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Pin-on-Substrate Gap Waveguide: An Extremely Low-Cost Realization of High-Performance Gap Waveguide Components

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***Abstract*—Considering the limitations of currently available technologies for the realization of microwave components and antennas, a trade-off between different factors including the efficiency and fabrication cost is required. The main objective of this letter is to propose a novel method for the realization of gap waveguides (GWGs) that take advantage of conventional PCB fabrication technology, thus are low cost and light weight. Moreover, by avoiding dielectric loss and minimizing conductive loss, the proposed GWGs benefit from a very low loss. To highlight potential applications, a high-performance slot-array antenna based on the proposed GWG is presented.**

***Index Terms*—Pin-on-Substrate, PoS GWG, gap waveguide, microwaves, slot-array antenna.**

I. Introduction

HIGH-performance, low-cost, and lightweight microwave components are highly demanded in communication systems. Therefore, the development of novel realization technologies that satisfy these requirements has been a major area of interest within the field of microwave and antenna engineering. In particular, despite the lightweight, easy, and low-cost realization of microwave devices in planar technologies such as microstrip lines, these technologies face the problem of high dielectric loss, low power handling, radiation and undesired substrate modes [1]. In contrast, metallic waveguides are very low loss, but bulky, heavy, and relatively expensive, especially at low microwave frequencies. Therefore, several technologies have been proposed to address these limitations, for instance, substrate integrated waveguides (SIWs) [2]. However, since in this technology the electromagnetic (EM) waves propagate inside a dielectric, SIWs suffer from a relatively high dielectric loss. Air-filled SIW technology was an effort to partially address this issue, albeit at the cost of using more expensive multi-layer printed circuit board (PCB) technologies and facing complexities in transition to standard transmission lines (TLs) [3], [4].

Gap waveguides (GWGs) are another recently proposed alternative technology for the realization of high-performance microwave components [5]–[7]. Currently, there are two general methods for the implementation of GWGs. In the first method, GWGs are produced by milling a block of metal to form the bed of pins that acts as an artificial magnetic conductor (AMC) [6]–[11]. Since the produced waveguide is air-filled and made of relatively thick metallic parts, it benefits from very low loss. However, the structures produced with this approach are generally heavy and bulky, and their fabrication is time-consuming and costly [12]. In the second method, conventional PCB technology is used. In this method, the required AMC structures are usually produced with electromagnetic band gap (EBG) structures such as mushroom-type resonators that are printed on a PCB [12]–[16]. As a result, EBG-type GWGs are lightweight, compact, and inexpensive. However, they suffer from dielectric and conductive losses associated to the substrate and EBG resonators [12].

The major objective of this letter is to address the mentioned difficulties by proposing a novel method for the realization of GWGs. As will be presented in the next section, with the aim of achieving lightweight and low-cost GWGs, the proposed method takes advantage of conventional PCB fabrication technology. However, to avoid conductor and dielectric losses the required AMC surfaces are realized using metallic pins rather than EBG structures. The proposed GWG is thus called pins-on-substrate gap waveguide (PoS GWG). For demonstration, the application of the proposed method for the realization of a high-performance GWG slot-array antenna is presented, and computed and measured characteristics of the antenna are compared to those of its metallic counterpart.

II. Pin-on-Substrate GWG

Lateral AMC walls of a GWG are formed by periodic structures that block the leakage of the electromagnetic field. A cross-section view of such periodic structure in the proposed PoS GWG is illustrated in Fig. 1. As shown in the figure, the bulky top and bottom metallic surfaces in conventional metallic GWGs are replaced with low-cost copper-clad FR4 substrates. Moreover, instead of generating the required bed of nails by CNC machining of a metallic block or etching EBG resonators, separately produced custom-designed or off-the-shelf metallic pins are mounted on the lower substrate. To this end, the substrate is perforated by conventional methods of fabricating PCBs at locations where the pins should be mounted. The metallic pins are then placed inside the via holes and soldered. Note that, as shown in Fig.1, the pins are soldered from the backside of the substrate. Therefore, the devised via holes should be metallized to provide an electrical connection between the pins and the upper metallic surface

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TABLE I
A COMPARISON BETWEEN THE CHARACTERISTICS OF THE PROPOSED PoS GWG AND THE COMMON MICROWAVE REALIZATION TECHNOLOGIES.

