New waveguide technology for antennas and circuits

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Abstract

This review paper describes a new type of metamaterial-based quasi-TEM waveguiding device. The transmission line is based on the principle that combining two parallel plates, one being a perfect electric conductor and the other a perfect magnetic conductor, provides a stop band area between them as long as the separation between plates is less than a quarter wavelength. In that scenario, metallic inclusions such as strips, ridges or grooves open a propagation path in the gap between the inclusion and the metallic conductor and at the same time fields remain confined without resorting to vertical walls. The paper explains this concept in detail; it describes its advantages and shows several application examples and experimental demonstrations.

Keywords Gap waveguides, metamaterial-based waveguides, hard surfaces, microwave circuits, millimeter-wave antennas, slot arrays, waveguide slot arrays.

1. Introduction

An increasing demand of applications at the millimeter- and submillimeter-wave bands is expected to be imminent. There are already some applications working at these frequencies, but they suffer from the limitations of the existing technologies. There is then a real need for new waveguide technologies which are more appropriate for high frequency applications. This paper presents two new topologies of guiding structures, which are especially suitable in many respects for frequencies over 30 GHz, stressing their properties and giving a physical insight. Their application to antennas and circuits is also shown through preliminary designs, some of which have already been validated experimentally.

Our first incursion in the study and research of new waveguides for high frequencies is caused by the difficulties found in the manufacturing of waveguide slot arrays for steerable antennas at frequencies over 30 GHz. One of the most common ways of feeding slot arrays is by means of a group of juxtaposed monomode rectangular waveguides. This solution is generally adopted for antennas requiring control of the beam steering. However, it presents serious problems in the manufacturing process derived from the physical constraints imposed by the design itself to meet antenna specifications. As it is well-known, from array theory, elements spacing must not exceed a maximum distance to avoid grating lobes. This maximum distance is even smaller when the radiated beam is scanned. On the other hand, rectangular waveguides cannot be as narrow as desired because they could be below cut-off. Both requirements force the waveguides to work close to the cut-off frequency, where losses at sidewalls are higher, especially at the millimeter- and submillimeter-bands, and make also the internal walls to be very thin, what means that a milling technique could be not the most suitable one for the fabrication. Besides, these waveguide slot arrays are usually made in two

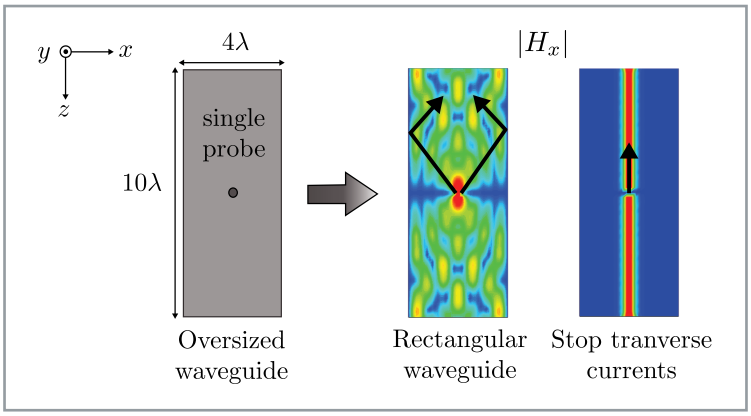


Figure 1. *Top view of an oversized rectangular waveguide excited by a single probe. Magnitude of the transverse x-component of the magnetic field inside this waveguide and also in case of transverse currents stopped.*

parts, the bottom part consisting of a groove surface, and the top part which is a metal plate containing the radiating slots. Both parts have to be joined together later assuring a good electrical contact at joints. The previous drawback added to the fact that the plate is never completely flat, presenting protrusions and irregularities, lead to a difficult manufacturing process which increases the final cost of making these antennas, only affordable for military applications.

Several attempts have been made at the Tokio Institute of Technology to solve the junction problem. One proposal consists of alternating phase-fed waveguides, where adjacent waveguides are fed with opposite phase. The net current at joints is zero, therefore a perfect electric contact is not required. Other solution was based on oversized waveguides, electrically wide, fed by a quasi-TEM wave. However, it is a narrow band solution and not valid at all for phase-scanning.

For the purpose of devising a low-cost solution to feed slot arrays, the first idea was to use an oversized rectangular waveguide, i.e., a waveguide that is much wider than the standard monomode ones. But now, some kind of material or periodic structure should be added to the waveguide in order to modify its propagation properties in such a way that this waveguide emulates the behavior of a collection of juxtaposed monomode rectangular waveguides. This new structure should be simpler from the manufacturing point of view.

Oversized rectangular waveguides can support a multiplicity of modes, each one with its own propagation constant. By a proper combination of TE modes it is possible to generate a uniform quasi-TEM mode [1]-[2], but its inherent dispersive behavior makes this quasi-TEM propagation very narrowband. As it is well-known, each TE mode in a waveguide can be seen as the result of the interference between two waves impinging and reflecting successively from both sidewalls with a particular angle of incidence [3]. Thus, it is easy to glimpse that if transverse currents are stopped so that only longitudinal currents can flow along the waveguide, then the two plane waves which form each of the TE modes are forced to change their propagation directions to the longitudinal direction of the waveguide (see Fig. 1). Thereby, only plane waves parallel to the longitudinal direction are allowed. In other words, any kind of propagation is suppressed except for the TEM-like one.

