Design of a Hybrid Directional Coupler in Empty Substrate Integrated Waveguide (ESIW)

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Abstract—This letter shows the procedure of design of a hybrid directional coupler based on Empty Substrate Integrated Waveguide (ESIW). Once proved in previous works the feasibility of ESIW and the good performance indexes this technology can achieve, the following step is designing useful devices to be integrated in planar circuits. The proposed hybrid coupler, which is the first ESIW 4-port available circuit, is designed at 15 GHz with 3-dB coupling factor and a minimum of 20 dB of isolation over 30% bandwidth. After manufacturing the circuit, simulated and measured results are presented and discussed.

Index Terms—Hybrid directional coupler, empty substrate integrated waveguide (ESIW), millimeter-wave devices.

I. INTRODUCTION

In 2001, Deslandes and Wu proposed the use of substrate integrated waveguides (SIW) as a solution to achieve the good characteristics of quality factor and insertion loss due to classical waveguides, but also with the integration capability and the economical cost of planar circuits [1].

Following that line, a new technological solution was presented by Belenguer et al. in 2014 [2] that integrates an empty waveguide into a dielectric substrate. This technique received the name of empty substrate integrated waveguide (ESIW). ESIW circuits present better performance indexes than the equivalent designs in SIW technology and preserve the low profile and low-cost fabrication of a standard planar circuit with high integration capability. Details of the fabrication process and experimental performance indexes of ESIW vs. SIW can be found in [2]. Once proved the feasibility of the ESIW technology, the following step is the development of the full suite of circuit designs, so that it could arise as a top technology to be taken into account for several applications, such as communication circuits in the X, Ku and Ka bands.

A directional coupler is a 4-port device that is widely used for splitting the input according to the specification requirements of frequency, bandwidth and size of the structure [3]. This paper describes and validates the design, fabrication and experimental measurement of a 3-dB directional coupler, or hybrid, according to the ESIW principles in the Ku band, being this the first available design of a 4-port ESIW circuit.

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II. COUPLER DESIGN CONSIDERATIONS

A. Design principles

ESIW circuits are based on rectangular waveguides embedded in a planar circuit, and therefore the design process to be followed is exactly the same as that of the classical methods used in standard rectangular waveguides [2]. The suggested coupler is a modification of the Riblet’s short-slot coupler [4]; it presents a compact aspect with a 3-dB coupling factor that is achievable by an H-plane central almost-squared cavity to which four arms are attached as the input/output ports, and with different irises and stings inserted in the cavity and the arms to adjust and control the design parameters. The geometrical structure of the directional coupler is that shown in Fig. 1. This circuit has two-fold symmetry about the planes AA’ and BB’ and hence, even-odd analysis regarding both symmetry planes can be applied by replacing each plane by a magnetic or electric boundary depending on an even or odd excitation [5].

According to the conditions stated in [4] and [6], the width

\[ d = \sqrt{2(a + c_s)} \]

of the hybrid junction in the coupling region must be large enough to propagate even TE_{10} and odd TE_{20} modes, but must prevent the propagation of the TE_{30} mode at the operating frequency. By this condition the value of \( c_s \) can be estimated, as \( a \) takes the width of a standard waveguide. Besides, the coupling iris \( 2r \) must guarantee a 90° phase-shift between the even and odd modes according to equation (1),

\[ 2\pi \left( \frac{2r}{\lambda_{ge}} - \frac{2r}{\lambda_{go}} \right) + \phi_r = \frac{\pi}{2} \]  

