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Gap Waveguide Technology for Millimeter Wave Antenna Systems

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Abstract—Millimeter wave communication systems require many innovative antennas adapted for the future application scenarios such as the upcoming 5G cellular networks. Due to the strong path loss in free space at millimeter wave frequency range, high gain and low cost antennas are of great demand. Also, advanced features such as multi-beam for multiple user, dual-pol or even complete phased arrays with enormous degrees of freedom in beamforming are some of the key research lines for antenna designers nowadays. In this paper an overview of a new type of family of low loss antennas and components based on the recently developed gap waveguide technology is presented. With the advent of new millimeter wave applications, this low cost and low loss waveguide technology can be considered as a good candidate to be used as the core RF building block.

Index Terms—Gap waveguide Technology, millimeter wave antennas, millimeter wave components.

I. INTRODUCTION

Nowadays, wireless connectivity is considered to be an important factor and essential index for assessing the quality of life as wireless communication systems continue to drive human productivity and innovation in many areas. Communication at millimeter wave frequencies can be considered as the most recent game-changing development for wireless systems. At millimeter wave frequencies, the available spectrum is way larger compared to the today's cellular networks that are operating below 10 GHz. Over 20 GHz of spectrum is waiting to be used for cellular or WLAN data traffic in the 28, 38, 60 and 72 GHz bands alone, and several tenths of consecutive gigahertz band could be used at frequencies above 100 GHz. Thus, millimeter wave wireless communication is an enabling technology that will be utilized by numerous emerging wireless applications and we foresee that millimeter wave will play a key role in fifth generation (5G) cellular networks.

Implementation challenges for millimeter wave communication involve many aspects. Specially, at the hardware level of the physical layer (PHY), antennas and waveguide components are one of the major challenges. Antenna systems

with high performance will be required at these bands to compensate the strong propagation losses. Above the PHY, the medium access control (MAC) of the millimeter wave systems must also consider unique design factors. Most of the computational burden of beam steering would fall in the MAC layer. In this article, we will deal mainly with the hardware challenges in PHY layer. There are plenty of technological issues and mechanical challenges in designing millimeter-wave front-ends. These factors are cost pressure, compact size requirement, improved system integration density, packaging and cross-talk suppression, lower DC power consumption and lower RF power dissipation.

Conventional rectangular waveguides, planar transmission lines such as coplanar waveguides or microstrip lines are well characterized transmission media which are used in a variety of complex RF component and circuit designs until today. However, there are some factors to be considered while using these conventional technologies at millimeter wave frequencies or above, particularly for low cost RF applications. Classical waveguide technology is well known to provide the lowest losses and to have a higher power handling capability. For these reasons it is often used in space applications. Unfortunately, it is a non flexible technology and becomes expensive and difficult to manufacture when complex components are designed (as for instance an antenna feed network), especially because it is critical to ensure good electrical contact when manufacturing in two pieces. Connection between the split blocks can be achieved by screwing, diffusion bonding or dip-brazing techniques. These techniques are costly, complex and often not scalable to higher frequencies. As the frequency of operation of waveguides approaches millimeter wave frequencies, the physical dimensions of the components decrease and a “watchmaker” level of precision is required for manufacturing and assembling the metal split-blocks by conventional methods.

On the other hand, microstrip and coplanar lines are the most representative planar transmission lines. These are robust, low cost solutions and very suitable for integrating active microwave components on circuit boards. However, the transmission properties of both microstrip and coplanar lines greatly depend on the substrate parameters. Both lines suffer from high insertion loss at millimeter wave frequency spectrum due to the presence of lossy dielectric material, as well as conductor losses caused by the small dimensions. Additionally, the excitation of unwanted surface waves and propagation via substrate modes is another serious problem of printed technology.