Technology	Losses	PPHC	Mass	Fabrication Cost	Power Leak	Operating Freq	Remarks
Hollow WG	Low	High	High	High	Almost Zero[1]	High[2]	[1] Possible leak due to imperfect connections [2] Heavy and costly at lower frequencies
Planar TLs	High[3]	Low	Low	Low	Relatively High	Low[4]	[3] Dielectric, conductive, and radiation losses [4] Radiation and surface wave modes at high frequencies
SIW	Relatively High	Low	Low	Low[5]	Low	Low to Moderate[6]	[5] Requires a relatively expensive low-loss substrate. [6] High dielectric and radiation losses at high frequencies
Air-Filled SIW	Moderate	Low	Low	Moderate[7]	Low	Low to Moderate[8]	[7] Requires expensive multi-layer low-loss substrates. [8] High dielectric and radiation losses at high frequencies
Metallic GWG	Low	High	High	High	Close to Zero[9]	High[10]	[9] Less than -50 dB only by two rows of pins. [10] Heavy and costly at lower frequencies.
EBG-Type GWG	Relatively High[11]	Low	Low	Low[12]	Close to Zero	Low to High	[11] Both dielectric and conductive losses [12] Requires relatively expensive low-loss substrates.
Proposed PoS GWG	Low	High	Low	Extremely Low[13]	Close to Zero	Low to High[14]	[13] No need to low-loss substrates [14] Low-cost and lightweight even at low frequencies

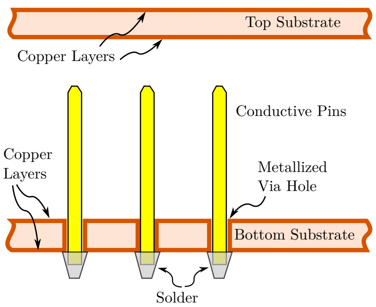


Fig. 1. An illustration of a unit cell of the proposed PoS GWG.

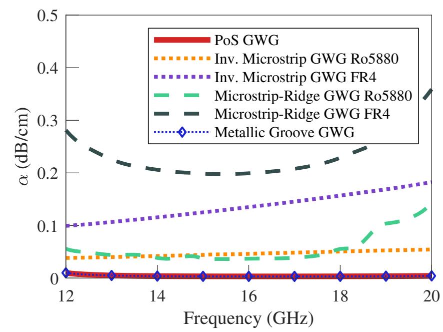


Fig. 2. A comparison between the attenuation of the proposed PoS GWG with that of inverted-microstrip GWGs, microstrip-ridge GWG, and metallic groove GWG.

of the PCB. It is worth mentioning that the top substrate can have a single copper layer facing down. However, the bottom PCB substrate has to be double clad as the application of a single-layer copper-clad PCB for the bottom substrate would result in dielectric loss.

While extremely simple, the proposed method is very efficient in producing high-performance low-cost microwave components. In the following, the advantages of the PoS GWG compared to the most commonly-used microwave technologies, including the metallic and EBG-type GWGs, are described. A summary of the comparison is given in Table I. Parameters of interest in this comparison are as follows.

- *Dielectric and Conductor Losses:* Fig. 2 compares the attenuation constant of the proposed PoS GWG to metallic groove gap waveguide, inverted-microstrip gap waveguides, and EBG-type microstrip-ridge gap waveguides using FR4 as well as low-loss Rogers substrates. The comparison shows that the proposed PoS gap waveguide has the same performance as a metallic groove gap waveguide, while it benefits from clear superior performance compared to the inverted-microstrip and EBG-type microstrip-ridge GWG realized using FR4. The results show that the attenuation constant of the proposed PoS GWG using FR4 material is even less than the attenuation of the inverted-microstrip and microstrip-ridge gap waveguides realized using low-loss Rogers RO5880 material. The results are intuitively explainable since partially dielectric-filled waveguides such as EBG-type GWGs suffer from dielectric loss, while air-filled structures such as the proposed PoS GWG have no dielectric loss. Also, resonant structures with thin conductive coating such as mushroom resonators utilized in EBG-type GWGs demonstrate relatively high conductive loss. In contrast, the PoS GWG proposed in this work is based on relatively thick metal pins, thus having much lower conductive loss compared to EBG-type GWGs.
- *Power Handling:* As shown in [17], [18], the pick power handling capability (PPHC) of a groove GWG can be calculated using

