Double Square Waveguide Directional Coupler for Polarimeter Calibration

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***Abstract* — A novel full-band square waveguide coupler design based on directional couplers which couple the TE_{10} and TE_{01} orthogonal modes in a square waveguide is presented. This waveguide coupler is aimed at calibration of polarization receivers. This is composed of a pair of rectangular waveguide directional couplers, which are rotated 90º between them and both are coupled to a main square waveguide through each one of the square section walls. The coupler covers the full frequency band from 10 GHz to 18.9 GHz. It has inherent low cross-polarization, which allows to obtain any known elliptically polarized wave at a square waveguide when a signal is applied to the couplers. The fabricated prototype of this coupler exhibits 31 dB of coupling, with flatness of ±3.8 dB and excellent cross polarization better than 50 dB over the whole band.**

***Index Terms*— Waveguide coupler, microwave passive components, polarization, directional couplers, polarimetric radiometers.**

I. Introduction

DIFFERENT polarimetric radiometer architectures have been developed with the aim of measuring the polarization of sky observations or geophysical purposes [1]-[10]. These polarimetric radiometers are very sensitive receiver instruments used for accurately measuring the Stokes parameters of polarized incident waves. The calibration of those instruments at microwave and millimeter waves is performed through different techniques. The use of a Dicke-switch [11], in which the reference signals are radiated from a black body at two different physical temperatures, is a common calibration technique for the entire receiver chain of radiometers. A method switching between internal noise injection and external reference loads has also been demonstrated to accurately calibrate radiometer gains and offsets [12]. But, on the other hand, wave polarization angle cannot be calibrated with those calibration techniques, although they are useful for conventional microwave radiometers measuring total brightness temperature.

In polarimetric radiometers the aim is to measure the Stokes parameters which define linearly and circularly polarized brightness temperature components. Therefore, the calibration of a fully polarimetric radiometer requires test signals with different well known polarizations, which number depends on the number of Stokes parameter outputs to calibrate.

The Stokes parameters for determining polarization in terms of two linearly polarized components of the electric field in standard Cartesian basis $(\hat{x}, \hat{y})$ are

$$Q \equiv \langle E_x^2 \rangle - \langle E_y^2 \rangle,\ U \equiv 2Re\langle E_x E_y^* \rangle,\ V \equiv -2Im\langle E_x E_y^* \rangle. \quad (1)$$

Some experiments devoted to measure the polarization of the cosmic microwave background use polarized astronomical sources for instruments calibration [1], [13]. On the other hand, the use of manufactured calibrators for polarimetric radiometer calibration is also commonly used, with a classic method consisting of the use of a linearly polarized reference load through two absorbing microwave black bodies and a polarization-selecting wire grid between them, which generates three reference noise levels [14]. Other similar methods consist in observing rotatable dielectric sheets to generate a partially polarized signal, where a dielectric sheet acts as a beam splitter transmitting most of the sky radiation but reflecting a small polarized fraction of the radiation from an ambient load perpendicular to the beam [15], [16], or polarization selecting wire-grids mounted on a mechanical rotating ring [17]. Additionally to those methods, a phase retardation plate can be added to produce an extra reference temperature with circular polarization and calibrate fully polarimetric radiometers [18]-[21]. Furthermore, other calibration methods apply the injection of polarized test signals through their components, such as correlated noise calibration standard coupled with directional couplers [22], an injector of reference signals with coaxial probes inserted in a circular waveguide [23], directional couplers [3] or circular waveguide directional coupler [24], [25]. These last two works have demonstrated waveguide couplers using a circular waveguide, nevertheless those directional couplers only allow to inject in the circular waveguide a broadband signal to produce a pure linearly polarized wave with a fixed angle. On the other hand, the injector presented in [23] allows to inject differently linearly polarized reference waves in a narrow band, without directivity and achieving a low level of parasitic circularly polarized wave.

