Novel Air-filled Waveguide Transmission line based on Multi-layer Thin Metal Plates

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Abstract—This paper presents a novel way of constructing wave guiding structures by stacking several thin metal plates for millimeter-wave applications. The metallic layers do not require any electrical contacts among them. An air-filled multi-layer waveguide (MLW) transmission line is successfully designed and manufactured at D-band. Five vertically stacked thin metal layers are used to form an air-filled rectangular waveguide line. The layers are simply assembled by allowing a small air gap among them, without the need of using advanced manufacturing methods such as adhesive bonding techniques. The possible field leakage due to the air gaps is prevented by using an electromagnetic band gap (EBG) structure, consisting of glide-symmetric holes. A straight MLW line and a line with a double 90° bends are fabricated by using chemical metal etching, as a proof of concept. The measurement results of the straight line show that the reflection coefficient is better than -18 dB with average insertion loss of 0.02 dB/mm over the frequency band 110-170 GHz. For the double 90° bends line, the reflection coefficient is better than -18 dB with an average insertion loss value of 0.02 dB/mm over the frequency band 110-150 GHz. The proposed concept could be an excellent candidate for designing compact and thin passive waveguide components and active components packaging, with a great potential for low-cost, light weight and mass-producible at millimeter-wave frequencies.

Index Terms—Electromagnetic band gap (EBG), multi-layer waveguide (MLW), chemical metal etching, millimeter-wave, waveguide.

I. INTRODUCTION

TRANSMISSION lines are the fundamental building blocks of any high frequency systems to guide, manipulate and transmit signals. They play an important role in passive and active components design and integration. Conventional guiding structures, such as metal-pipe hollow waveguides, planar transmission lines (e.g., microstrip, Substrate Integrated Waveguide (SIW), and coplanar waveguide) are popular and widely used technologies. Hollow waveguides show superior performance in terms of loss, whilst the planar technologies exhibit compact and flexible manufacturing advantages.

Due to the increasing demand for higher data rate transmission and the existing overcrowded frequency spectrum, the millimeter-wave frequency band (30-300 GHz) has received increasing attention to provide more available bandwidth and higher capacity [1], [2]. Using higher frequencies has the advantage of reducing the size of components, e.g., high gain

antennas with small aperture sizes, which led to more compact systems. However, increasing the operating frequency leads to enormous challenges in fabrication of components with small features. Mechanically small features in 3-D hollow waveguide structures requires precise and costly manufacturing techniques at high frequencies, while the high loss of planar transmission lines limits their usage, especially in electrically big components such as array antennas. For example, high-gain array antennas with physically small size have been presented at 120 GHz [3] and 350 GHz [4] based on rectangular hollow waveguide with a complex and high-cost manufacturing technique, where they have etched especial patterns in several thin metal plates and bonded them under high pressure and temperature condition in vacuum.

Substrate based planar transmission line technologies offer the advantages of easy fabrication and integration. However, they show higher losses mainly due to the presence of dielectric and field leakage. New substrate materials, such as Liquid Crystal Polymer (LCP), have been used for high frequency applications to have a low loss tangent and a stable dielectric constant. In [5] the electrical properties of LCP substrate has been characterized at D-band. It has been shown that the insertion loss of a microstrip line in 2 mil substrate increases from 0.176 dB/mm to 0.33dB/mm over the frequency band 110-170 GHz. Surface roughness becomes more important at frequencies above 100 GHz, and has a significant impact on the total system loss [6]. The performance of a SIW transmission line and the impact of surface roughness on dissipative loss has been study at D-band in [6]. The measured results show that the unpolished prototypes exhibit insertion loss around 0.8 dB/mm and by polishing the substrate, an average insertion loss of 0.35 dB/mm has been achieved.

