New Coplanar Waveguide Based on the Gap Waveguide Technology

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Abstract—A new planar waveguide, coined “Inverted Coplanar Gap Waveguide” is presented. The concept of Gap Waveguides and parallel plate suppression between Perfect Magnetic and a Perfect Electric Conductors is applied to Coplanar Waveguides in order to create a low-dispersion, low-loss transmission line. The combination of an Artificial Magnetic Conductor and top cover allow the propagation of an even coplanar mode with a strong component propagating over the air while solving encapsulation matters without the use of metallic vias. The main theory behind this new concept is presented and supported by FEM simulations on a commercial software package.

Index Terms—coplanar waveguide, gap waveguide, transmission lines, encapsulation.

I. INTRODUCTION

Coplanar waveguides (CPW) were first presented in late 60’s [1] and are planar transmission lines consisting on a metallic strip in between two metallic ground surfaces arranged on the same plane. These lines support a quasi-TEM mode, which make them suitable for broadband applications. They have been used extensively due to their advantages, such as simple manufacturing (the conductor strips lay on just one side of the substrate), ease for integrating active components, such as amplifiers or diodes; and low cross talk between lines on the same chip. Conductor-Backed Coplanar Waveguides (CBCPW) include a metallic ground plane on the bottom side of the substrate, which often serves as mechanical support and as heat sink [2]. This variation is widely used because end-components must generally be encapsulated in order to comply with EMC regulations, as well as to protect the active devices from moisture, dirt or other hazardous conditions. However, the presence of this back conductor entails the generation of parallel-plate modes on the substrate, which results in high-loss lines and high cross talk between lines on the same chip. This problem can be addressed in several ways, such as employing planar EBG structures [3] or using metallic vias between top and bottom ground planes [4]. The first solution solves the problem but, generally, these planar structures are somewhat narrowband in contrast to the low-dispersion, broadband behavior of the coplanar waveguide, thus limiting broadband operation. The second solution solves the problem without affecting the bandwidth of the line, given that vias are placed sufficiently close to each other. However, this solution is not suitable for some substrate materials that do not withstand drilling and it entails a challenging task when working at frequencies above 100 GHz, where manufacturing and plating capabilities are pushed to the limits, increasing the cost of the process.

One interesting technology for achieving low-loss, high frequency waveguides is the Gap Waveguide technology [5]. Here, a passband is defined between two parallel metallic plates supporting a quasi-TEM mode. These plates are surrounded by virtual magnetic walls, a combination of a Perfect Electric Conductor (PEC) surface and a Perfect Magnetic Conductor (PMC). When separated less than a quarter of a wavelength, they define a broad stopband for the parallel plate modes. The PMC is implemented artificially (AMC) and consists typically on a periodic “bed of pins” with rectangular or cylindrical section, although several shapes have been proposed in the literature, such as pyramid-shaped [6], double-cone [7] or half-height pins [8], which aim to reduce the fabrication complexity or to increase the operating bandwidth of the structure. Until now, three main types of Gap Waveguides (GW) have been presented: the ridge-GW (RGW) [9], groove-GW [10] and inverted microstrip-GW or microstrip-RGW [11], [12]. This technology has also been proposed for preventing cavity modes in encapsulated MMICs [13].

In the present work, a new transmission line based on the Gap Waveguide concept applied to CPW is proposed. The following sections of this paper present some basic theory and the main concepts concerning this new transmission line, for which we propose the terms “Gap Coplanar Waveguide” and “Inverted Coplanar Gap Waveguide” (ICPGW). Some 3D FEM simulations are included in order to validate these concepts. Fabrication and test of the proposed waveguide is expected in the near future.

II. INVERTED COPLANAR (GAP) WAVEGUIDE

The new transmission line proposed in this work relies on the fact that a PMC and a PEC separated a distance lower than a quarter of a wavelength define a stop-band for parallel plate modes. The fundamental mode of the coplanar waveguide, also called “even mode” or “coplanar mode” is a quasi-TEM mode where the metal on the sides acts as grounds while the center strip acts as the positive electrode.
Fig. 1. Modes in coplanar waveguide @ 110 GHz: a) even mode, b) odd mode, c) microstrip-like mode. The substrate is a 127um-TOPAS COC with 2.35 relative permittivity. (red colour). The metallic pattern has been oversized for clarity purposes.