$$P = \frac{1}{4}\frac{\sqrt{1-k_c/k_0}}{\eta_0}|E_{10}|^2 \times w_{eff} \times (d+h), \qquad (1)$$

  that shows the PPHC is directly proportional to the height of the waveguide. Therefore, the PPHC of the PoS GWG is similar to the metallic GWGs and significantly higher than that of SIWs and EBG-type GWGs.
- *Mass and Volume:* The weight of the proposed GWG is significantly less than that of metallic GWGs and hollow waveguides, and slightly higher than that of SIW and EBG-type GWGs. Considering that thin PCBs are used as the top and bottom conductive surfaces, the structure also benefits from smaller volume compared to hollow waveguides and metallic GWGs.
- *Ease of manufacturing and fabrication Cost:* It is clear that while CNC machining of metallic waveguides including metallic GWGs is quite costly, the PoS GWGs are extremely low-cost and easy to manufacture as only a standard PCB process is required. It can be also shown

that the proposed PoS GWG has the lowest fabrication cost even among all the substrate-integrated waveguides in Table. I. This is because as shown in Fig. 2 to reduce dielectric loss in SIWs and EBG-type GWGs, relatively expensive low-loss substrates have to be used. In contrast, in the PoS GWG, the electromagnetic field inside the substrate is zero. Therefore, very low-cost lossy substrates such as FR4 material can be utilized for both bottom and top conductive surfaces. Moreover, as will be shown in the next section, although the construction of conductive pins is simple and inexpensive, in a wide range of microwave frequencies, off-the-shelf available metallic pins such as electronic pin headers, or various types of metallic wires with circular, square, or polygonal cross-sections can be used for this purpose. Finally the PoS GWGs are extremely easy to manufacture as only a standard PCB process is required.

- *Power Leak:* EM power leak is one of the main issues of planar TLs, especially at higher frequencies. This issue is also observed in both dielectric- and air-filled SIW structures. In contrast, conventional hollow waveguides and different GWGs including the proposed PoS GWG benefit from extremely low radiation.
- *Operating Frequency:* GWGs are well suited for millimetre waves. An additional advantage of the proposed PoS GWG is that it can be used at a wide range of frequencies, including RF and low microwave frequencies where metallic waveguides are extremely heavy and costly.

In short, microwave components based on the PoS GWGs are expected to show a performance similar to metallic gap waveguides, while in terms of weight and cost are comparable to the EBG-type ones. They also benefit from less radiation and dielectric losses and higher power handling compared to SIWs and EBG-type GWGs.

III. Slot-Array Antenna

While the proposed method can be generally used for the realization of various low-cost, lightweight, and highly efficient GWG structures for diverse applications, for demonstration, a linear slot-array PoS GWG antenna is presented in this section.

A. Design Procedure

The procedure for the design of slot array antennas in metallic groove GWG technology has been already presented in [19]. However, for completeness, the design steps are briefly presented here:

1) The preliminary step towards the design of the antenna, is the design of the parallel PEC-AMC structure with the desired bandgap behavior. The bandgap should be wide enough to cover the operating frequency of the antenna, plus safe margins at both ends of the frequency band [14], [20].

2) Then, the designed AMC structure is used to form the sidewalls of the groove GWG. For a properly designed AMC, the EM field leak from only two rows of pins is less than -50 dB [21], [22], which is sufficient for most applications.