Metallic air-filled hollow waveguides are attractive low loss solutions in spite of the fact that fabrication of complex 3-D waveguide structures is challenging at high frequencies. Computerized Numerically Controlled (CNC) milling and die-sink Electric Discharge Machining (EDM) are conventional manufacturing techniques to fabricate waveguide structures in low volume. The waveguide structures with EDM and CNC machining are usually fabricated in E-plane split-blocks in order to have a simple assembly and avoid field leakage. In [7] rectangular waveguide lines in different planes cuts and different material (e.g., aluminum and brass) have been fabricated by CNC milling. The lowest insertion loss has been reported for the E-plane split-block prototype in aluminum with a loss of around 0.005 dB/mm over the frequency band 75-110 GHz. Alternative fabrication approaches with features of low-cost, suitable for mass production and easy integration have been

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studied and developed recently, especially for millimeter-wave applications.

Adaptive manufacturing (3-D printing) [8], [9], micromachining technology [10], [11], and micro-molding [12] have been recently introduced as alternative manufacturing techniques for high frequency applications. The 3-D printing technology has advantages of low cost and rapid prototyping, even for fabrication of complex structures. In [13] high-resolution metal-coated stereolithography apparatus (SLA) technique is used to manufacture a rectangular waveguide and a bandpass filter in a E-plane split-block configuration at W-band. It has been demonstrated a measured average dissipative loss of 0.013 dB/mm for the copper coated waveguide line at W-band. A 25 mm long straight copper-plated plastic waveguide is printed in [8] with the same technique (SLA) at H-band (220 - 325 GHz) showing an insertion loss of 0.014 dB/mm. Waveguide structures can be also manufactured in one piece by using direct metal printing. In [9], rectangular waveguide lines by using selective laser melting (SLM) technique are fabricated by melting Cu-15Sn powder. The insertion losses of 0.075 dB/mm, 0.019 dB/mm, and 0.12 dB/mm have been reported for waveguide lines at E-, D-, and H-band, respectively.

Micromachining is a high-precision elaborate manufacturing method to make high-performance waveguide devices. A micromachined gold-plated H-plane split-block rectangular waveguide with a very low insertion loss of 0.008-0.016 dB/mm at D-band is reported in [14]. Moreover, a silicon-based micromachined bandpass rectangular waveguide filter is presented at D-band in [10], with insertion losses better than 0.5 dB and 0.7 dB for third and fifth order filters, respectively. Silicon micromachining is limited by maximum etching depth and it is more suitable for higher frequencies, e.g., above 250 GHz, since the physical dimensions are relatively large at W- and D-band for this technique. In [11], the use of SU-8 photoresist micromachining technology to manufacture rectangular waveguide lines in D- and H-band are studied by using 5 silver plated layers. An insertion loss of better than 0.03 dB/mm is reported in both bands. A W-band gold-plated plastic rectangular waveguide by using micro-molding (micro hot embossing) has been presented in [12]. It has been reported a return loss better than 14 dB with an insertion loss of around 0.03 dB/mm at W-band.

Low-loss waveguide components, interconnections, and packaging solutions with futures of low cost and suitable for mass production are needed for frequencies above 100 GHz. In this paper we introduce a novel and flexible approach to make affordable air-filled waveguide structures for millimeter-wave applications. A rectangular multi-layer waveguide (MLW) line is created by stacking thin unconnected petal plates. The layers do not need to have electrical and galvanic contacts. This introduces a cost-effective manufacturing with a simple mechanical assembly, especially at high frequencies. In Section II we present the design methodology of the MLW transmission line, including the design and characterization of the electromagnetic band gap (EBG) unit cells, straight line, and a line with two 90° bends. In Section III experimental results of the fabricated prototypes are presented. Finally,

Fig. 1. Configuration of the proposed MLW transmission line. (a) Cross-section view of the WR-6 waveguide which consists of 5 layers with small gaps between them. (b) Field-leakage suppression by using glide-symmetric holes.

Section IV gives some concluding remarks.

II. MULTI-LAYER WAVEGUIDE TRANSMISSION LINE CONFIGURATION AND DESIGN

The use of EBG structures and high impedance surfaces in order to prevent field leakage in metallic waveguide structures for high frequency applications was proposed by means of gap waveguide technology in [15], [16] for the first time. In this novel transmission line a low-loss waveguide was built in two metal blocks, without the need for electrical contact between them. Therefore, this waveguide structure can be manufactured with cost-effective fabrication methods, such as plastic and metal injection molding. A periodic EBG pin texture, which provides a stop-band for the desired frequency band, is used to eliminate unwanted leakages. Several waveguide components such as planar array antennas [17]–[20], filters [21], [22], diplexer [23], and integrated modules [24], [25] have been reported, which show the advantages of this technology at millimeter-wave frequencies.