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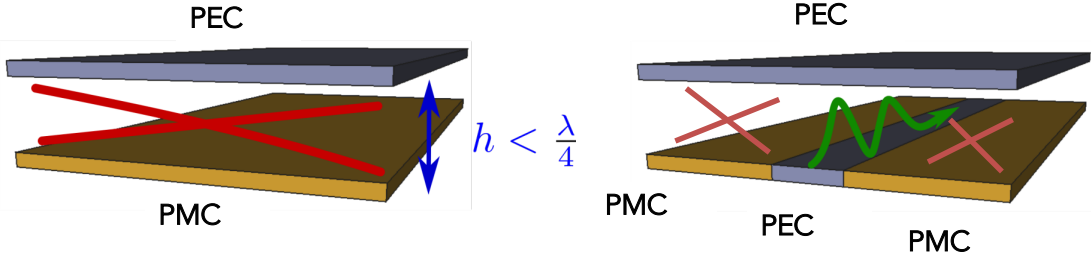


Fig. 1. Fundamentals of gap waveguide technology. Green arrow means propagation is allowed. Red crosses mean propagation is forbidden.

Therefore, there is a definite need for new RF technology (in particular at 30 GHz and above) which will allow low cost manufacturing of large multi-beam MIMO antenna arrays for 5G wireless application. Alternatives have been developed already to replace the two main conventional technologies (PCB technology and hollow waveguide technology). For instance, such an alternative technology is the Substrate Integrated Waveguide (SIW), that still suffers from the dielectric losses at millimeter wave frequency range. In this regard, recently evolved gap waveguide is also an innovative technology well suited for millimeter-wave RF applications. It is based on Prof. Kildal's invention from 2009 and described in the introductory papers [1], [2]. The papers describe several types of gap waveguides that can replace microstrip technology, coplanar waveguides, and standard rectangular waveguides in millimeter wave RF systems and antennas. The gap waveguide can be a low loss RF building block having big advantages in manufacturing waveguide components such as antennas or filters and at the same time integrating RF electronics with waveguide components.

In this paper, a summary of the fundamentals of the technology and the existing versions will be presented with special discussion on the losses analysis. This constitutes Section II of the manuscript. Section III is devoted to an overview of the antenna designs focused on creating high directive antennas for the 60 GHz frequency range. Examples of components designed and discussion on the integration capability of this technology for these bands are presented in Section IV and some final conclusions are included in Section V.

II. FUNDAMENTALS OF THE TECHNOLOGY

The gap-waveguiding concept is based on controlling the propagation of the electromagnetic waves in desired directions inside a parallel-plate waveguide by using fundamentals of boundary conditions and canonical surfaces. In principle, a parallel plate waveguide is made of two unconnected metal plates that can be modeled as ideal perfect electric conductors (PEC) and the propagation of electromagnetic waves is always allowed in this structure independently of the distance between the two plates (there is always a solution of Maxwell equations for these boundary conditions). If now one of the plates is replaced by an ideal perfect magnetic conductor (PMC), no electromagnetic wave can propagate provided that the two plates are separated by less than $\lambda/4$ (see Fig. 1). Unfortunately, there are no PMCs in nature but metasurfaces

made with periodic structures can be used to create equivalent boundary conditions same as the ideal PMC within a frequency range. If you now allow some path (implemented as a ridge, groove or strip) made of PEC in the middle of the PMC surface for propagating the signal, the field will be propagating strictly confined along that path without being leaked in unwanted directions. The losses will be minimized as the field propagates in the air gap and at the same time, the guiding structure will be packaged avoiding any leakage or coupling, and the potential radiation from discontinuities or corners will be suppressed due to the prevention of any kind of EM mode propagation outside the PEC/PEC area. This is what the drawings in Fig.1 represent. The green arrow means propagation is possible whilst the red cross means no wave can propagate.