The previous reasoning leads us to try to find out a waveguide in which propagation in the transverse direction is inhibited while it is favored in the longitudinal direction. As a result, the Single Hard Wall Waveguide (SHWW) comes up [4]-[6]. The waveguide is comprised of a conducting upper face and a hard surface [7] as the lower face. The gap between these two faces, d, must not be higher than a quarter wavelength. The waveguide can be as many wavelengths wide as desired and its left and right sides can be left open since walls are not required to support the modes. Nevertheless, conducting sidewalls may be used, closing the waveguide to assure rigidity of the whole structure, as sketched in Fig. 2.

Single hard wall waveguides are a new type of waveguides that are able to propagate a plurality of degenerate independent quasi-TEM modes within the same waveguide. Each of these local modes would be excited by its own source (see Fig. 3). The waveguide does not require vertical walls to isolate these parallel modes from each other since they experience a strong transverse attenuation. This property makes the waveguide very attractive for applications over 30 GHz. In particular, those applications requiring multiple rectangular waveguides, like planar slot array antennas or slotted waveguide power amplifiers, can benefit from this type of waveguiding structure.

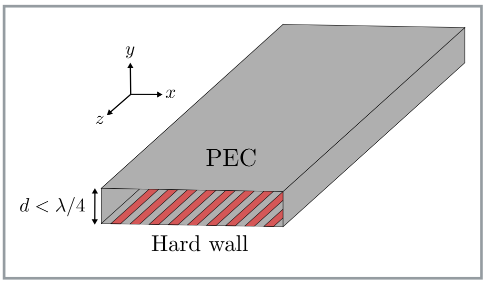


Figure 2. *Sketch of a Single Hard Wall Waveguide (SHWW).*

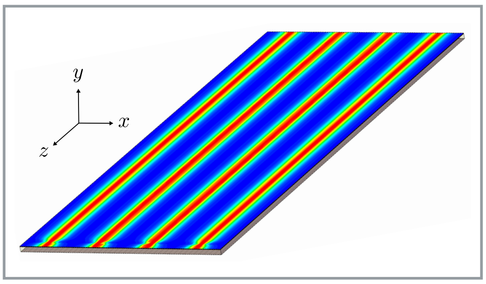
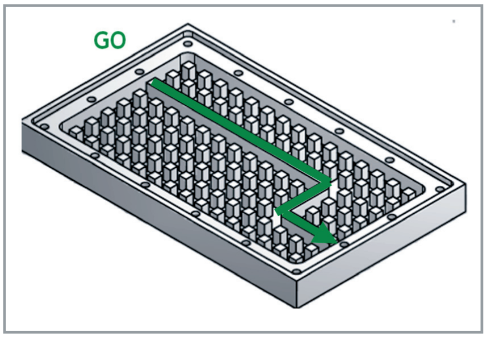


Figure 3. *Four local quasi-TEM waves excited by four probes within a SHWW.*

This idea has been later improved so that the waves are no longer constrained to follow straight paths, as shown in Fig. 4. The wave follows in the gap between a conducting ridge and the metallic upper face because the ridge is surrounded by artificial PMC surfaces on both sides, e.g., in the form of a bed of nails [8], i.e., a surface formed by metal pins standing on a ground plane. The bed of nails is more effective than the grooves when the ridge supporting the wave has to split, bend, make a corner, etc. Therefore, this other new type of waveguide, so-called Ridge Gap Waveguide (RGW) [9]-[11], is especially suitable to make millimeter- and submillimeter-wave circuits and components.



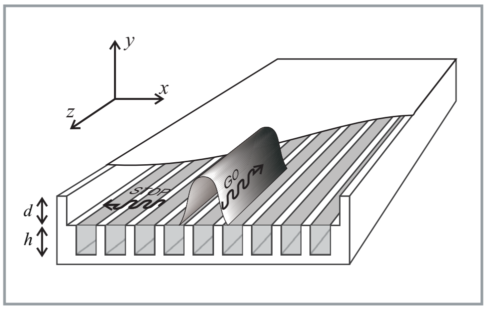
■ **Figure 4.** *Bottom part of a circuit in Ridge Gap Waveguide (RGW).*

2. Single hard wall waveguides

2.1. Propagation properties

Propagation in hollow waveguides is generally described in terms of eigenmodes. As it is well-known, the collection of eigenmodes that can propagate depends on the waveguide cross-section and the working frequency. Let us refer to the eigenmodes as global waves to emphasize the fact that these solutions of Helmholtz's wave equation extend to the whole cross-section of the waveguide. Let us now introduce local waves. Local waves, unlike global waves, would be field solutions that propagate in a highly confined fashion, using mainly a certain portion of the waveguide cross-section. Certainly these waves are the result of a linear combination of eigenmodes and extend also to the whole waveguide cross-section, but they are negligible for most part of it [12]. Consequently, if we consider an electrically wide waveguide, several of these local waves could share the same waveguide using different portions of the waveguide cross-section without resorting to walls to keep them separated [13]. Single hard wall waveguides have such a particular property; thereby it is possible to propagate multiple local waves within the same waveguide, as shown in Fig. 3. These waves may show some degree of overlapping depending on the spacing between them, but beyond a given separation they can be considered independent. To drive waves locally, the waveguide is formed in the gap between a conducting plate and a hard surface.