Fig. 1a) shows an example of the even mode, simulated in HFSS. In addition, the CPW presents a parasitic mode called “odd mode” or “slot line mode” (Fig. 1b) were the field in one of the gaps between the conductors is shifted 180 degrees in comparison to the even mode. This mode can be excited on discontinuities or bends and is usually prevented by using air-bridges or wire bonds between the grounds [2]. Additionally, a microstrip-like, parallel plate mode can exist in a CBCPW (Fig. 1c). This mode shall be confined by using metallic vias in order to avoid a parallel plate propagation across the substrate. While it can also be useful in specific situations, like when transitioning from CBCPW to microstrip [14], it has also higher losses, since most part of the field travels across the substrate. However, as mentioned in the introduction, not every substrate can stand a drilling or etching process for creating the vias. This is the case of some polymers like TOPAS COC [15]. Other materials, such as Indium Phosphide, have specific etching processes that might not be cost-effective in every situation. Furthermore, when scaling up in frequency, i.e. above 100 GHz and especially at the 300 GHz band, accurately drilling and plating via holes might stand as a challenging and tedious task. The waveguide proposed in this work aims to solve the issues of parasitic modes and encapsulation by applying the concepts of the Gap Waveguide technology.

A first step in the realization of this new waveguide would be to include a PMC below the substrate. We could refer to this as “Gap Coplanar Waveguide” or “GCPW”. The GCPW with its fundamental mode are sketched in Fig. 2a. It consists of a coplanar metallic pattern printed on top of a substrate with permittivity \( \varepsilon_r \), with a PMC ground at the bottom. In contrast to usual gap waveguide technology, no air gap is considered between the PEC and PMC boundaries, although small gaps between the pins and the substrate might be present and their effect assessed when thinking of an actual implementation. Instead of air, the substrate must be taken into account when choosing the dimensions of the pin to achieve the desired stopband.

![Fig. 1](image1.png)

![Fig. 2](image2.png)

In order to create a stop-band for the parallel plate modes, the thickness \( h_s \) of the substrate, with relative permittivity \( \varepsilon_r \), must fulfil the following condition:

\[
h_s \leq \lambda / (4 \sqrt{\varepsilon_r})
\]

(1)

The PEC/PMC stopband not only prevents the microstrip-like, parallel-plate mode from propagating but also reduces the amount of energy that travels across the substrate in the even-mode. This is due to the central conductor of the CPW generating also a stop band together with the PMC at the bottom. Hence, a lower loss is expected. Taking a step forward, it was observed by means of FEM simulation that it is possible to excite an inverted coplanar, microstrip-like mode (Fig. 2b), with a significant portion of the E-field travelling through the air between the CPW and a PEC plane located on top of it. This mode could reduce the dielectric loss of the transmission line even further. It is worth noting that, at this point, the parasitic slot line mode, as well as parasitic parallel plate modes over the air can still propagate across the structure. This can be solved by connecting both grounds of the coplanar waveguide to the PEC located on top, as shown in Fig. 2c. This also allows...
providing physical support to the PEC plane on top. The resulting is a coplanar waveguide with a surrounding “channel”, which fundamental mode resembles the even mode of the CBCPW, flipped upside-down. This resemblance and the application of the Gap technology motivates the choice for the name “Inverted Gap Coplanar Waveguide” or “IGCPW”. While performing simulations, it was observed that the height of the channel controls the amount of power that propagates over the air in this even mode. The lower the air channel, the stronger the contribution. A more in-depth study of this influence must be carried out in the future.

Fig. 3 shows a side view of the magnitude of the E-field propagating along a 10-mm-long ICPGW at 110 GHz with an ideal PMC ground. It is seen that most part of the E-field is propagating above the substrate. While simulating the structure, it was checked that increasing the height of the channel on top of the CPW increases the characteristic impedance computed by HFSS on the wave ports. Some slight variations were observed when modifying the width of the channel, but no direct relationship could be established. This width, however, controls the propagation or cutoff for the slotline mode. Nevertheless, no analytical expressions within these regards could be found yet.

It is worth noting that the walls of the channel interconnecting both grounds should be as close to the slots of the CPW as possible, so as to push the cutoff frequency for the slot-line mode to higher frequencies. A more in-depth study on the influence of the channel’s dimensions and obtaining analytical expressions for the characteristic impedance and propagation properties of this line is required and intended to be carried out in the near future. In the following sections of this paper, a 50-Ohm ICPGW will be considered. This impedance corresponds to the wave port impedance calculated by HFSS with a very fine meshing.