A similar approach is used in [26], [27] in order to construct metallic waveguides in split-blocks without having galvanic contact. A rectangular Waveguide in H-plane split-block with holey glide-symmetric EBG structures in both plates is designed to have a simple mechanical assembly and suppressing field leakage. The two metal blocks allow to have a small gap between them and any leakage is avoided by the provided stop-band from the periodic glide-symmetric holes. A waveguide phase shifter [28] and a contactless flange [29] have also designed with a similar approach.

Fig. 1 shows the configuration and arrangement of the proposed MLW transmission line. A rectangular waveguide is formed by vertically stacked unconnected thin metal plates. In Fig. 1(a), five layers are used to build up a rectangular shaped waveguide, by removing the channel in the middle layers. The height of the waveguide channel depends on the thickness and the number of the layers. Since the metal plates do not have electrical and galvanic contact, a strong field leakage occurs

Fig. 2. Configuration of the unit cell, consisting of five metallic layers. (a) Perspective view and cross-section view of the unit cell with circular holes, (b) Perspective view and cross-section view of the unit cell with diamond-shaped holes. ($P = 1.86$ mm, $d = 1$ mm, $h = 0.2$ mm, and $g = 0.01$ mm)

between the layers. In order to solve this problem we used an EBG structure to avoid any possible leakage. A periodic pattern of holes in a glide-symmetric arrangement is applied for this purpose, as shown in Fig. 1(b). The periodic holes provide stop-band for a certain frequency band which suppresses the propagation of any wave in undesired directions. This introduces a huge mechanical assembly advantage and manufacturing flexibility. Each layer can be fabricated with its special pattern separately and simply assemble afterwards without the need of a complex and costly method.

A. Unit Cell Design

The first step is to design a periodic unit cell that provides a sufficient stop-band that covers the desired operating frequency band. The geometries of the proposed unit cells are shown in Fig. 2. The unit cells consist of holes in thin metal plates. The holes are allocated in a glide-symmetric configuration. The glide symmetry is a higher order symmetry than the simple periodic pin structure in gap waveguide technology in [16]. The holes in each layer have an offset of half of the period (P) with respect to the ones at the top and bottom layers. As shown in Fig. 2, there is a small gap (g) between the layers. The holes can have any arbitrary geometrical shape. Fig. 2 shows two unit cells with circular and diamond-shaped holes.

The dispersion diagram of the unit cells for the given values are presented in Fig. 3. We used the CST Eigenmode solver in order to calculate the dispersion diagrams. Both unit cells provide a stop-band which covers the desired frequency bands (100-200 GHz). Fig. 3 shows that, even though the unit cells consist of several unconnected layers, the structure does not support any modes within the stop-band.

Furthermore, we have also studied the effect of the unit cell parameters on the stop-band performance. Fig. 4 shows the effect of the dimension of the holes for different periodicities. The other parameters are kept the same as the unit cells of

Fig. 3. Dispersion diagram for the infinite periodic unit cell with (a) circular holes, and (b) diamond-shaped holes. ($P = 1.86$ mm, $d = 1$ mm, $h = 0.2$ mm, and $g = 0.01$ mm)

Fig. 2, as a reference. The lower and upper limits in the Fig. 4 are corresponding to the stop-band's start and end frequencies, respectively. Fig. 4 shows that the center frequency of the stop-band is controlled by the periodicity (P) of the unit cell. Moreover, a maximum relative bandwidth is achieved by a certain value of the holes dimensions (d/P). As can be seen, the shape of the holes has a significant impact on the relative bandwidth behavior of the stop-band.

Fig. 5 shows the relative bandwidth as a function of d/P for different periodicities. For the circular hole unit cell, there is maximum bandwidth of 60% for d/P equal to 0.52. That means there is an optimum case when the diameter of the holes are around half of the periodicity. On the other hand, the diamond-shaped hole unit cell shows a more robust performance. A maximum of more than 85% relative bandwidth is achieved for d/P equal to 0.46. Moreover, this unit cell shows a wider bandwidth for a wider range of values of hole dimensions. This makes the unit cell with diamond-shaped holes less sensitive to manufacturing tolerances, which is very critical for frequencies above 100 GHz.