3) Finally, the antenna is formed by devising an array of N slot resonators in the upper conductive surface of the designed groove GWG while they are $\lambda_g/2$ apart. The lengths and offsets of the slots are designed to meet the following two criteria: a) The normalized active admittance y_{in}^a observed from the waveguide port, which is the sum of the normalized active admittances y_n^a of all the N individual slots, i.e.,

$$y_{in}^a = \sum_{n=1}^{N} y_n^a \tag{2}$$

should be $y_{in}^a = 1 + j0$ for the matched condition. b) The slots should be excited with a specifically designed distribution to produce the desired pattern with a specified side-lobe level (SLL). To this end, one needs to first find the effective width w_{eff} of the GWG as

$$w_{eff} = \frac{\pi}{\sqrt{k^2 - \beta^2}}. \tag{3}$$

In this equation, β is the phase constant of the waveguide, which can be found from the eigen mode analysis of a unit-cell of the GWG. Once the effective width of the groove gap waveguide at the frequency of interest is obtained, the conventional equations for the design of slot-array rectangular waveguide can be utilized to accurately design the slot array antenna in groove GWG technology [19].

B. Antenna Design and Numerical Results

This subsection is devoted to the design and numerical validation of a slot-array antenna in the proposed low-cost GWG technology. With the aim of comparing the characteristics and performance, the slot-array antenna presented in [19], which was realized in conventional metallic gap waveguide technology is considered as the reference antenna. Therefore, the antenna specifications are chosen to be identical to the reference antenna in [19], i.e., $N = 10$, the operating frequency $f = 14$ GHz, an antenna radiation gain of at least 15 dBi, and an SLL better than -25 dB.

To minimize the fabrication costs, off-the-shelf available pin headers with the cross-sectional dimension of $a = 0.625$ mm are used for the realization of the bed of nails. Note that pin dimension $a = 1$ mm was used in the reference antenna, because thinner pins could easily break during the CNC machining of the metallic GWGs. The Chebyshev coefficients used to achieve the required SLL in both antennas are I={1, 2.086, 3.552, 4.896, 5.707, 5.707, 4.896, 3.552, 2.086, 1} [23]. The slots in the reference antenna have a rectangular shape. However, to avoid costly fabrication methods, oval slots (i.e. rectangular slots with round corners) that can be easily produced using conventional PCB prototyping are used in this work. As a result, the lengths of the slots, which are slightly longer than their counterpart in the metallic antenna, are ℓ_i = 10.79, 10.66, 10.69, 10.74, 10.79, 10.79, 10.74, 10.69, 10.66, 10.79. Other dimensions are identical to those in [19].

Simulated reflection coefficients shown in Fig. 3 demonstrate very good impedance matching at the desired operating frequency for both antennas. EM simulated co- and cross-polarized far filed patterns of the designed PoS GWG antenna and the reference antenna in the H-plane are demonstrated in Fig. 4. The results show a computed radiation gain of 15 dBi and an SLL better than -28 dB.

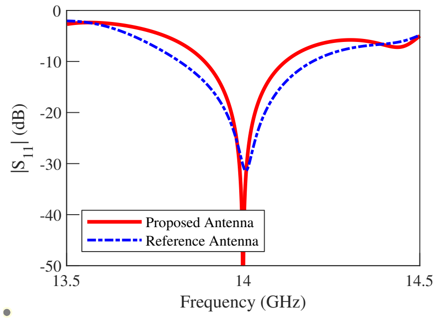


Fig. 3. Simulated reflection coefficients of the proposed PoS GWG antenna and the reference antenna fabricated using CNC milling.

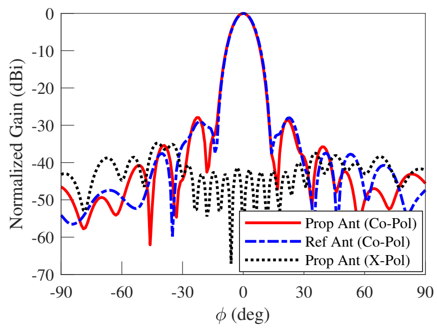
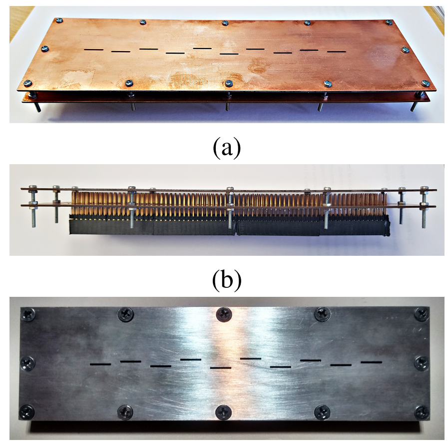


Fig. 4. Comparison between the simulated co-polarized radiation gains at $f = 14$ GHz for the proposed antenna and the reference antenna. The figure also shows the Simulated cross-polarized radiation gain of the proposed antenna.