Artificially soft and hard surfaces in electromagnetics are realized by corrugations or by metal strips loading a grounded substrate [14] (see Fig. 5). Such surfaces make use of surface resonances owing to the depths of the grooves, appearing for depths of , where is the effective permittivity of the dielectric material, which is for corrugated soft surfaces and for the hard surface. In the soft case, corrugations are oriented transversely to the propagation and they form so-called electric and magnetic current fences that stop the waves. On the contrary, in the hard case, corrugations form electric and magnetic current lines that support wave propagation. Actually, the corrugated surface used in this waveguide must act simultaneously as a hard surface in the direction of propagation and as a soft surface in the transverse direction. Yet the name given to the waveguide, single hard wall waveguide, put the emphasis on type of surface in the propagation direction.



■ **Figure 5.** *Single hard wall waveguide made up of dielectric-filled corrugations. A sketch of the quasi-TEM wave is also shown.*

From the description above, it might be drawn that the conducting plate on top plays a secondary role, since all the guiding seems to be done by the corrugated surface. However, the truth is that the height of the gap left between the plate and the hard surface decisively contributes to keep waves bounded despite the absence of walls. Indeed the plate must be less than a quarter wavelength above the hard surface to achieve the desired effect. To better understand this effect we should look at the ideal model of a hard surface. Ideally, a hard surface can be seen as a grid of parallel strips where every second strip is a perfect electric conductor (PEC) and a perfect magnetic conductor (PMC), respectively [15]. It can be easily shown that by placing the metallic upper face not higher than a quarter wavelength from the hard surface, propagation in any direction other than the longitudinal one is stopped. A PEC strip combined with the PEC plate above forms a transmission line. On the contrary, when a wave encounters a PEC on the upper plate and a PMC strip on the lower, it can barely trespass it for the given gap height. After crossing a few of these PEC/PMC strips in the transverse direction, the wave is deeply attenuated, producing a confined wave propagating only in the longitudinal direction as depicted in Fig. 5.

There is a real need for new waveguide technologies which are more appropriate for high frequency applications.

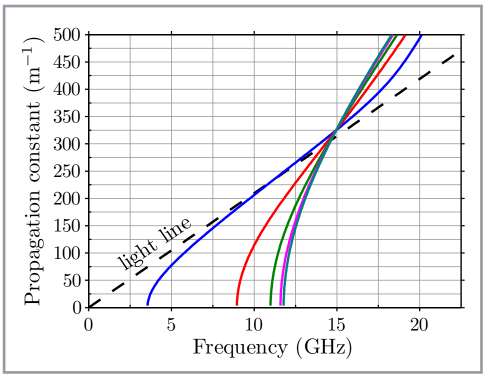


Figure 6. *Dispersion diagram in the hard direction of a SHWW with a groove-filling material of εr=4. Groove depth is h = 2.95 mm, edge width s = 1 mm, corrugation period p = 3 mm. The gap between the corrugated surface and the PEC plate on top is d = 2 mm.*

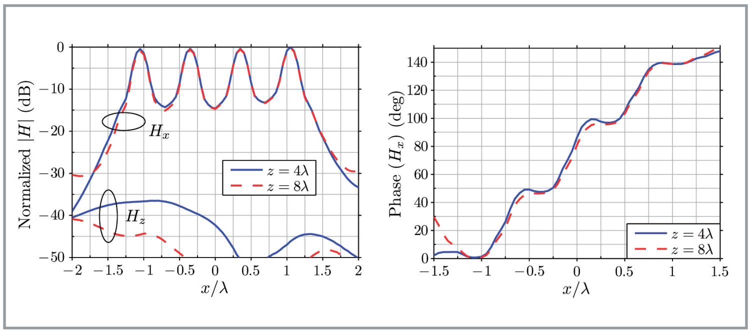


Figure 7. *Magnetic field produced by four probes fed with uniform magnitude and a linear phase of 45º. Two transverse cuts, at 4λ and 8λ away from the source, are shown.*

It is worth noticing that the corrugated surface should not be seen as a mere choke to the transverse propagation. If that was the case, deep, air-filled grooves could have been used. The fact is that air-filled grooves do not work and the reason was stated above: the corrugated surface must be simultaneously soft and hard. In other words, the frequency band for which the corrugated surface functions in hard mode coincides with the soft mode band of the surface, and that only happens when grooves are filled with a dielectric material.