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It consists of three probes inserted in circular waveguide in which the mechanical manufacturing involving penetration and position of the probes is crucial for obtaining the required performance. Nevertheless, that solution needs a wide diameter of the circular waveguide to better control the required coupling and fabrication tolerances, which reduces the working frequency band for being operated a multimodal regime.

With the purpose of calibrating a fully polarimetric receiver, in which at least three linearly polarized waves and one circularly polarized wave are needed, a solution based on waveguide couplers to inject test signals is proposed. For this design, waveguide aperture directional couplers, which are based on Bethe's theory about small aperture coupling [26], [27], have been designed. Aperture couplers work by the interaction of two metallic waveguides through holes in their common walls. These couplers are used to obtain high directivity over broadband frequency ranges [28]-[31]. Moreover, the technique of crossed-waveguide directional couplers is also used, which provides the compactness and simplicity for the fabrication. Besides, although a common way used to improve directivity are crossed slots as coupling apertures, rectangular slots are implemented achieving good performance.

In this work, a novel square waveguide coupler based on rectangular waveguide directional couplers is presented. This coupler allows to inject two broadband signals to the rectangular waveguides and to obtain an elliptically polarized wave in the square waveguide. Moreover, when those signals are in-phase coupled to the square waveguide, a linear polarization is obtained and its angle can be controlled with the amplitude of one of the injected signals. This would allow to calibrate three out of four Stokes parameters. In addition, an external phase shift of 90º in one of the coupled signal produces a circularly polarized wave. Furthermore, this coupler avoids the use of complex mechanical rotating structures with wire-grids needed for polarization selection of incoming signals in polarimeter calibration, as well as being mechanically simple to manufacture. The detailed design and manufacturing of the proposed square waveguide directional coupler are described in Section II. Its experimental results are presented in Section III. Finally, conclusions are explained in Section IV.

II. Square Waveguide Coupler Design

The double square waveguide coupler is composed of two identical couplers which are connected through the square waveguide rotated 90º between them as it is shown in Fig. 1. This combination of the two couplers results in a dual mode coupler which allows to provide a known elliptically polarized wave in the square waveguide when two signals are applied to each individual waveguide coupler. The physical structure of this dual mode coupler has inherent low cross-polarization, since the coupled modes into the square waveguide from each coupler are orthogonal. Moreover, this coupler with square waveguide has the advantage of being easy to fabricate with E-plane split blocks.

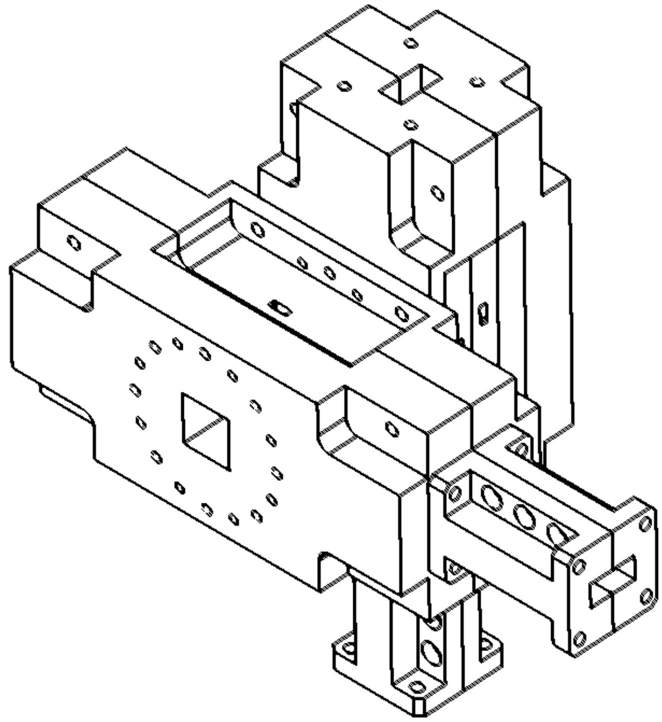

Fig. 1. General view of the dual mode coupler structure.