How to realize the metasurface providing the PMC boundary conditions, is an important aspect that will influence the losses, manufacturing cost and the operating bandwidth of the gap waveguide components. For the majority of the gap waveguide components published in literature, the structure known as “bed of nails” is the preferred as PMC surface [3]. This structure is made of metallic pins and can be seen as a 2-D corrugated surface (see Fig. 2). It is very wideband, isotropic and as it is made of metal it has negligible losses. The second preferred PMC structure is the use of mushroom-type EBG periodic structure consisting of little metal patches printed on a substrate and with grounded vias (shown in Fig. 2.d) whose main advantage is that it can be manufactured by the cheap PCB technology.

With this view, four realizations of the technology have been proposed from the beginning. They are represented in Fig. 2 and are termed respectively ridge gap, groove gap, inverted-microstrip gap and microstrip-ridge gap. The operating modes in the different gap waveguide geometries are different. The groove version is equivalent to a rectangular waveguide and consequently supports propagation of TE/TM modes depending on the dimensions of its cross section although in most cases the TE_{10} mode is preferred.

The desired modes in ridge gap waveguide, inverted-microstrip gap waveguide and microstrip-ridge gap waveguide are similar in nature and all of these geometries allow a quasi-TEM mode within the stopband created by the periodic structures. Advantages and disadvantages of each version are related to the manufacturing simplicity, the compactness, power handling capability, etc [3]. If what you need is to

reduce manufacturing cost assuming higher losses, the versions including dielectrics are a good option. In the inverted microstrip version the designed circuit is printed on a thin dielectric slab and the ground plane is replaced by the uniform PMC ground plane made of pins. The microstrip ridge version can be completely made in PCB technology with grounded vias.

In the same Fig.2 a representation of the field confinement is included for each one of the realizations. As mentioned before, in all four cases most of the propagating field is located in air, being this one of the key aspects of this technology to be low loss.

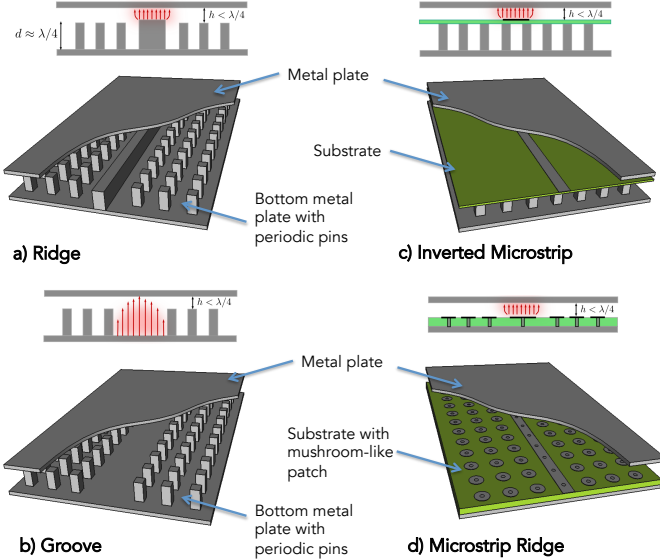


Fig. 2. Description of the main realizations of gap waveguide technology. On top of each realization there is a figure with a cross-sectional view that shows the localization of the propagating field (red arrows).

A. Losses

As the arrangements of guiding structures and propagating modes are different in the gap waveguide structures presented in Fig. 2, the attenuation will also be different. Consequently, it is important to characterize the attenuation and losses accurately for all these four categories of gap waveguide structures in the millimeter frequency range. In order to do that, several sufficiently long gap waveguide prototypes have been manufactured and directly measured with a conventional network analyzer (VNA) to determine the attenuation and losses directly from the measurement of the transmission coefficient S_{21} . Several manufactured gap waveguide sections used for the loss study are shown in the photo of Fig. 3. A comparison with classical technologies is of interest and for this reason in the loss study, rectangular waveguide, SIW and microstrip lines are also included.

