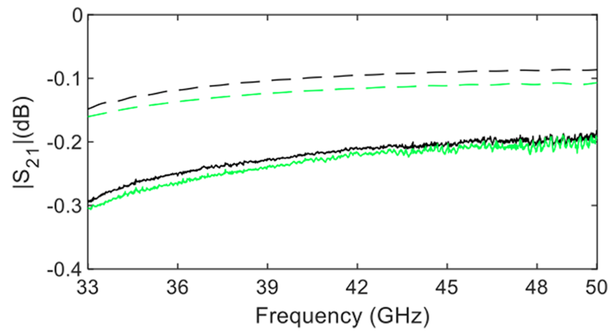

Figure 8. Insertion loss comparison of the GGW topologies ($W = 5.69$ mm; $H = 2.845$ mm; $g = 0.1$ mm; $r = 1.56$ mm; and $p = 1.23$ mm) using conventional pin height $h_c = 1.9$ mm and $b_c = 0.845$ mm (green line) and the reduced height $h_p = 0.95$ mm and $b_p = 1.795$ mm (black line), with simulation results (dashed line) and measurement results (solid line).

2) bandpass from $f_1 = 38$ GHz to $f_2 = 40$ GHz; 3) return loss better than 20 dB; 4) order $N = 5$; and 5) WR22 standard ports ($W = 5.69$ mm, $H = 2.845$ mm).

Considering these specifications and using (1) and (2), the external quality factor and the coupling coefficients were calculated: $Q_{\text{ext}} = 26.04$, $k_{12} = k_{45} = 0.044$, and $k_{23} = k_{34} = 0.033$. Using a post diameter $d = 2$ mm, the coupling coefficients were achieved with the following heights: $h_{01} = h_{45} = 1.15$ mm; $h_{12} = h_{34} = 1.68$ mm; and $h_{23} = 1.87$ mm, where h_{01} corresponds to the post height that determines the coupling between the source and the first resonator (external quality factor Q_{ext}), h_{12} the coupling between the first and second resonator (k_{12}), h_{23} the coupling between the second and third resonator (k_{23}), h_{34} the coupling between the third and fourth resonator (k_{34}), and h_{45} between the last resonator and the load (Q_{ext}). The cavity lengths are

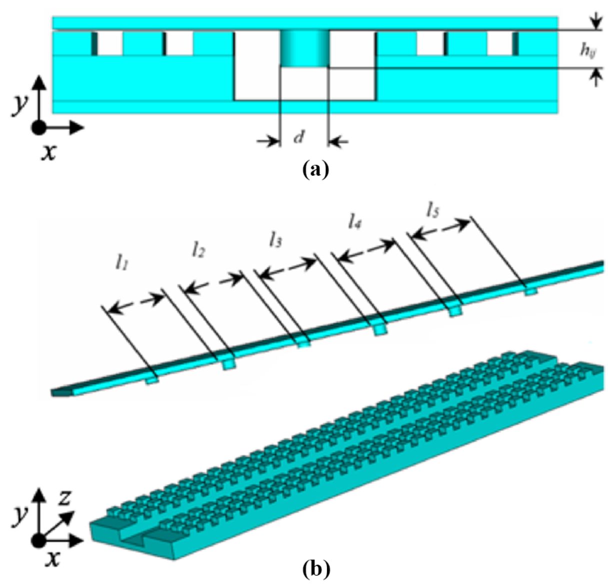

Figure 9. Schematic of the bandpass filter: (a) front view and (b) pin bed structure in the bottom plate and cylindrical posts in the top plate.

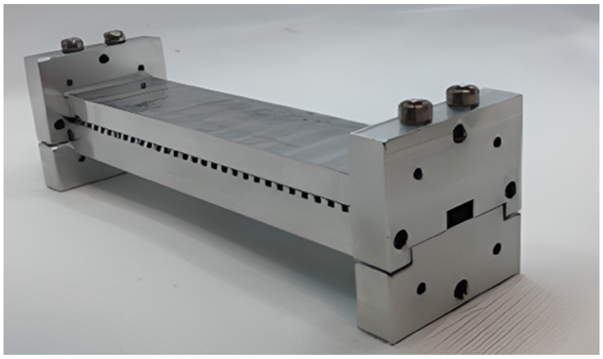

Figure 10. Manufactured bandpass filter.

$l_1 = l_5 = 9.94$ mm, $l_2 = l_4 = 9.82$ mm, and $l_3 = 9.81$ mm. As a result, the designed device is shown in Figure 9b.

The bandpass filter was manufactured by CNC milling (see Figure 10), and the comparison between the measurement and the simulated response is shown in Figure 11. An excellent agreement between both results was achieved.

4. Conclusion

In this work, a novel topology with reduced height pins for the GGW technology was proposed, facilitating the fabrication process. Moreover, this configuration allows us to maintain the standard port dimensions of the equivalent rectangular waveguide and the operation in its corresponding bandwidth. A comparison with previous alternatives was done, obtaining a similar frequency behavior (or even better) for the bandwidth of interest. Finally, a bandpass filter was designed and fabricated, also obtaining very good results. Therefore, this proposal can be considered an excellent alternative to the previous GGW topologies for easy fabrication.

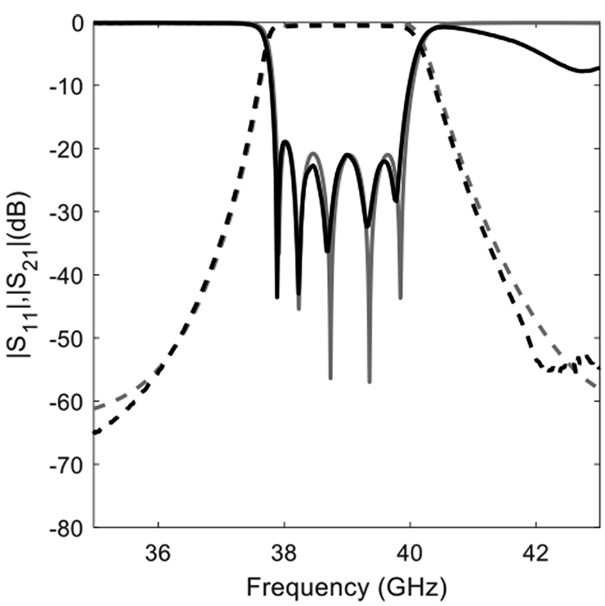

Figure 11. Measured parameters of the manufactured prototype (black line) and simulated results (grey line) with $|S_{11}|$ (solid line) and $|S_{21}|$ (dashed line).

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