where \( \lambda_{ge} \) and \( \lambda_{go} \) are the guide wavelengths in the coupling region of the even and odd modes respectively, whereas \( \phi_r \) accounts for reflections at the ends of the coupling iris and can be neglected at first, so that a consistent initial design point could be found by estimating the value of \( r \). Those improper reflections can be avoided, according to [7], by using a step structure in the coupling region, where the ratio between the length of the step structure, \( \sqrt{2}c_1 \), and the length of the coupling iris, \( 2r \), must be adjusted; taking as an initial point for a hybrid that \( 2\sqrt{2}c_1 = 2r \), the value of \( c_1 \) can be estimated. In the step structure, the transition from the arms to the coupling region is smoothed with the insertion of two stings defined by the parameters \( c_s \), \( r \), \( p \); the value of \( p \) is fixed a priori, so that the resulting sting is mechanically stable and can be manufactured. On the other hand, a completely matched state is required for this circuit to become a quadrature directional coupler. Inductive windows are inserted in each arm of the coupler to help to completely fulfill a 3-dB coupling factor.
and a matched state [8]; they are defined by the iris width b and position ($x_b$, $y_b$). The inductive window is analogue to a parallel adaptation network that makes possible the matching between the impedance at the end of the arm and the characteristic impedance of the waveguide; therefore, the value of $x_b$ and $y_b$ can be estimated by solving the adaptation network at the beginning of the useful bandwidth where the adaptation difficulties arise, whereas the width b is fixed a priori, so that the resulting iris is mechanically stable. Summarizing, the coupling ratio can be controlled essentially by adjusting the parameters ($r$, $c_r$, $c_l$) of the central coupling region, whereas return loss can be controlled with the parameters ($x_b$, $y_b$) of the iris.

B. Proposed directional coupler

This hybrid directional coupler is designed to operate at 15 GHz with a minimum bandwidth of 4 GHz (13 – 17 GHz), in which the coupling ratio must be 3 dB and the difference between the coupled and the through ports must be less than 0.5 dB with a phase-shift around 90°; on the other hand, isolation ratio and return loss must be 20 dB, at least. The circuit has been carried out using a commercial software (CST Studio) and considering the following constraints: $\alpha=15.799$ mm is the width of the WR-62 waveguide for the Ku band; $h=1.524$ mm is given by the underlying substrate used; the width of the stings p and the irises b is forced to 0.75 mm for mechanical consistence reasons in the manufacturing process; the length of the arm $l_y$ is set to 15 mm so that, at least, there is half-wavelength up to arrive to the inductive iris. The application of the design principles of the former section allows to establish an initial design point: the cut-off frequency of the TE$_{30}$ mode in the coupling region is set to 17 GHz, so $c_s=2.919$ mm; $r=9.244$ mm by the Riblet’s equation (1); $c_l=6.537$ mm by adjusting the step structure in the coupling region. Using the specified values, the circuit without the inductive windows is simulated and optimized regarding the power-split unbalance; those preliminary results reveal an adaptation problem in the margin among 13 and 14 GHz with high values of $S_{11}$ and $S_{14}$. To solve that problem, impedance adaptation and matched state are forced at the frequency of 13.5 GHz by the insertion of an inductive window with calculated values of $x_b=3.783$ mm and $y_b=3.270$ mm.

The initial design is optimized in the bandwidth of interest (13 – 17 GHz) by repeating these steps: first, the values of ($r$, $c_r$, $c_l$) are optimized to minimize the power-split unbalance; second, the values of ($x_b$, $y_b$) are optimized to maximize both, return loss and isolation; then the former two steps are repeated considering in each case the three optimization conditions; and eventually, all the values ($r$, $c_r$, $c_l$, $x_b$, $y_b$) are optimized together with the three optimization conditions. Finally, the values used to manufacture the circuit are: $r=9.266$ mm, $c_s=2.908$ mm, $c_l=7.156$ mm, $x_b=3.912$ mm, $y_b=2.106$ mm.

III. RESULTS

So that the circuit could be measured in a commercial vector network analyzer, the ports must have attached tapered microstrip-ESIW transitions according to those proposed by Belenguer et al. in [2]. Final layout is depicted in Fig. 2(a).