A. *Coupler Design*

The design of the coupler is based on the design of a circular waveguide directional coupler described in [24], but with the improvement of being able to produce linearly polarized wave with any angle or circular polarization, as opposed to only a linearly polarized wave with fixed angle. The goals are a coupling of around 30 dB in the frequency band from 10 to 18.9 GHz. This coupling is chosen for injecting a calibration signal into a receiver, taking also into account the incoming noise power level to the receiver when none calibration signal is applied and a termination is connected to the coupler.

The WR62 standard (a = 15.80 mm, b= 7.90 mm) is used for the rectangular waveguides and a square waveguide of side 16.8 mm is adopted in the design of the coupler.

An electromagnetic 3D model of the double directional coupler with the six physical ports is depicted in Fig. 2. Each directional coupler is composed of a waveguide power divider, which comprises two parallel waveguides coupled in their broadwall, to a crossed square waveguide in its opposite walls. The couplings of each parallel rectangular waveguides induce the components of the TE_{10} mode or the TE_{01} mode in the square waveguide, but not both, since for a mode the fields are added in phase and for the other one out of phase.

According to Fig. 2, regarding the rectangular waveguide port#1 and port#2 of the double directional coupler, port#5 is the coupled port and port#6 is the isolated one. Since the double directional coupler is symmetric, for the rectangular waveguide port#3 and port#4 the coupled port is port#6, and the isolated one is port#5. Each square waveguide port can be represented as two electrical ports, one for each propagating mode TE_{10} (X) and TE_{01} (Y). The complete S-parameters matrix of the waveguide coupler with all the electrical ports is given as:

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & C1_{5Y} & C1_{5X} & I1_{6Y} & I1_{6X} \\ S_{12} & S_{22} & S_{23} & S_{24} & C2_{5Y} & C2_{5X} & I2_{6Y} & I2_{6X} \\ S_{13} & S_{23} & S_{33} & S_{34} & I1_{5Y} & I1_{5X} & C1_{6Y} & C1_{6X} \\ S_{14} & S_{42} & S_{34} & S_{44} & I2_{5Y} & I2_{5X} & C2_{6Y} & C2_{6X} \\ C1_{5Y} & C2_{5Y} & I1_{5Y} & I2_{5Y} & S_{55Y} & S_{55YX} & T_Y & T_{YX} \\ C1_{5X} & C2_{5X} & I1_{5X} & I2_{5X} & S_{55YX} & S_{55X} & T_{YX} & T_X \\ I1_{6Y} & I2_{6Y} & C1_{6Y} & C2_{6Y} & T_Y & T_{YX} & S_{66Y} & S_{66YX} \\ I1_{6X} & I2_{6X} & C1_{6X} & C2_{6X} & T_{6X5Y} & T_X & S_{66YX} & S_{66X} \end{bmatrix}$$

where C1 and I1 are the coupling and isolation parameters of the Coupler#1 and C2 and I2 are the coupling and isolation parameters of the Coupler#2 respectively. Sii and Sij indicate the reflection and transmission coefficients of the rectangular ports. In the square waveguide, T_Y, T_X and T_{YX} are the transmission coefficients, and Sii_V, Sii_H, Sii_{VH} are the reflection coefficients for each propagating mode.

The coupling parameters C1 and C2 have ideally no phase difference, because the electrical length of the square waveguide section between both couplers is compensated with additional sections of rectangular waveguide, connected one to the port#1 of Coupler#1 and the other one to port#4 of Coupler#2. These sections of rectangular waveguide have a width of 16.8 mm, like the side of the square waveguide (a_s), in order to have the same phase constant β, and a length of 51.4 mm (Ls2 + a), which compensates the propagation delay between Coupler#1 and Coupler#2. Therefore, a known elliptically polarized wave in the square waveguide is obtained when signals with a general phase difference are applied to each waveguide coupler. Moreover, if the signal is applied to only one of the couplers, the resultant wave at the square waveguide port is a linearly polarized wave, horizontal or vertical depending on the feeding coupler. Furthermore, in-phase signals simultaneously applied to Coupler#1 and Coupler#2 produce an output signal coupled to the square waveguide with linear polarization in the whole frequency band, and its angle depends on the amplitudes of the applied signals.