The impact of the gap between the layers is presented in Fig. 6. The other parameters have the same values as the ones presented in Fig. 2. By increasing the gap between the layers the stop-band shrinks. The unit cells do not provide a stop-band if the gap between the layers becomes bigger than a certain value. The diamond-shaped hole unit cell shows

Fig. 4. Effect of diameter versus period ratio (d/P) in the stopband for a number of periodicities P with $h = 0.2$ mm and $g = 0.01$ mm. (a) Unit cell with circular holes, (b) Unit cell with diamond-shaped holes.

Fig. 5. Bandwidth of the stopband as a function of d/P for a number of periods P with $h = 0.1$ mm and $g = 0.01$ mm. (a) Unit cell with circular holes, (b) Unit cell with diamond-shaped holes.

less sensitivity to the gap size, and still works for larger gap sizes. Again this involves advantages related to the mechanical assembly, especially for complex waveguide components such as planar array antennas. Fig. 7 illustrates the effect of the thickness of the plates, which determines the depth of the holes (h). By increasing the depth of the holes the relative bandwidth of the stop-band increases, and it saturates when the depth is

Fig. 6. Effect of gap g in the stopband for circular unit cell ($h = 0.1$ mm, $P = 1.86$ mm, and $d = 1$ mm) and diamond-shaped unit cell ($h = 0.1$ mm, $P = 1.86$ mm, and $r = 0.86$ mm).

Fig. 7. Effect of depth of the holes H in the stopband for circular unit cell ($g = 0.01$ mm, $P = 1.86$ mm, and $r = 1$ mm) and diamond-shaped unit cell ($g = 0.01$ mm, $P = 1.86$ mm, and $r = 0.86$ mm).

bigger than quarter of a wavelength at center frequency of the stop-band. In order to have one octave bandwidth the depth of the gap should be larger than $\lambda/10$ at the center frequency of the stop-band. However, the unit cells provide a stop-band for thinner plates, with a smaller bandwidth.

B. Straight MLW line with right-angle transitions

A straight air-filled waveguide line with the proposed architecture is designed in order to investigate the performance of MLW. The designed line has two standard WR-6 inputs at the top to have a simpler interface with the measurement equipment. The geometry of the straight MLW transmission line is shown in Fig. 8. The waveguide line consists of five 200 μm thick metal plates with 10 μm gap between the layers. An elongated rectangular slot with a width of 1.65 mm is removed from the middle layers. After stacking the layers, a rectangular waveguide line with dimensions 1.65 mm $\times$ 0.642 mm will be formed. It is worthy to mention that the height of the designed waveguide is slightly smaller than the standard WR-6 waveguide (0.82 mm) at D-band. Therefore, we expect slightly higher loss than the standard waveguide.

The length of the straight MLW line in Fig. 8 is 30 mm, which corresponds to $15 \lambda_0$ at 150 GHz. The geometry of the transition is shown in Fig. 8(b). Simple steps are made by extending the layers into the waveguide channel to achieve a wideband input matching. Fig. 8(c) shows the middle layer (the layer #3) with more details. We have removed a periodic rectangular slot along the waveguide channel in order to avoid the coupling of the wave into the gap between the layers.

Fig. 8. The proposed multi-layer waveguide (MLW) transmission line configuration. (a) 3-D exploded view. (b) Cross-section view. (c) Top view of layer #3.

Without the slots, the wave couples to the edges of the waveguide and propagates, which adds extra losses.

We have designed two straight MLW lines with the circular and diamond-shaped EBG hole unit cells. The simulated performance of the designed lines with two right-angle transitions are shown in Fig. 9. We have used CST Microwave Studio for all simulations. The simulated reflection coefficients are below -16 dB in the whole desired frequency band (over 110-170 GHz), and below -20 dB for the most of the band. The simulated transmission coefficient is better than -0.5 dB for most of the band. Silver has been considered as constructing material in all simulations.