To manufacture the circuit, the underlying substrate for the empty waveguide is Rogers-4003C ($\epsilon_r=3.55$, $\tan\delta=0.0027$, $h=1.524$mm) and top and bottom walls are made with FR4 sheets. All the pieces have been processed with a milling machine and metallized following a thru-hole electroplating procedure. The three layers have been finally aligned using some holes drilled around the waveguide and soldered using a tin solder paste, which is dried in a reflow oven. Different steps of building up the circuit are shown in Fig. 2.

The scattering parameters have been finally measured using fixtures and after a typical TRL calibration of the vector network analyzer. Measured results compared to the equivalent simulated results are exhibited in Fig. 3.

The simulated S-parameters for the coupled and through ports are very close to -3 dB, with maximum power-split unbalance between them of less than 0.5 dB and phase-shift around 90° (varying among 89.75°–91.25°); the S-parameters for the input and isolated ports are always far below -20 dB. Hence, the design circuit accomplishes in the CST-simulator with all the imposed requirements.

The measured S-parameters for the coupled and through ports matches almost always the simulated values. In the case of the input and isolated ports the measured values are slightly higher than the simulated ones, but always near the stablished limit of -20 dB of isolation and return loss, whereas the insertion loss is 0.083 dB at the central frequency. Regarding the power-split unbalance, the measurements show differences.
below 0.5 dB, except for scarce peaks that arrive at a maximum difference of 0.7 dB; and about the phase-shift, the results are among 86° and 94°, so both parameters the measurements are very close to the simulations and the design requirements. The causes for these deviations among the simulated and measured values are due to losses in the real material, tolerances of the manufacturing process and especially the inherent deviations in the measurement procedure due to the fact of using a two-port analyzer and the consequent reflections introduced by the respective loads at the unconnected ports. Taking these causes into account, it can be stated that the response of the real device matches with that of a typical hybrid circuit in the whole bandwidth from 13 to 17 GHz.

To compare and contrast the proposed circuit in ESIW, the equivalent circuits [5] in SIW—using the same substrate Rogers-4003C as in ESIW— and classical waveguide—using a standard WR-62—have been simulated in CST Studio considering only the stand-alone circuits without transitions. The ESIW hybrid is not as compact as the equivalent in SIW due to the absence of dielectric, but fabrication tolerances have a greater impact in SIW devices due to the smaller dimensions and due to the substrate permittivity [2], and even more, this effect is aggravated as the frequency increases; on the other hand, the ESIW circuit has the same footprint as the equivalent in classical waveguide, but with a very small height. Regarding the losses, the best is the classical waveguide circuit with 0.055 dB of insertion loss, followed by the ESIW hybrid with 0.083 dB, and then the SIW circuit with 0.304 dB. ESIW circuits are planar low-cost, like SIW ones, in comparison with the high-cost of manufacturing classical waveguides. Regarding the quality factor, where applicable, the ESIW technology achieves values 4.5 times higher than the equivalent SIW designs [2]. As a stand-alone component, this circuit presents good performance indexes, better than the equivalent SIW circuit, which is more compact but with higher insertion loss; but if this is used within a larger structure, specially if filters are also present, the whole ESIW structure would be much better regarding low-losses and high quality factor than SIW, and much better regarding total volume and weight, integration and low-cost than classical waveguides.

Therefore, ESIW devices, like the proposed hybrid, are a good option whenever conditions of space, low-weight, low-cost, low-losses, high quality factor, high frequency and integration have to be taken into account.

IV. CONCLUSIONS

The first 4-port device in ESIW technology has been described in this letter. The design constraints of the proposed hybrid directional coupler have been stated and the circuit has been simulated, manufactured and measured. The results show that this real device accomplishes the imposed characteristics, accepting the differences between the simulated and measured values of the S-parameters that are within the manufacturing tolerance limits. Comparing equivalent designs of this hybrid in ESIW, SIW and classical waveguides, the ESIW circuit is revealed as a promising candidate if limits about volume, weight, losses and cost are considered.

The realization and validation of this circuit proves again the feasibility of the ESIW technology and initiates the path for the design of the full suite of useful devices in ESIW.

REFERENCES