As an example, the measured S-parameter results for the groove gap waveguide, ridge gap waveguide and the reference rectangular waveguide prototype having split in E-plane, are presented in Fig. 3. The rectangular waveguide has the lowest reflection coefficient (S_{11}) over the entire V-band frequency range because no transitions are needed for measuring it. The

TABLE I
LOSSES FOR THE DIFFERENT VERSIONS OF GAP WAVEGUIDE IN THE 60 GHz BAND

Prototype (frequency)	Simulated loss (dB/cm)	Measured min-max loss (dB/cm)
Rect. Waveguide (50 - 75 GHz)	0.0136	0.0295 - 0.042
Groove gap (50 - 75 GHz)	0.019	0.03 - 0.0442
Ridge gap (50 - 75 GHz)	0.0373	0.058 - 0.0705
Microstrip-ridge gap (56 - 68 GHz)	0.0805	0.162 - 0.23
Invert-micro gap (56 - 72 GHz)	0.0934	0.21 - 0.288
Microstrip line (50 - 75 GHz) 0.127-0.2mm substrate	LCP : 0.23	0.62 - 0.77
Microstrip line (50 - 75 GHz) 0.127-0.2mm substrate	Rogers 4003 : 0.271	0.7055
Air filled SIW (50 GHz)	0.0621	0.0615
Rogers-5880, SIW (50 GHz)	0.1327	0.2172

groove gap waveguide and the ridge gap waveguide also have low reflection over the entire V-band: below -20 dB for the groove gap waveguide and below -17 dB for the ridge gap waveguide.

Once the prototypes have been measured, the losses are analyzed and calculated using the well-known formula:

$$Loss(dB) = 10 \log \frac{1 - |S_{11}|^2}{|S_{21}|^2}. \quad (1)$$

In this way, the reflective component of the total loss is neglected and only the dissipative part of the loss is taken into consideration. The losses for all the measured prototypes (not only the ones in the example of Fig. 3 but also the other realizations of gap waveguide) are summarized in Table 1. To be fair we have compared the groove gap waveguide and ridge gap waveguide with a standard rectangular waveguide. On the other hand, the losses of microstrip-ridge gap and inverted microstrip gap waveguide have been compared with losses of the two open millimeter wave microstrip lines presented in [4] and [5].

From the table, it is clear that the losses in groove gap and ridge gap waveguide are comparable and are in the same order of magnitude as rectangular waveguide. The ridge gap waveguide has larger losses than the rectangular waveguide because the guiding ridge is narrower than the waveguide width. As a result, the current density is larger over the ridge section and the higher the current density, the larger is the conductor loss.

The microstrip-ridge gap and inverted microstrip ridge gap waveguide are lossier, but both these versions of gap waveguide still outperform regular microstrip lines working at 60 GHz frequency range [6]. The reason behind this is that the gap waveguide principle allows much wider guiding strips than the regular width of microstrip lines, which in turn reduces significantly the conductor losses. Also, for both these two gap waveguide versions, the EM field propagates mainly in the air

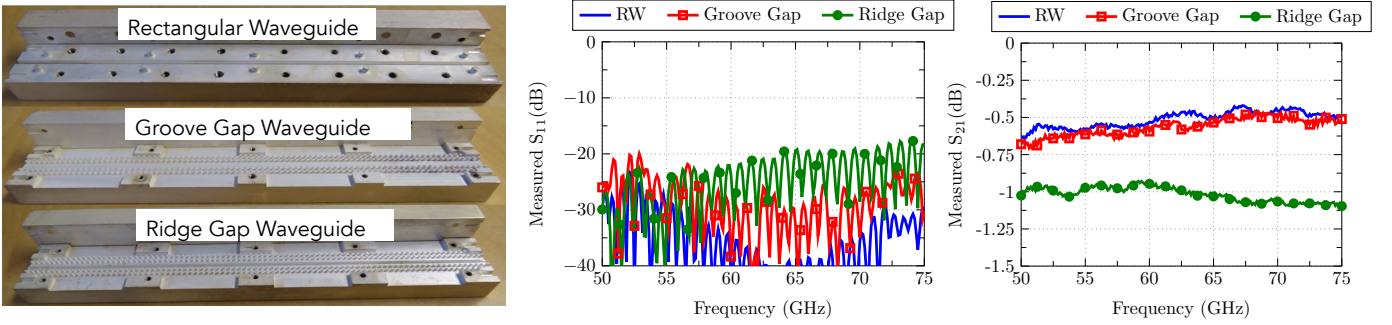


Fig. 3. Prototypes for the experimental characterization of losses and measured reflection coefficients S_{11} and transmission coefficients S_{21} .