Fig. 10 shows the simulated amplitude of the E-field distribution within the layers in two different frequencies (110 and 170 GHz). As expected, there is no field leakage within the layers, even though there is a small gap between the layers and they do not have galvanic contacts. As mentioned before, the EBG glide-symmetric holes prevent the wave propagation and unwanted modes within the stop-band.

C. MLW line with double 90 degrees bend

Any discontinuity such as bends and T-junctions can cause severe leakage. Therefore, to investigate the potential use of this technology for the design of more complex waveguide structures, we have designed a double 90° bends waveguide line. The geometry of the proposed line is illustrated in Fig. 11. It has a similar configuration (number of layers, gap size, and right-angle transitions) as the straight line in Fig. 8. The total length of the line is 38 mm.

Fig. 9. Simulated performance of a 30 mm long straight MLW line with circular and diamond-shaped EBG unit cell. (a) Reflection coefficient. (b) Transmission coefficient.

Fig. 10. Simulated E-field distribution within the layers at (a) 110 GHz, and (b) 170 GHz for a line with circular EBG unit cells (refers to Fig. 2).

The simulated S-parameters of the MLW double 90° bends line are presented in Fig. 12. Two waveguide lines with the proposed circular and diamond-shaped holes EBG unit cells

Fig. 11. Proposed multi-layer waveguide (MLW) transmission line with double 90° bends.

Fig. 12. Simulated performance of the MLW line with a double 90° bends with circular and diamond-shaped EBG unit cell. (a) Reflection coefficient. (b) Transmission coefficient.

have been designed. Some resonances appear in the simulated results in Fig. 12, which degrade the performance and decrease the operating frequency bandwidth. The simulated reflection coefficients of the line with the diamond-shaped holes is below -18 dB over the frequency band 110-152 GHz, with the average $|S_{21}|$ value better than -0.75 dB over the same frequency band. The line with the circular-shaped unit cell has similar performance, but there exists a small resonance at 115 GHz.

The simulated E-field distribution within the different layers at 140 GHz is shown in Fig. 13. This figure verifies again that the EBG holes prevent field leakage and propagation of any wave in unwanted directions. We did an investigation to understand the reason of the unwanted resonance in Fig. 12. We found out that the location of the resonances are around

Fig. 13. Simulated E-field distribution within the layers at 140 GHz.

Fig. 14. Simulated E-field distribution within the layer number 4 at 155 GHz.

the corners of the bends. Due to the formation of parts at the designs with length of around one wavelength, a resonance accrues in the structure, as shown in Fig. 14. Fig. 14 shows the simulated time-averaged amplitude of the E-field in the layer number 4 at 155 GHz. The red spots on the corners depicts the positions of the response. This problem can be solved by avoiding any metal sections with length of λ and $\lambda/2$, especially around the discontinuities.

III. EXPERIMENTAL RESULTS AND DISCUSSION

We have manufactured the presented MLW lines in Section II-A and B, as a proof-of-concept and performance validation. Fig. 15 shows the fabricated prototypes. The special pattern of each layer is made on a 200 μm thick brass plate, by using metal chemical etching. The plates are silver plated in order to have lower conductive loss. The chemical etching provides a precise fabrication, which is scalable and suitable for mass production. Any arbitrary shape can be cut through thin metal plates with an aspect ratio of 1. The manufacturing tolerance is approximately $\pm 20\%$ of the metal thickness, which in our case becomes around $\pm 40\ \mu\text{m}$. Based on our experience, we have over-etching in most of the time, which makes the holes bigger than expected. Therefore, we have considered this effect and compensated the manufacturing tolerances in our design before fabrication. We decreased all the through holes dimensions 40 μm . By doing that, a maximum of 5 μm error in the final fabricated parts has been achieved. The layers are simply assembled and glued together by using non-conductive epoxy glue.

The fabricated prototypes have been measured by using Keysight N5241A PNA-X and VDI WR-6 extenders, as shown in Fig. 16. The measured performance of the straight lines with circular and diamond-shaped holes is presented in Fig. 17.