The structure has been simulated with the FEM-based software ANSYS® HFSS Electronics Desktop using driven model. Fig. 2 shows the HFSS model of the 3D structure. Waveguide walls are taken as copper material and inside boxes are taken as vacuum.

B. Prototype fabrication

The two waveguide couplers are connected through the square waveguide with a rotation of 90º between them. The double coupler is simple to fabricate with four E-plane split blocks, with two of them composing each waveguide coupler, and the two waveguide sections with a_s = 16.8 mm to compensate the phase of the square waveguide between couplers.

In Fig. 3, there are two views of the two directional couplers to square waveguide, comprising four pieces all together. This view has not the sections of rectangular waveguide used to compensate the phase of the square waveguide between couplers. The view to the right shows two out of four rectangular holes of each coupler section. The dimensions indicated in Fig. 3 are summarized in Table I.

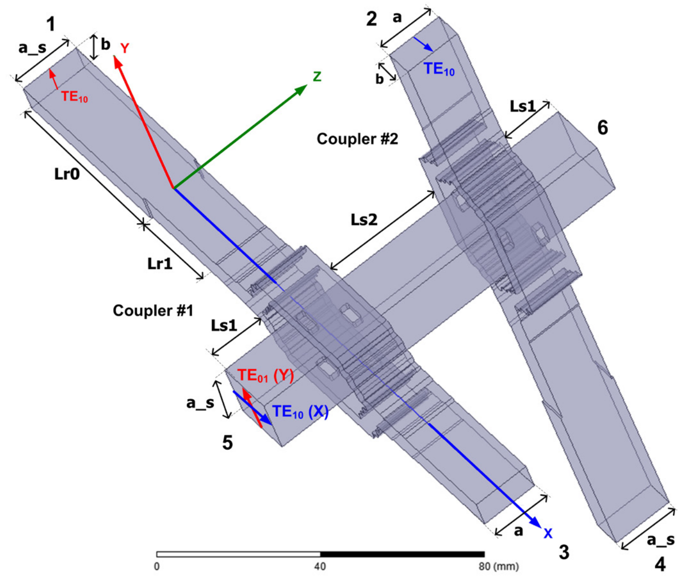

Fig. 2. Electromagnetic model of the double directional coupler to square waveguide. Port# 5 is the coupled port and port# 6 is the isolated one both respect to the rectangular waveguide port#1 and port#2. Dimensions are in Table I.

The internal machining of each block is identical, and the rectangular waveguide is split in two branches bordering the square waveguide as shown in the internal section in Fig. 4. Then, each block has two rectangular through holes from the branches of the rectangular waveguide to the square waveguide, whose shape and position are critical because they determine the performance of the coupler. All the dimensions of the coupler are summarized in Table I (see Fig. 2, Fig. 3 and Fig. 4).

An aluminum prototype is fabricated composed of the two split block waveguide parts, which are shown in Fig. 5. The complete double directional coupler to square waveguide, with waveguide sections in two of the rectangular waveguide ports to compensate phases, and waveguide matched terminations in two of the rectangular waveguide ports named 3 and 4 is shown in Fig. 6.

