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Gap Waveguides and PMC Packaging: Octave Bandwidth mm- and submm-Wave Applications of Soft & Hard Surfaces, EBGs and AMCs

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***Abstract* — AMCs, EBGs and other surface-based metamaterials are known to have narrow bandwidths. However, when they are used to generate stopbands for parallel-plate modes, the bandwidth can be very large. This characteristic is used in the gap waveguide technology that was invented in 2008, based on old research on soft and hard surfaces. The gap waveguide technology can be used to package microstrip and CPW circuits, but can also with advantage replace such standard technologies and in particular above 30 GHz. The gap waveguides can have similar lowloss performance as solid rectangular waveguides, but they can be realized in a much better way. Rectangular waveguides are normally realized by split blocks which are screwed tightly together to ensure good conductive contact, whereas gap waveguides can be realized between parallel plates without metal connection. This paper overviews how the gap waveguide technology has been explored during the passed five years including: demonstrations of the wideband lowloss guiding characteristics up to 260 GHz, demonstrations of packaging in different frequency ranges with different AMCs or EBGs, and demonstrations of filters, transitions, MMIC packaging, corporate distribution networks, and slot and horn array antennas. The technology demonstrators cover the three different versions of gap waveguides: groove gap waveguide, ridge gap waveguides and microstrip gap waveguides.**

***Index Terms* — Gap waveguides, packaging, filters, millimeterwaves, submillimeterwaves, AMC, EBG, soft and hard surfaces, metamaterials.**

I. Introduction

The concept of soft and hard surfaces was introduced in 1988 [1] and 1990 [2], based on the characteristics of the corrugated surfaces used in corrugated horn antennas. The soft surface is related to the more common EBG surface appearing in the literature since year 2000, but it is an anisotropic and wideband version of it, stopping waves along the surface in one direction only. The hard surface was used to realize cloaking in 1997, referred to as reduction of forward scattering [3] or blockage reduction (and even superstealth in a conference paper). This is ten years before cloaking became a popular research topic. The relations between soft and hard surfaces and EBG surfaces and in particular artificial magnetic conductors was described in 2005 [4]. Actually, the soft and hard surfaces are ideally grids of parallel perfect electric conducting (PEC) and perfect magnetic conducting strips, i.e. PEC/PMC strip grids.

The gap waveguides were invented in 2008. The basic design was inspired by works on hard surfaces at Polytechnic University of Valencia (UPV) [5], and they also contributed to the first paper defining the concept [6]. The principle idea is to generate a stopband between two parallel plates, so that no parallel-plate modes can propagate, and then to introduce grooves or conductive ridges or metal strips along which waves can propagate. The stopband characteristics in other directions make the waves confined to the groove, ridge or strip. This also then defines the three different gap waveguides that exist: groove, ridge and microstrip gap waveguides (Figure 1).

The parallel-plate stopband can be realized in many ways, by many types of periodic elements. The easiest way to explain it is to let one plate be a PMC and the other a PEC. Then, no parallel-plate modes can propagate as long as the gap between then plates is smaller than quarter wavelength. When introducing PEC strips in the PMC surface, we get the gap waveguide transmission line. The high surface impedance of artificial magnetic conductors (AMCs) has normally very narrow bandwidth. Still, a stopband for parallel-plate modes can be easily realized over a significant octave 2:1 bandwidth. Some of the periodic elements used to design the stopband so far are studied in [7], but others have also been published. The surface with most potential in mm- and submm-wave region is made of periodic metal pins/posts(nails.

The rest of this paper overviews what we have developed so far.

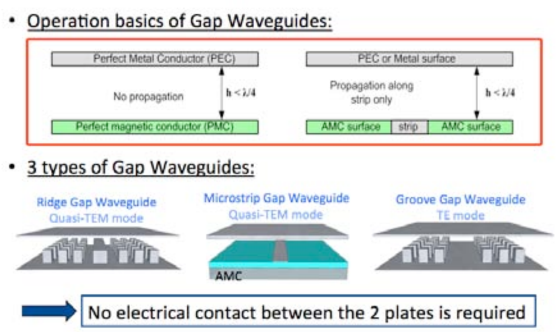

Figure 1. Illustration of the principle of operation of the gap waveguides (upper), and three different types of gap waveguides (lower). The AMC in the middle microstrip gap waveguide case can also be realized with pins like in the two other cases.

II. Demonstrations of low loss up to 260 GHz

The topologies of ridge and microstrip gap waveguide circuits are similar to that of microstrip circuits, but the losses are much lower. One reason is of course that there is no dielectric in the gap waveguide cases, but this does normally not make up more than 25% of the total loss as seen in Figure 2. The low loss is coming from the increased dimensions. Microstrip lines must be used on thin substrates in order to avoid surface waves and radiation, whereas in ridge and microstrip gap waveguides the airgap can be two and even four times larger without any similar problems, and this reduces the conductive losses from 4.5 dB/dm to 1 dB/dm, as seen in Figure 2, and there is no dielectric losses.