Additional understanding comes from the observation of the dispersion diagram obtained for the hard direction of a single hard wall waveguide with metal sidewalls (Fig. 6).

A set of quasi-TEM eigenmodes can be seen. At the intersection point, all the eigenmodes share the same phase velocity, and the propagation constant is almost that one of light in vacuum. That point establishes the hard condition. As explained above, local waves are obtained at this point as a linear combination of these eigenmodes. Interestingly, when corrugations are air-filled there is no intersection point. Therefore eigenmodes have different phase velocities and the sought local wave cannot be obtained. Simultaneously, a wide stopband exists in the soft direction around the frequency where the hard condition holds. As a result, fields excited by a given local source are forced to propagate locally in the corrugations direction, which means that inner walls are not required to isolate waves. Thereby, the manufacturing process of planar slot array antennas can be greatly simplified if we can avoid the walls between the waveguides, which become increasingly thinner as we go above 30 GHz.

The presence of four local quasi-TEM waves sharing the waveguide cross-section is shown in Fig. 7. These waves are excited by four source probes fed with a uniform magnitude and a linear phase of 45º. The probes are equally spaced apart 0.7λ, a typical spacing between rows of slots in slot arrays to avoid grating lobes. Four independent quasi-TEM waves can be observed. It is worth recalling that, unlike a parallel plate waveguide, where a linear phase-front would inevitably lead to linear amplitude patterns in transverse cuts, the single hard wall waveguide amplitude pattern seen in Fig. 7a remains uniform. The preservation of the phase profile is also shown in Fig. 7b.

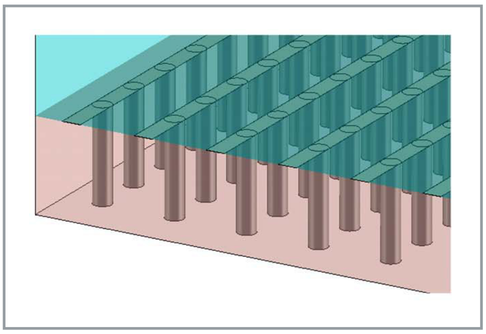
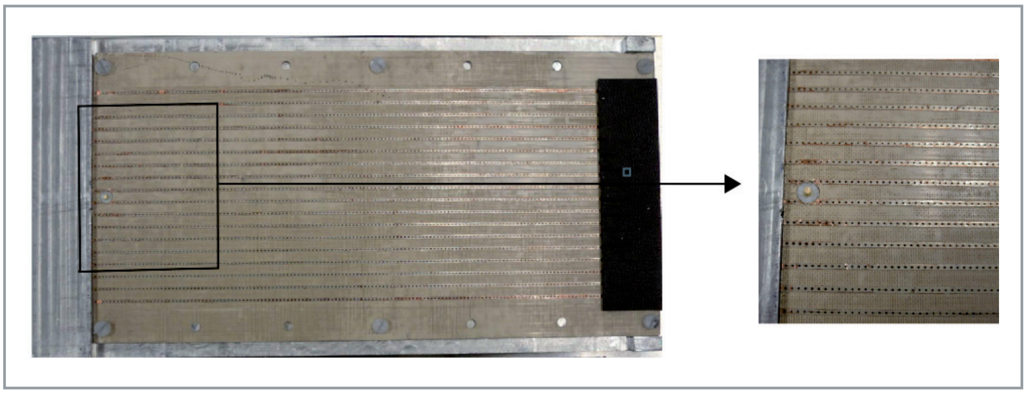


Figure 8. *Drawing of the hard surface consisting of narrow strips and via-holes connecting the strips to the ground plane.*

2.2. Experimental demonstration

A practical realization has been manufactured and measured to show the remarkable properties observed previously in simulations. As stated above, longitudinal grooves must be filled with a dielectric material of permittivity , in order to work as a hard surface, and the groove depth should be approximately at the working frequency. From a manufacturing point of view, it is easier to construct the edges between corrugations by perforating a copper-clad laminate with a series of via-holes than machining a corrugated surface and filling the grooves up with the desired material (see Fig. 8). This is the procedure followed here to construct the hard surface at the expense of experiencing some deviation from the expected theoretical performance of a corrugated hard surface.

Fig. 9 shows the hard surface made out of metallic strips etched on a copper-clad laminate, and via-holes connecting the strips to the ground plane. A detail of the hard surface is also shown

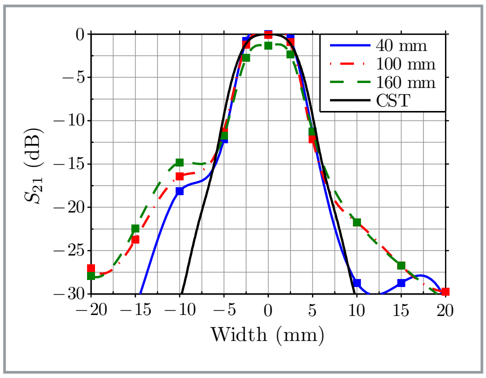


■ **Figure 9.** *Hard surface made out of etched copper strips and plated via-holes on a PCB. Detail showing the coaxial probe.*

Gap waveguide are advantageous relative to existing high-frequency transmission lines, in terms of losses, cost, bandwidth, packaging and integration.

in the picture where the coaxial probe used to feed the waveguide can also be seen. The probe is placed a quarter wavelength away from the short-circuit.