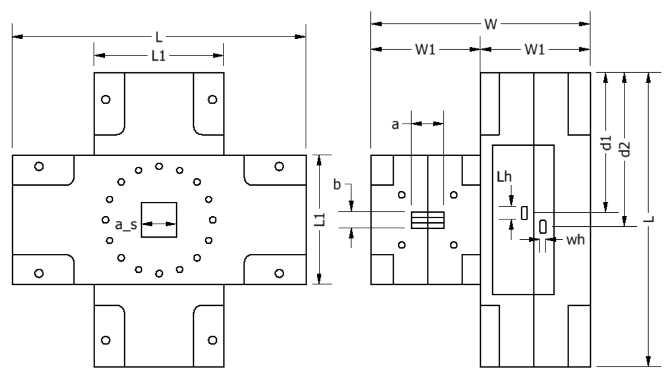

Fig. 3. External view of the four pieces comprising the two directional couplers to square waveguide, without the sections of rectangular waveguide used to compensate the phase of the square waveguide between couplers. Each coupler is composed of two pieces. Dimensions are in Table I.

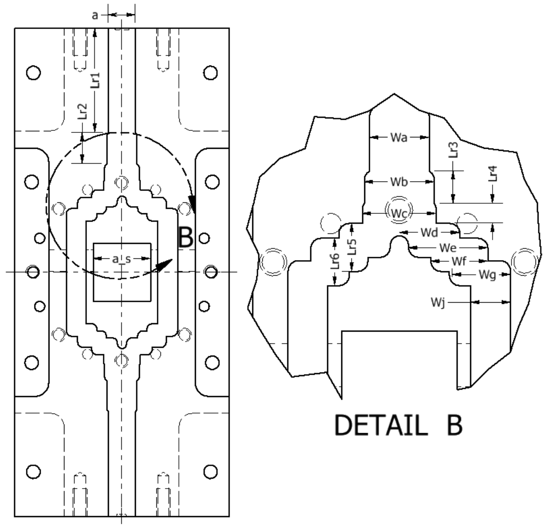

Fig. 4. Internal section of the rectangular to square waveguide coupler. Dimensions are in Table I.

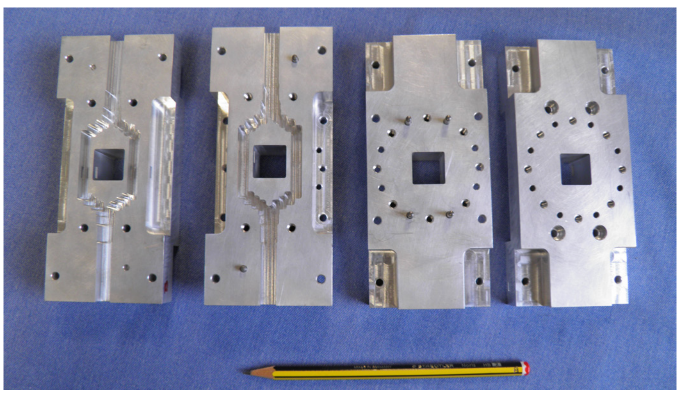

Fig. 5. Four E-plane split-block waveguide parts on aluminum of the double directional coupler to square waveguide prototype. Internal view of one rectangular to square waveguide coupler (two pieces on the left).

III. Experimental Results

The S-parameters of the coupler are measured with an Agilent Technologies E8364B vector network analyzer (VNA) using a TRL calibration of the WR62 standard waveguide. The measurements were always two-port, with waveguide terminations in the other rectangular waveguide ports, or a radiating element in the square waveguide with a microwave absorber material placed facing the port. The square waveguide was connected to the VNA through coaxial-to-waveguide WR62 transitions and square-to-circular and circular-to-rectangular waveguide transitions. All the measurements are compared to electromagnetic simulations done with the Finite Element Method-based software ANSYS® High Frequency Structure Simulation (HFSS) Electronics Desktop, using driven modal solution type and adaptive mesh analysis with convergence set to a maximum delta S of 0.005.