gap between the upper plate and lower plate, thus reducing the dielectric losses compared to the regular microstrip lines.

Finally, two SIW structures were also considered during comparison. One of these SIW structures is the conventional dielectric filled (Rogers-5880 SIW). The other SIW structure is the air-filled structure, where the dielectric part of the substrate has been removed to allow field propagation in the air which results in a reduction of the dielectric losses in SIW structures.

III. ANTENNA DESIGNS

The design of gap waveguide based antennas at 60 GHz have been focused mainly on high-gain antennas, above 32 dBi gain values, typically composed of 16×16 radiating elements, with an aperture efficiency of more than 70%. Compared to similar antennas implemented in other technologies, such as SIW or LTCC (Low Temperature Co-fired Ceramic), the 60 GHz gap waveguide arrays provide a higher gain and efficiency. A detailed comparative table of different 60GHz antennas is presented in [7]. Gap waveguide designs are based on the use of arrays of aperture antennas (either slots, horns or open cavities) which are fed by corporate networks made in one of the versions of gap waveguide technology, i.e., inverted microstrip, ridge, groove or a combination of them. All these antenna designs use several layers (bottom layers for the feed network dividing the power, and a top layer for the radiators and polarizers). The design of compact feed networks is challenging as in this technology the field propagates in air and consequently the dimensions of the power dividers are big.

A. Feed network designs

In the existing feed networks designed in gap waveguide technology, two main strategies have been used. The first strategy consists of using two layers for the division of the power and energy coupling to the radiating elements. From the bottom up, there is a first layer where a corporate feed network is located (typically achieving a 1 to 16 or 1 to 64 power division). On top of it, there is a coupling layer that also does a second level of power distribution to the radiating elements. The radiating elements are usually rectangular or circular apertures that constitute the third (top) layer. The main reason for using two layers for the power division lies on the size of power dividers, not being compact enough to

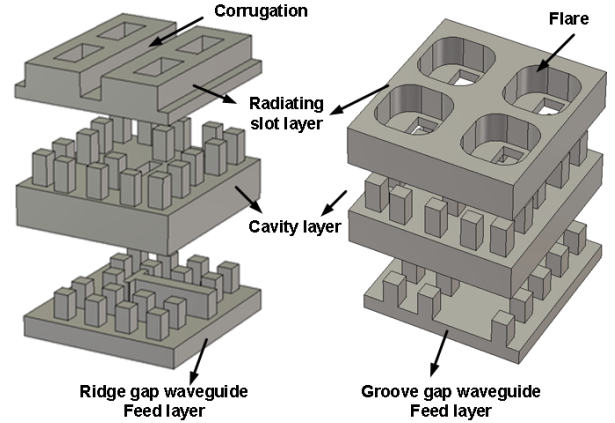


Fig. 4. Two different implementations for the unit cell of an array designed with gap waveguide technology. The one on the left, fed by ridge gap waveguide and corrugations on the top. The one on the right fed by groove version and flares in the radiating layer. The intermediate coupling cavity layer implemented in groove can be seen in the two examples.

locate the radiating elements at a distance less than λ_0 (being λ_0 the free space wavelength) to avoid grating lobes. As a consequence, part of the power division is made vertically using the mentioned second coupling layer. The energy is coupled from one layer to the one on top by using rectangular opening or slots. That intermediate layer (named “cavity layer” in Fig. 4) distributes the energy coupled from the bottom equally to the four radiating elements (2×2) using a cavity made in groove gap waveguide technology. Two examples of implementations of the unit cell of these arrays with the described philosophy are shown in Fig. 4. The four versions of the technology presented in Fig. 2 have been explored to design the feed layer. The antenna group at Chalmers University of Technology has recently investigated this type of corporate-feed networks [8], [9]. Two examples of antennas using this type of topology are presented in Fig. 5 with the only difference in the bottom feed layer that is made in groove and ridge respectively.