A conducting surface is 2 mm above the hard surface. The waveguide is short-circuited at 5 mm from the receiving probe and terminated with an absorbing material. Both, left and right sides are left open. The electric field pattern was measured in the waveguide section at a given frequency. Cuts measured at several sections along the waveguide will show divergence of the local wave. Fig. 10 shows the patterns obtained for three cuts taken at 40, 100, and 160mm (2λ, 5λ, and 10λ) away from the source in longitudinal direction. Samples were taken at the points shown with symbols. The field obtained from simulations on a SHWW whose hard surface use continuous grooves is also shown for reference. As can be seen, the pattern is very well preserved with distance. The beam is certainly very narrow: levels are more than 10 dB below the maximum 5 mm (λ/4) away from it. All values are normalized with respect to the first cut maximum.



■ **Figure 10.** *S21 parameter measured for three transverse cuts taken at 40, 100, and 160mm (2λ, 5λ, and 10λ) away from the source in longitudinal direction. A CST simulation is shown for reference.*

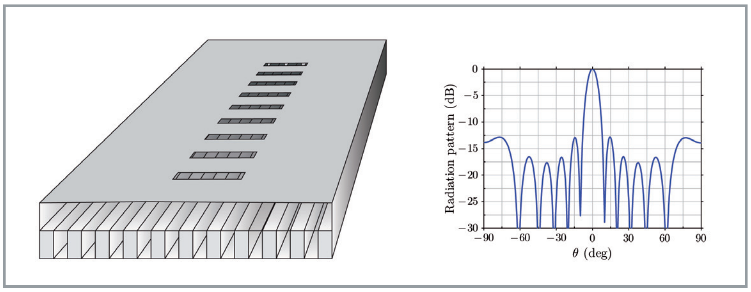
2.3. Application to slot array antennas

The capability of a SHWW to channel several independent local quasi-TEM waves lend it a promising potential to feed slot arrays, especially antennas for millimeter- and submillimiter-wave frequencies requiring control of the beam steering, for instance for satellite mobile communications.

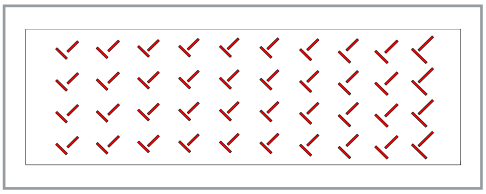
A preliminary design of a 1-D slot array on a SHWW for linear polarization is shown in Fig. 11. Eight transverse slots excited by a single probe are considered. The waveguide is filled with a dielectric material of permittivity 1.5 to reduce grating lobes. Slots are equally spaced apart one waveguide wavelength (λg). The radiation pattern pointing at broadside direction can be seen.

A complete design of a circularly polarized 2-D array was done. Given that the unique propagation allowed inside a SHW-waveguide is of quasi-TEM type, circularly-polarized waves can be generated by a radiating element constituted by a pair of slots oriented at ±45º which are λg/4 apart. First, a row of slots, i.e. a 1-D array, was designed. Later, the 2-D array was obtained just by replicating that row of slots. This was possible due to the insignificant mutual coupling among rows of slots on a SHWW, unlike an oversized rectangular waveguide where the coupling among rows of slots cannot be neglected.

For the 1-D array design, an optimization process is always needed to fulfill antenna specifications. Magnitude and phase of the array elements must be tuned up by adjusting element position and slot length. In our case, the design is broadside and for maximum efficiency. Besides, position of each slot of a pair must be adjusted to get circular polarization. The algorithm

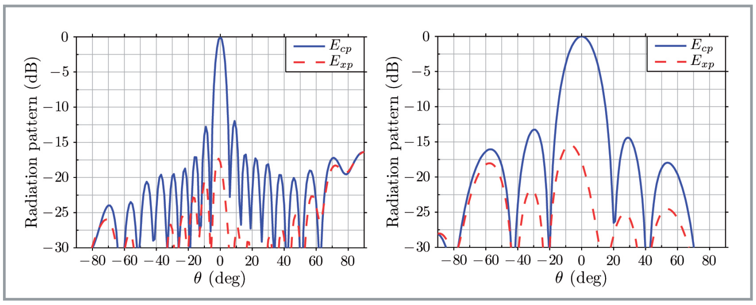


■ **Figure 11.** *8-element linear array of transverse slots on a SHWW: (a) sketch, (b) simulated radiation pattern.*



■ **Figure 12.** *Sketch of a circularly polarized 2-D slot array of 4 × 10 elements.*

proceeds in an iterative fashion adjusting location and size of the slots to accomplish desired magnitude and phase of the fields radiated by the array elements. The iterative procedure ends when a convergence criterion is reached. Once the 1-D array has been obtained, it is replicated to give the 2-D array of Fig. 12. Rows are 0.75λ equally spaced apart to avoid grating lobes. Two cuts of the radiation pattern in longitudinal and transverse directions are shown in Fig. 13.