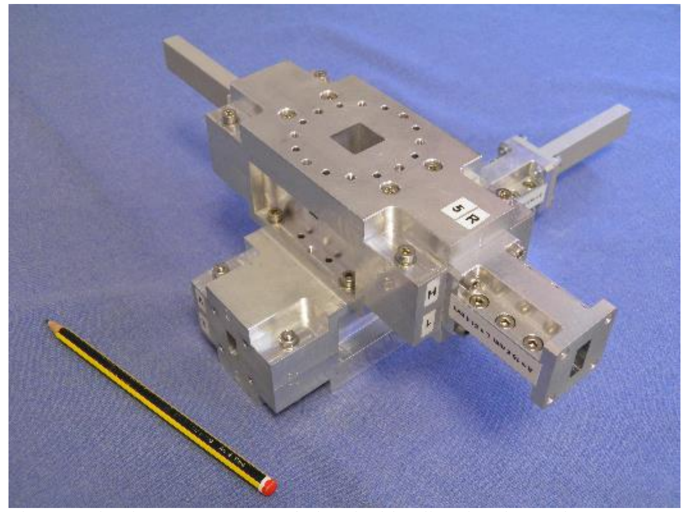

Fig. 6. Aluminum prototype of the double directional coupler to square waveguide with waveguide terminations in two of the rectangular waveguide ports named 3 and 4. Dimensions 193.9 mm x 193.9 mm x 106.2 mm.

Table I
Dimensions of the Double Directional Coupler to Square Waveguide

Parameter	Dimension (mm)	Parameter	Dimension (mm)
a	15.8	b	7.9
a_s	16.8	Lh	6.3
W	106.2	Wh	2.7
W1	53.1	d1	67.9
L	142.5	d2	74.6
L1	62.8	Ls1	19.5
Wa	8.7	Ls2	35.6
Wb	10.2	Lr0	51.4
Wc	10.7	Lr1	30.5
Wd	8.8	Lr2	9.0
We	11.6	Lr3	4.7
Wf	8.3	Lr4	2.9
Wg	8.5	Lr5	7
Wj	5.8	Lr6	7

The measured and simulated coupling factor for both couplers (C1 and C2) for both propagating modes (Y and X) to port#5 of the square waveguide are depicted in Fig. 7. These results are measured with waveguide terminations in three ports of the rectangular waveguides and a well matched horn facing a microwave absorber material in port#6. Waveguide terminations are in port#3 of Coupler#1, port#4 of Coupler#2, and in port#2 of Coupler#2 for measuring C1 or in port#1 of Coupler#1 for measuring C2. The obtained coupling factor to the desired mode is -31±3.8 dB in the frequency band from 10 to 18.9 GHz, with C1 coupling to the mode V ($C1_{5Y}$) and C2 to the mode H ($C2_{5X}$). On the other hand, the coupling to the orthogonal modes for both couplers are lower than -80 dB, except for some frequencies that achieve -60 dB, measuring with 10 MHz frequency step, which corresponds to an average cross-polarization of 48 dB.

The difference in amplitude and phase of the coupling $C1_{5Y}$ and $C2_{5X}$ is depicted in Fig. 8. The amplitude and phase errors are ± 0.2 dB and ± 1º from 10 to 18.9 GHz.

Subsequently, the isolation measurement for both orthogonal modes is performed from port#1 or port#2 to port#6, with waveguide terminations in three of the rectangular waveguides ports and a well matched horn facing a microwave absorber material in port#5. These isolation measurements together with simulation results are shown in Fig. 9. The obtained isolation is better than -50 dB at the low frequencies of the band. The directivity is reduced up to 5 dB for the high frequencies of the band.

The insertion loss of the square waveguide section itself is lower than 0.3 dB up to 15 GHz and lower than 0.2 dB up to 18.9 GHz, with return loss better than 15 dB over the whole frequency band as it is shown in Fig. 10.

Measurements of the coupling and isolation for both waveguide directional couplers to square waveguide showing the symmetry of the double directional coupler are depicted in Fig. 11. For Coupler#1 both coupling and isolation parameters are for mode TE_{01}(Y) in port#5 and for Coupler#2 both coupling and isolation parameters are for mode TE_{10}(X) in port#6.