Fig. 15. Photograph of the fabricated MLW lines by using chemical metal etching.

Fig. 16. Measurement setup.

The measured reflection coefficient is below -18 dB over the frequency band 110-170 GHz, showing insertion loss values between 1.5-0.45 dB over the same frequency band. Both lines with different EBG unit cells show a similar performance. The measured reflection and transmission coefficients of the lines with two 90° bends are presented in Fig. 18. The measured reflection coefficients are below -18 dB, with insertion loss between 1-0.65 dB, over the frequency band 110-150 GHz. As expected a resonance appears around 158 GHz, as discussed in Section II-B. The measured results in Fig. 17 and Fig. 18 are in very good agreement with the simulated results shown in Fig. 9 and Fig. 12, respectively. However, a slightly higher loss (around 0.1 dB) and a small shift to higher frequencies are noticeable. These discrepancies are due to the existing higher conductive loss of the prototypes and fabrication and assembly tolerances.

A. Comparison and discussion

TABLE I shows a comparison between the proposed concept and several published works on different technologies. The commercial gold plated rectangular waveguide exhibits lower insertion loss than microstrip and SIW lines. The 3-D printed waveguides have comparable losses to the commercial one, after applying polishing techniques to maintain a low surface roughness. A very low insertion loss has been reported for the deep reactive ion etching (DRIE) silicon micromachined waveguide in [14], by achieving very low surface roughness. The average measured insertion loss per unit length of the proposed MLW line is around 0.02 dB/mm at D-band. It should be remarked that the effect of the two right-angle

(a)

(b)

Fig. 17. Measured performance of the fabricated straight MLW lines at D-band. (a) Reflection coefficient. (b) Transmission coefficient.

(a)

(b)

Fig. 18. Measured performance of the fabricated MLW line with double 90° at D-band. (a) Reflection coefficient. (b) Transmission coefficient.

transitions are also included in the reported insertion loss. The presented transmission line shows a comparable performance to the commercial waveguide in terms of losses. Comparing with the dielectric based transmission lines, the proposed technology shows more than 10 times lower dissipative loss. Moreover, the proposed technology can be manufactured with very low cost techniques, by using mature fabrication methods such as metal laser-cutting and chemical etching.

TABLE I
COMPARISON BETWEEN STATE-OF-THE-ART WAVEGUIDE
TECHNOLOGIES

Ref.	Technology	Freq. (GHz)	Split- block	Loss (dB/mm)
Commercial	-	110-170	-	0.012
[5]	Microstrip	110-170	-	0.33
[6]	SIW	110-170	-	0.35
[7]	CNC (Al)	75-110	E-plane	0.005
[13]	3-D printing ¹	75-110	E-plane	0.011
[8]	3-D printing ²	220-325	-	0.012
[9]	3-D printing ³	110-170	-	0.019
[14]	micromachining ⁴	110-170	H-plane	0.016
[11]	micromachining ⁵	110-170	H-plane	0.03
[12]	micro-molding	75-110	H-plane	0.03
This work	MLW	110-170	H-plane	0.02

¹ Stereolithography apparatus (SLA) with copper plating.

² Stereolithography apparatus (SLA) with copper plating.

³ Selective laser melting (SLM) with Cu-15Sn powder.

⁴ Deep reactive-ion etching (DRIE) in silicon with gold plating.

⁵ Multilayer silver plated SU-8.

IV. CONCLUSION

We have presented a novel air-filled transmission line for millimeter-wave applications. In the proposed concept a waveguide is constructed by staking several thin unconnected metal plates. There is no requirement for having any electrical and galvanic contact between the layers. We have used EBG glide-symmetric holes to control the direction of propagation and eliminate field leakages. A straight line and a line with a double 90° bends with two different EBG unit cells have been designed and fabricated. A high-precision and cost-effective effective manufacturing method, i.e., metal chemical etching, is used to fabricate the prototypes. The measured performance of the fabricated prototypes were presented in order to verify the performance of the proposed concept. A very low-loss performance has been successfully achieved with average insertion loss of 0.02 dB/mm. The proposed unique architecture opens up an opportunity to provide low-loss and cost-effective millimeter-wave waveguide components and system packaging.

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