■ **Figure 13.** *Radiation pattern of the circularly polarized 2-D slot array: (a) longitudinal cut, (b) transverse cut.*

3. Ridge gap waveguides

3.1. Structure and operation

The single hard wall waveguide (SHWW) was originally conceived to feed a slot array. The SHWW consists of an oversized rectangular metal waveguide or parallel-plate waveguide with the bottom metal plate replaced by a hard surface. Another interpretation of using a hard surface as the bottom surface comes from the observation of how fields propagate within a parallel-plate waveguide (PPW) (see Fig. 14). On the one hand, a vertical electric field propagates freely between two parallel metal plates or PEC plates regardless of the distance between them. On the other, all modes are below cut-off between a PEC plate and a PMC plate provided the distance between the plates is smaller than λ/4. Thus, by using a hard surface (ideally, a PEC/PMC strip grating) and a parallel PEC plate separated by an air gap smaller than λ/4, it is possible to combine both performances depending on the direction of propagation, so that this waveguide works like a PEC-over-PEC PPW in the longitudinal direction, favoring vertically polarized waves, whereas it works like a PEC-over-PMC PPW (with h<λ/4) in the direction transverse to the strips suppressing any kind of propagation.

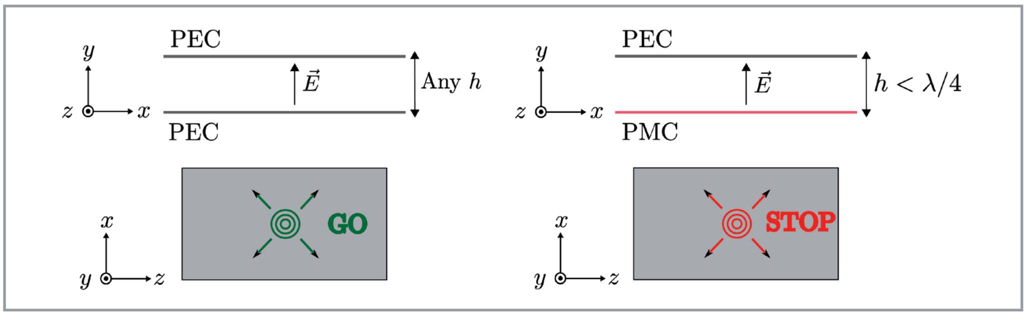
The previous idea was also inspiration for a new metamaterial-based waveguide technology especially appropriate for millimeter and sub-millimeter waves. This new technology, so-called ridge gap waveguide (RGW), was first introduced in [9]-[11]. This waveguide is made between two parallel metal plates. One of them is made of a texture to create a high impedance condition at the surface (ideally, a PMC boundary), and therefore to impose a cut-off for the parallel-plate modes. In between the textured plate, there is a metal ridge to guide the wave along a particular path. Thereby, the waveguide is formed in the gap between the ridge and the metal plate on top, as illustrated in Fig. 15.

Both waveguiding structures, the SHWW and the RGW, can guide local quasi-TEM waves. However, the waves are forced to follow straight paths within the SHWW since they must go parallel to the corrugations. Whereas, for the RGW the waves have to follow metal ridges, which can bend, split, make corners, etc. Therefore, the RGW is a more versatile structure than the SHWW to make high-frequency circuits.

The key factors of this new waveguide technology can be enumerated as follows:

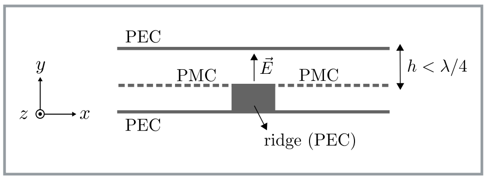
- low losses, since gap waveguides do not require dielectrics and they can be completely realized with metal,
- low cost, as there is no need for any conducting joint between the two plates, what makes the manufacturing easier,
- large bandwidth, indeed a bandwidth larger than one octave appears to be feasible [16],
- no packaging trouble, because gap waveguides can be designed to be completely enclosed, without the presence of cavity modes, which also makes it an attractive packaging technology for microstrip circuits [17],
- easy integration of active components like amplifiers and MMICs because shielding and packaging are more or less automatically provided by the gap waveguide itself.