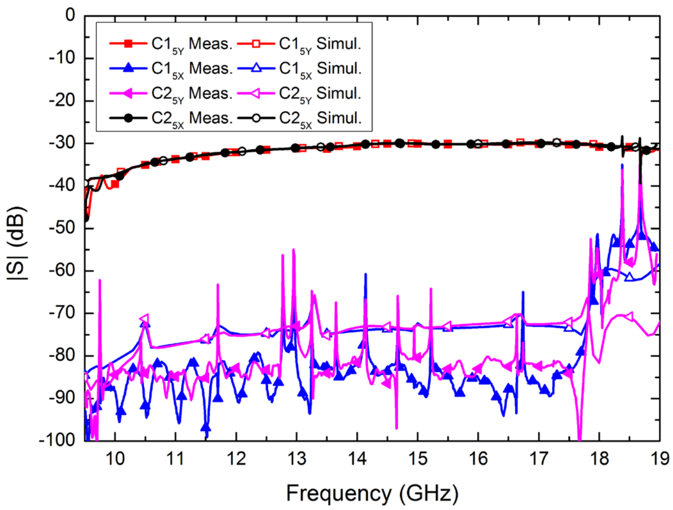

Fig. 7. Simulation and measurements of the coupling for both directional coupler to square waveguide and for both modes TE_{01} (Y) and TE_{10} (X). Results with waveguide terminations in port#3, port#4, and port#2 for C1 or port#1 for C2.

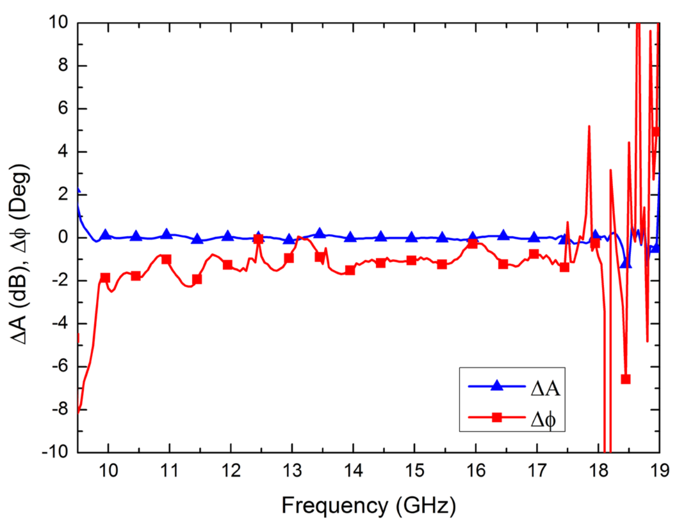

Fig. 8. Simulation and measurements of the amplitude and phase difference between both directional coupler to square waveguide for the coupled modes TE_{01}(Y) ($C1_{5Y}$) and TE_{10}(X) ($C2_{5X}$).

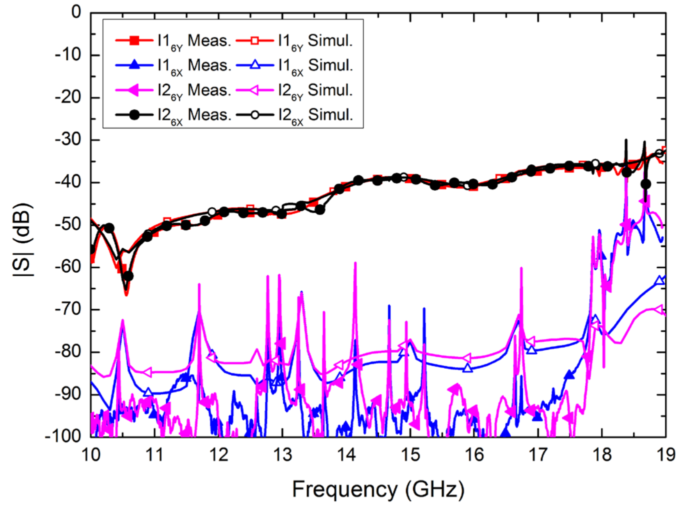

Fig. 9. Simulation and measurements of the isolation for both directional couplers to square waveguide and for both modes TE_{01}(Y) and TE_{10}(X). The results are with waveguide terminations in port#3, port#4, and port#2 for I1 or port#1 for I2.