The second strategy consists on eliminating the intermediate coupling (cavity) layer in order to obtain antennas with even lower profile, made of just the feed layer and the radiating layer. Currently, there are just a few examples of antennas that have succeeded in omitting this intermediate coupling layer. One successful example is presented in [3] where a planar

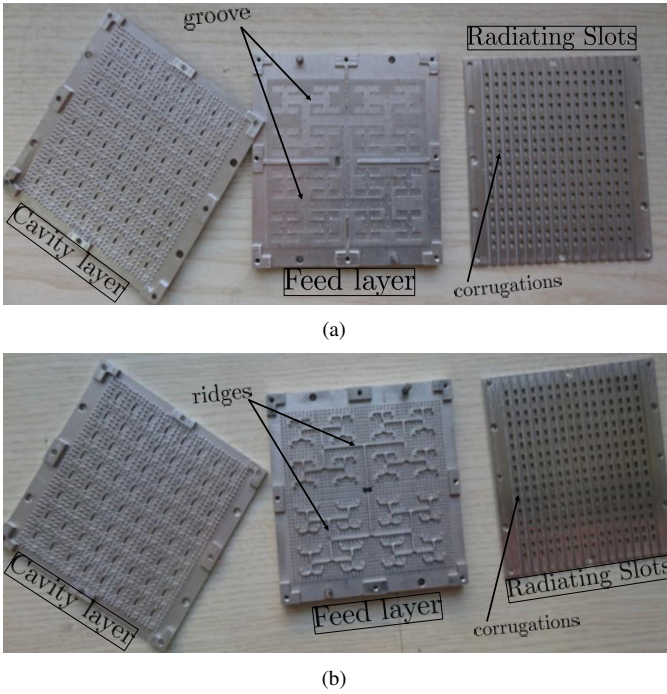


Fig. 5. 16×16 V-band arrays using Gap Waveguide. (a) Feed layer using H-plane power dividers with grooves [7], and (b) feed layer using ridges [8].

dual-mode horn array is fed directly by an inverted microstrip gap feeding network. Another effective feeding procedure for slotted waveguide arrays has been demonstrated in [10]. In that design, the slots are fed through a corporate feed network designed in groove gap version with E-plane splitters. The cavity that distributes the power to the groups of four radiating elements is made in coaxial version and integrated in the same layer used to host the groove feed network. Finally, the combination of ridge and groove version in the same layer is the basis of a recently proposed single layer solution [11]. This demonstrates the versatility of this technology and how there is still room for new contributions.

B. Aperture designs

Among the three options for the aperture design (the radiating layer), the two that have been mainly developed so far in the context of arrays fed by gap waveguides are rectangular slots and horns. In both cases linear polarization has been considered.

As a general rule, slot arrays must exhibit an inter-element spacing lower than $0.9\lambda_0$ in a rectangular lattice, which forces a corporate distribution network reaching a large number of slots within a compact area. As explained above, the development of corporate distribution networks for array feeding is not a simple task. The first strategy resorts to a second layer in which one slot feeds 4 cavities. Each cavity is, in turn, feeding a radiating slot. These radiating slots are placed on a thin metal plate that can give some problems in fabrication and assembling process degrading the aperture efficiency if the plate is not totally flat. To overcome this problem one option is to add corrugations in the radiating layer. Some successful examples of 16×16 V-band arrays with

corrugations in their radiating layer were presented in [8] and [7]. The corrugations work as a soft surface, thereby stopping waves from coupling into the neighboring slots and increasing the aperture efficiency. At the same time they make the radiating layer thicker and more robust to avoid potential bending.