All these factors make the gap waveguide advantageous relative to existing high-frequency transmission lines, such as microstrip or coplanar waveguides, and hollow metal waveguides. On one hand, microstrip or coplanar waveguides need dielectrics and in consequence suffer from losses with increasing frequency; they have limited power handling capability, and spurious resonances when encapsulated. On the other, conventional hollow waveguides are realized in two parts which have to be joined together, what increases its manufacturing cost, especially at high frequencies when the sidewalls become thinner and thinner. Thus, this new technology seems



■ **Figure 14.** *Field propagation in (a) PEC-over-PEC PPW, (b) PEC-over-PMC PPW.*

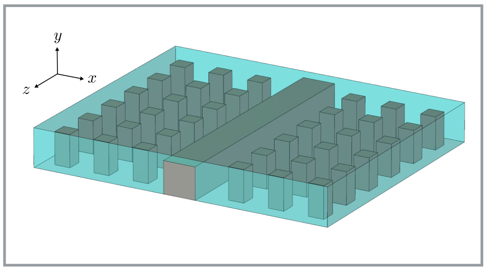
to be an interesting transmission line for realizing components and circuits from a frequency around 30 GHz, when the current technologies already exhibit some deficiencies, up to 100 GHz. The basic geometry of the ridge gap waveguide comprises two parallel conducting surfaces. One of the surfaces is provided with a texture that is used to realize conducting ridges surrounded by a high impedance surface. The new waveguide is located in the gap between metal surfaces. The gap is usually filled with air, but it can also be dielectric-filled, and its size should be smaller than λ/4. The textured surface stops waves in all directions (provided the waveguide height is low enough) in such a way that the waves have to follow the metal ridges.



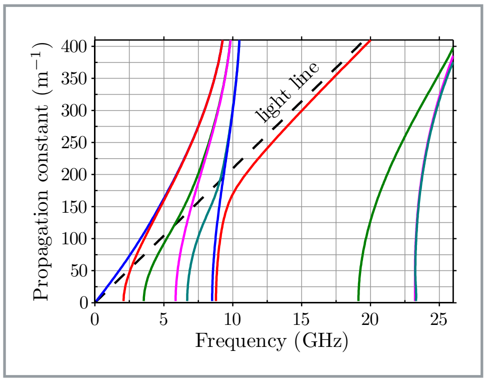
■ **Figure 15.** *Cross section of a canonical ridge gap waveguide, with a ridge surrounded by a high impedance surface.*

A metal parallel-plate waveguide with h<λ/2 can only guide vertically polarized TEM waves in any direction without any low-frequency cut-off. These TEM waves span throughout the whole waveguide, thus they are global parallel-plate modes. Whereas, the quasi-TEM waves of a ridge gap waveguide are local waves following one ridge. If the global parallel-plate modes are present in this waveguide, they will destroy the local gap waveguide performance completely. Therefore, it is crucial for the performance of the ridge gap waveguide that all kinds of global parallel-plate modes are prohibited from propagating. This is achieved by texturing the metal surface on both sides of the ridge in such a way that it gets high surface impedance and provides cut-off for the global parallel-plate modes within a certain frequency band. A bed of nails or a Fakir's bed has been chosen to realize the high impedance surface because it can mimic an ideal impedance boundary [8]. This bed of nails is formed by metal pins standing vertically over a ground plane (see Fig. 16). The depth or height of the pins should be approximately λ/4 to transform the ground plane (PEC plate) to a high impedance surface (ideally, a PMC plate).

The characteristics of the ridge gap waveguide can be seen from its dispersion diagram. The diagram shows a set of rectangular waveguide type modes appearing below 10 GHz. They have a lower cut-off similar to normal rectangular waveguide modes, but go into a stopband at 10 GHz approximately, and appear again at the end of this stopband, around 20 GHz. Inside the whole stopband there is only one mode very close to the light line. This is the desired local quasi-TEM mode following one ridge. Therefore, it can be stated that the bandwidth of the ridge gap waveguide, i.e. the frequency band where the waveguide works as expected, is nearly the unimodal band within which only one quasi-TEM mode is present.



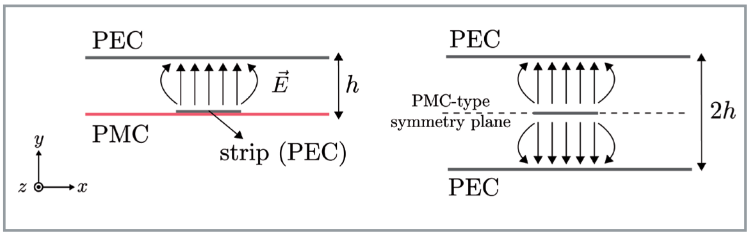
■ **Figure 16.** *Geometry of the ridge gap waveguide in bed of nails.*



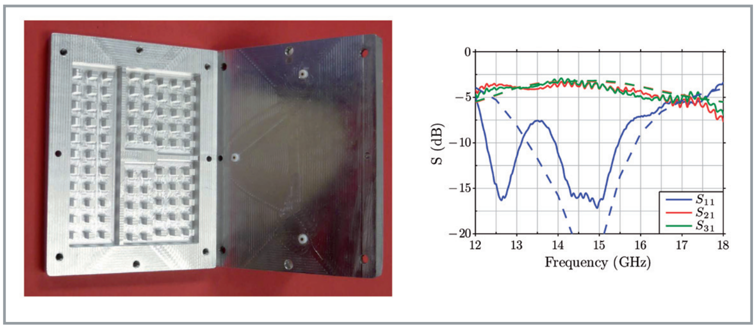
■ **Figure 17.** *Dispersion diagram in the ridge direction of a RGW in bed of nails.*