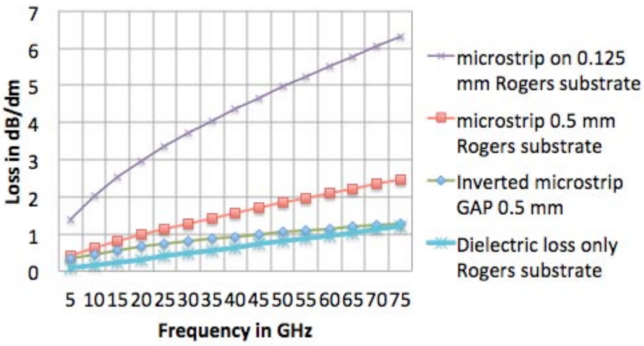

Figure 2. Graph showing the total losses in microstrip line on thin 0.125 mm lowloss substrate, thick 0.5 mm lowloss substrate, and for comparison the contribution only from dielectric losses, which is independent of substrate thickness and line widths. With ridge and microstrip gap waveguides we can use air gaps that are much larger than the substrate thickness without problems with surface waves or radiation, and thereby we can get losses of 1.0 dB/dm compared to 5.5 dB/dm for a microstrip circuit at 60 GHz.

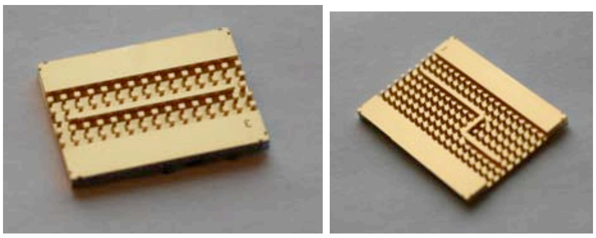

Figure 3. Gap waveguide resonator for measuring losses, and a demonstrator with two 90 deg bends, both realized for 100 GHz by micromachining on Gold-sputtered Silicon. Similar circuits exist at 260 GHz. The measured results confirm the theory.

Figure 4. Tx and Rx MMIC amplifier chains packaged by lid of nails. The configuration has also been built and measured.

The topology of groove gap waveguide components is similar to that of rectangular waveguide components. We have also shown that the losses of the groove gap waveguides are about 20% larger than of normal rectangular waveguides.

The experimental studies of the losses are documented in [8] for microwave frequencies, and in [9] for frequencies above 100 GHz. The latter higher-frequency gap waveguides have been realized by micromaching.

III. Packaging

A. AMC gap waveguide packaging

The packaging by an AMC pin lid was first demonstrated in [10], and it has later been used successfully also to package microstrip filters [11]. At frequencies below 10 GHz the pins may with advantage be replaced by springs [12] or zigzag wires [13].

B. Numerical PMC prepackaging to reduce computation time

The pins, springs or zigzag wires can initially in a design process be replaced by a PMC lid to reduce computational volume and time. This results in a complete new procedure of designing high-frequency circuits and modules. They can be initially designed with a PMC lid, thereby removing cavity resonances that otherwise would appear with with PEC or metal lid, and the PMC lid can later be replaced by a realized lid consisting of pins or other periodic elements. This numerical approach is referred to as PMC prepackaging [14] and reduce the computational effort of the initial design, but the design has to be fine-tuned after introduction of the realization of the PMC.

C. Packaging of MMICs

A major development during 2012 was the packaging of Tx and Rx amplifier chains [15], see Figure 4. It was found that the lid of nails packaging makes it possible to use the amplifiers for 25 dB larger output power than with normal packaging using metal cavities with absorbers in the roof. Also, a minimum isolation between the Tx and Rx amplifier chains of 78 dB was achieved without any solid metal wall between the Tx and Rx sides. The 78 dB isolation is entirely due to the parallel-plate cut-off created by the pins.

IV. Filters and Antennas

The gap waveguides have low losses, so they naturally can be applied to make high-Q filters. This was first demonstrated in [16], and thereafter a 38 GHz filter was made according to commercial radio link specifications and successfully tested, see Figure 5. The manufacturing cost is not yet comparable with rectangular waveguide filters, but it has shown better temperature stability, and manufacturing should become cheaper when a good way to realize the pins have been developed [17].

We have now started to realize gap waveguide antennas. The first linear ridge gap waveguide slot arrays with a corporate feeding is presented in [18], and a planar 2x2 horn array in microstrip gap waveguide is reported in [19]. Some larger 4x4 example of the horn antenna array is shown in Figure 5a, and in addition a 2x2 ridge gap waveguide slot array with 25% bandwidth in Figure 5b. The simulations and measurements will soon be reported.

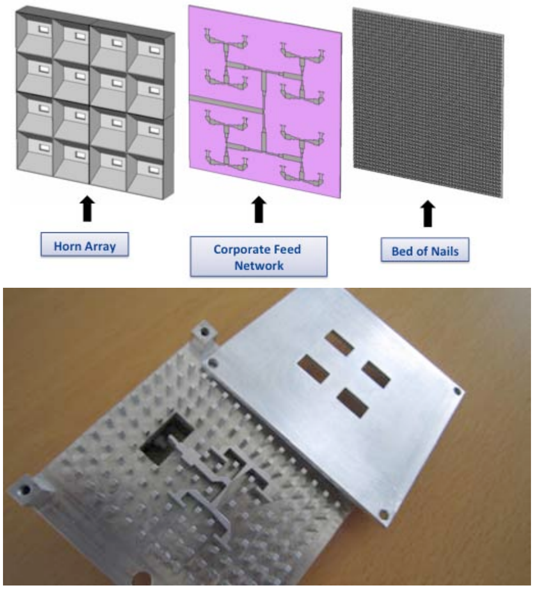

Figure 5. Examples of gap waveguide antennas. 4x4 microstrip gap waveguide slot array (upper), and 2x2 ridge gap waveguide array (lower).

VII. Conclusion and Acknowledgement

The research on gap waveguides has since it was started in 2008 progressed well, and the technology has many attractive features that have major advantages above 30 GHz.

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