III. ARTIFICIAL MAGNETIC CONDUCTOR

In order to add one more degree of realism in our model, an AMC was realized with a structure based on the well-known bed of pins. The AMC structure was designed with HFSS Eigenmode solver and the targeted working frequency band was the corresponding to a WR10 (75-110 GHz). The designed unit cell is shown in Fig. 4 together with its dispersion diagram. A 127-um-thick TOPAS substrate with relative permittivity 2.35 is included in the design of the AMC. The cell is enclosed in between Master/Slave boundaries parallel to the X- and Y-planes, while both boundaries parallel to the Z-plane are defined as PEC. The dimensions of the cell are shown in Table 1. A 10-mm-long ICPGW section (Fig. 5) implementing the AMC ground with the bed of pins has been simulated. The dimensions selected were 150um and 400um for the height and width of the channel, respectively. A 170um center strip with 10um slot width in the coplanar structure were chosen to provide an approximated value of 50 Ohm as the port impedance and also to be compatible with the probe station available at our lab.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value [um]</th>
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<tbody>
<tr>
<td>Substrate thickness (h)</td>
<td>127</td>
</tr>
<tr>
<td>Pin height (d)</td>
<td>675</td>
</tr>
<tr>
<td>Pin width (a)</td>
<td>400</td>
</tr>
<tr>
<td>Pin pitch (p)</td>
<td>850</td>
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Fig. 3. E-field in dB propagating across the proposed ICPGW at 110 GHz. The substrate is a 127um-TOPAS COC with 2.35 relative permittivity. Ideal PMC boundary was set at the bottom.

Fig. 4. Dispersion diagram of the bed of pins. Inset: section of the unit cell with its corresponding dimensions. Blue: PEC pin. Red: Topas substrate.

Fig. 5. Perspective of the YZ-cut of the simulated structure (10mm long). Inset: detailed layer disposition (left bottom); fundamental mode at wave ports (top right).
IV. DISCUSSION

The E-field plotted in Fig. 5 shows how the bed of pins structure effectively achieves the same effect as an ideal PMC boundary, allowing most part of the energy to propagate over the air with very low leakage into the substrate. Fig. 6 provides a graphical comparison of the insertion loss simulated on 10-mm-long a) CPW, b) CB-CPW with infinite ground, c) CB-CPW with finite ground, d) PMC-ICPGW (ideal) and e) Bed-of-nails-ICPGW for the same substrate, considering no conductor loss. It is worth noting that “a)” would not be realizable without a support material on the bottom and that is why approaches b) and c) are considered. In this graph it is possible to observe how the losses for b) are the highest (dashed blue), mainly due to leakage across the substrate in the form of substrate parallel plate modes. Furthermore, we are able to check that d) (dashed red) and e) (solid green) are similar. The value obtained for their insertion loss in simulation lays around 0.04 dB/cm, which is lower than the 0.2 dB observed for an “air suspended” CPW. This supports the idea of EM fields propagating over the air. Moreover, it can be observed that the line offers a great bandwidth (i.e. low dispersion), performing equally for the full WR10 band. Last, c) (dashed brown) shows that the finite coplanar grounds are not affected by the parallel-plate mode leakage as much as the infinite coplanar grounds have, but it is observable how a frequency-dependent standing wave is excited due to the finite extent of the coplanar grounds. In this case, 200 micron were considered on each side of the CPW.

V. CONCLUSIONS AND FUTURE WORK

In this communication, a new planar transmission line has been proposed. The names “Inverted Coplanar Gap Waveguide” or “Gap Coplanar Waveguide” are suggested to coin this new concept since the Gap Waveguide technology is applied to solve both issues regarding substrate modes and encapsulation. To the best knowledge of the authors, this is the first time the Gap Waveguide concept has been employed to propose a transmission line like the one presented here. By controlling the height of the channel created on top of the substrate, a fundamental mode for the coplanar waveguide with a strong component over the air is proposed; hence, the term “Inverted” is included in the name suggested for the new line.

While there is a need for obtaining analytic expressions for the characteristic impedance and propagation features, the main basic theory has been presented and supported by simulations on a FEM Solver. It is believed that the proposed line has several interesting potential applications, providing a low-loss, low-dispersion, planar transmission line for high frequency applications that also solves the encapsulation matters. The proposed structure provides an alternative to the use of metallic vias, which can be challenging for some particular materials and especially at higher frequencies.

Future work will aim to characterize the new waveguide analytically with dependency on the substrate employed and the dimensions chosen for the coplanar pattern as well as the channel. The structure shown in Fig. 5 is expected to be fabricated and measured in the near future, being able to provide a comparison between the new proposed waveguide and the conventional ones in terms of loss [dB/cm]. This fabrication entails some challenges, such as ensuring that the top metallic cover makes electrical contact with both ground planes. The bed of nails will be realized on silicon by means of Deep Reactive Ion Etching. Future work will also involve the development of transitions and comparisons with some of the most used waveguide technologies, as well as the use of different substrate materials and comparison with CPW using metallic vias.

ACKNOWLEDGMENT

The FPU Program of the Spanish Ministry of Science, Innovation and Universities, (FPU18/00013) supported this work.

REFERENCES