3.2. Application to microwave circuits

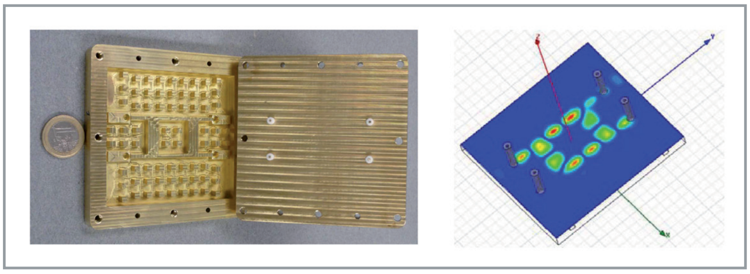
To be able to design circuits in a new waveguide technology is essential to characterize it as a transmission line and therefore to know its propagation constant and characteristic impedance. The similarity between the ideal model of a RGW and the stripline, as it is shown in Fig. 17, allow using the formulas for the characteristic impedance of the latest as a first approximation to the characteristic impedance of a RGW. It is easy to see that the gap waveguide is a sort of half stripline. Nevertheless, this approximation is not accurate enough for real cases, and we have to resort to numerical approaches as referred in [18].



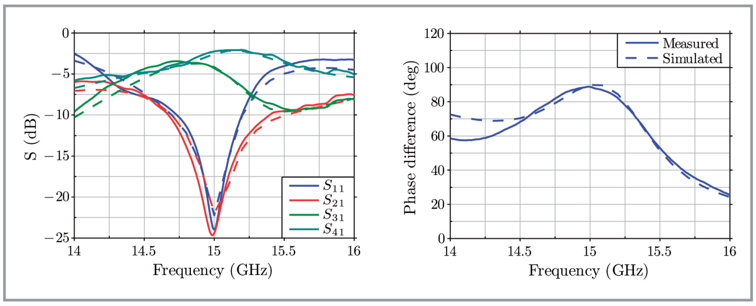
■ **Figure 18.** *(a) Ideal gap waveguide and (b) stripline models.*



■ **Figure 19.** *(a) Prototype of the power divider in RGW; (b) simulated (dashed lines) and measured (continuous lines) S parameters*



■ **Figure 20.** *(a) Prototype of the branch line coupler in RGW; (b) electric field at 15 GHz.*



■ **Figure 21.** *(a) Simulated (dashed lines) and measured (continuous lines) S parameters; (b) coupled branch phase difference.*

Once a RGW in bed of nails has been characterized, we can design circuits in RGW in the same way as we do it in microstrip technology, for instance. Some microwave circuits in ridge gap waveguide technology, in particular a power splitter and a coupler have been designed, manufactured and measured. Numerical results as well as measurements demonstrate good performance within a wide frequency band. Even though this technology is particularly interesting for millimeter and submillimeter-wave bands, initial developments have been done in the microwave band for the sake of simplicity during the manufacturing stage.

- A power divider at 15 GHz was designed and manufactured. Fig. 18a shows the manufactured prototype. Measurements were made with a Network Analyzer using an APC-3.5mm calibration kit. Good agreement between HFSS simulations and measurements can be observed at 15 GHz in Fig. 18b. Return loss are lower than -15 dB while insertion loss is around 4 dB.

- A typical branch line coupler was designed at 15 GHz. Fig. 19a shows a photo of the constructed prototype. Fig. 19b shows simulated total electric field at the top of the ridge. The directional aptitude can be noted.

The magnitude of S parameters are shown in Fig. 21.a where a good agreement between simulations and measurements can be observed around 15 GHz. Return loss are lower than -24 dB at 15 GHz while insertion loss in the coupled branches are 2.2 dB and 4.2 dB. A bandwidth of 3% has been measured with a threshold of -10 dB in S11 parameter. In this bandwidth a phase difference between 81º and 89º has been measured, as it is shown in Fig. 21.b.

Some microwave circuits have been designed in ridge gap waveguide technology showing good performance not only in simulations but also in measurements. These circuits can be useful to design more complex circuits, like microwave filters and corporate feeding networks for array antennas, in future.

4. Conclusions

Gap waveguide technology is a promising proposal for easy integration of active and passive components and may eventually replace conventional packaging techniques. This technology is still in its infancy and has to go a long way to demonstrate its feasibility. Therefore, more work needs to be done regarding actual losses, transitions to other technologies and simplified models to ease circuit design. In this review paper, the physical principles and some experimental demonstrations have been provided.

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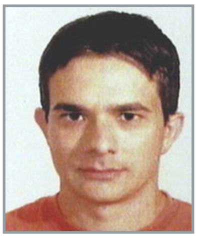

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