When using conventional waveguides, such multilayer structures encounter known problems due to the needed good electrical contact between layers, otherwise causing a significant unwanted field leakage. Gap waveguides prevent this undesired effect, thanks to the inherent advantages of this technology already explained before.

On the other hand, horn arrays may be a good solution since their element size can be larger than one wavelength, reducing the complexity of the feed network. As a consequence, the intermediate coupling layer is not needed (in fact, the first designed antenna in gap waveguide technology was made using horns [3]). The main inconvenience of horns is the higher thickness of the overall structure. As previously stated, the final objective of reducing the number of layers is precisely to decrease the profile. One additional drawback accounts for the non-uniform nature of the field in the horn's aperture that can decrease the aperture efficiency.

As mentioned, there is a third option for the radiating element that is under development and it is the use of open circular cavities as radiating elements. A first approximation to this idea has been implemented to feed a dual polarized antenna as presented in [12].

All the presented examples are designed with the multi-layer approach, being the key aspect of gap waveguide technology that the assembling of the layers does not need to guarantee good electrical contact afterwards. This constitutes the main advantage when compared with other existing solutions.

IV. MILLIMETER WAVE COMPONENTS

The proposed technology can be used to design complete front-ends for millimeter wave applications. Up to now, most of the focus has been devoted to the design of passive components such as filters [13] and diplexers, power dividers and hybrid couplers. When designing these components, the design philosophy is similar to the equivalent when designing them in either conventional printed or rectangular waveguide technology. The advantages come from the low losses studied in section 3 but also with the manufacturing in two pieces that does not require afterwards any good metal contact. On the other hand this technology is always packaged.

Mechanically flexible narrow-band diplexer is a very critical component in a full duplex communication wireless link. There is a need for developing new types of high Q filters which are more robust in terms of mechanical assembly and can be integrated with other modules of passive components such as antennas. The groove gap waveguide based on high Q filters can be of interest in this case. These high Q filters can be built in an open parallel plate structure surrounded by periodic metal pins without any side walls. This opens up the possibility of placing the diplexer filter in an integrated module together with RF electronics and even with the antennas.

Several narrow band filters and diplexers have been designed so far at different frequency ranges. Several coupling mechanisms for achieving the required coupling between two adjacent resonators have been also studied. The electrical performances of the gap waveguide filters are very similar to the standard rectangular waveguide based filters. As an example, a 7th order groove gap waveguide based cavity filter working at 38 GHz has only 1.5 dB insertion losses when the prototype is milled in aluminium [3]. Another example in V-band designed with inverted microstrip version can be found in [13].

Also, one of the key aspects of this technology is its flexibility to be integrated with all kind of RF electronic components. In this sense a recent article about the integration of an amplifier with the ridge version is a first step to the future development of complete front-ends in gap waveguide technology [14]. The packaging implicit in the technology has evident advantages when dealing with active components. The newly proposed gap waveguide based packaging is very suitable for creating high isolation among different critical components within an RF module which helps to suppress the commonly known oscillation problems and cross-talk problems [15], [3].

V. CONCLUSIONS

An overview of the emerging technology known as gap waveguide is presented in this article to demonstrate its potential for millimeter wave RF applications. A study of the losses of the different versions of this technology has been presented together with the comparison with reference technologies such as rectangular waveguide or printed circuit based transmission lines. Directive antennas at 60 GHz for the future 5G communication systems have been designed with different approaches using different versions of this technology. All the designs have either two or three metal layers but they can be assembled together with simple screws because good electrical contact among these metal layers is not required at all. This flexible mechanical feature, the low loss performance and the easiness to design all the critical RF components of the front-end in the same technology (that includes also inherent packaging) makes gap waveguide technology as one of the candidates for future antenna systems and RF front-ends in the millimeter wave frequency range.

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