C. Experimental Validation

To validate the computational results, the designed slot array antenna is fabricated and its experimental radiation characteristics are compared to those of the reference antenna. Photographs of the fabricated low-cost prototype as well as the reference antenna are shown in Fig. 5. The figure shows that the AMC structure in the low-cost antenna is realized by mounting arrays of pin headers on an FR4 substrate with two layers of 35 μm copper coatings on both sides. The pins are placed inside the metallized via holes and soldered to the copper layer on the backside of the FR4 substrate. The array of radiating elements is formed as metallized oval-shaped slots in the top copper-clad FR4 substrate. The spatial gap between the lower and upper FR4 boards can be maintained by a lightweight 3D printed structure forming a rim that provides rigidity and protects the top and bottom boards from deformations, and the interior area of the antenna from dust and unwanted objects. However, for demonstration, spacers are used here. Once the pin headers are soldered their excess lengths located outside the GWG can be safely removed. However, in the prototype shown in Fig. 5 the excess lengths of pins are intentionally left untouched.

The measured and simulated reflection coefficients of the designed antenna in Fig. 6 are in good agreement. Fig. 7 shows the measured radiation patterns of the fabricated PoS GWG prototype (red solid line) and the reference metallic antenna (blue dashed line). The measured results show an identical gain of 15 dBi for both antennas. The low-cost prototype shows an SLL of -25 dB, which is slightly better than the SLL for the reference antenna. In summary, it is shown, both numerically and experimentally, that while the slot-array antenna realized in the proposed GWG technology benefits from extremely lower cost and weight, it provides the exact same efficiency and radiation characteristics as its metallic counterpart.



(c)

Fig. 5. Photographs of (a) top , and (b) side views of the fabricated prototype of the proposed PoS GWG antenna, and (c) reference antenna.

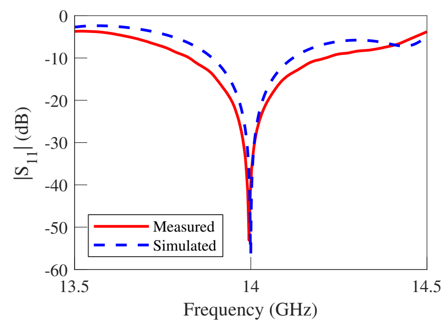


Fig. 6. Measured (red solid line) and simulated (blue dashed line) reflection coefficients of the proposed antenna.

IV. Conclusion

A novel method for the realization of groove gap waveguides has been presented and the performance of the proposed method is compared to the state-of-the-art technologies. It has been shown that while microwave components based on the proposed method benefit from very low loss, light weight, and high power handling, their fabrication is extremely low cost. For demonstration, the proposed method has been used for the realization of a slot-array antenna. The computed and measured characteristics of the designed antenna have been compared to those of a metallic counterpart.

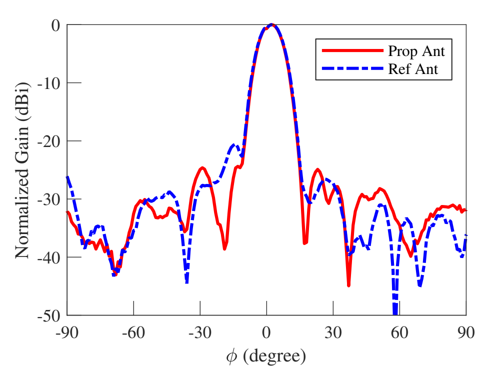


Fig. 7. Measured co-polarized H-plane radiation pattern of the proposed antenna in comparison to that of the reference metallic antenna.

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