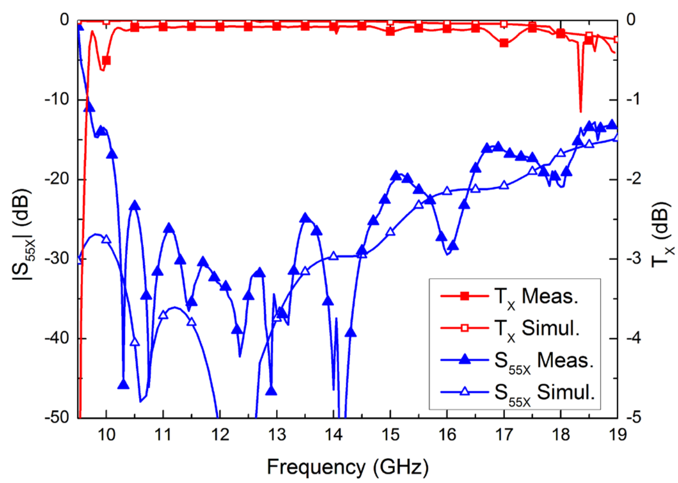

Fig. 10. Simulation and measurements of the transmission and matching for the square waveguide. All the rectangular waveguide ports are with waveguide terminations.

A. Stokes parameters of calibration signals

The Stokes parameters at the receiver input, relative to two in-phase signals with the same amplitude applied to the coupler, can be calculated using the measured parameters $C1_{5Y}$ and $C2_{5X}$ with axis basis $(\hat{x}, \hat{y})$ according to Fig. 2. The calculated Stokes parameters are normalized respect to the intensity I and they are shown in Fig. 12 (a). The parameter V indicates the level of circularly polarized wave, which appears as a parasitic due to the small phase difference between the two coupled signals depicted in Fig. 8. The component $\sqrt{Q^2 + U^2}$ is the output signal power level with respect to the applied input signal power, and the V component, which is more than 15 dB lower, are depicted in Fig. 12 (b).

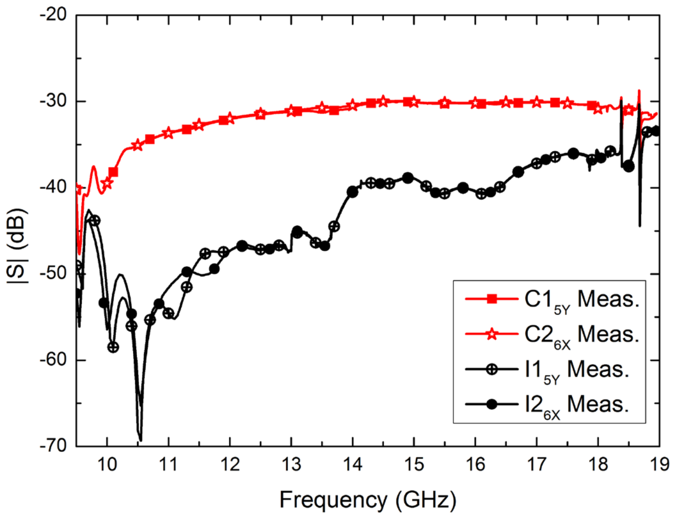

Fig. 11. Measurements of the coupling and isolation for both directional couplers to square waveguide. For Coupler#1 to mode TE_{01}(Y) and for Coupler#2 to mode TE_{10}(X).

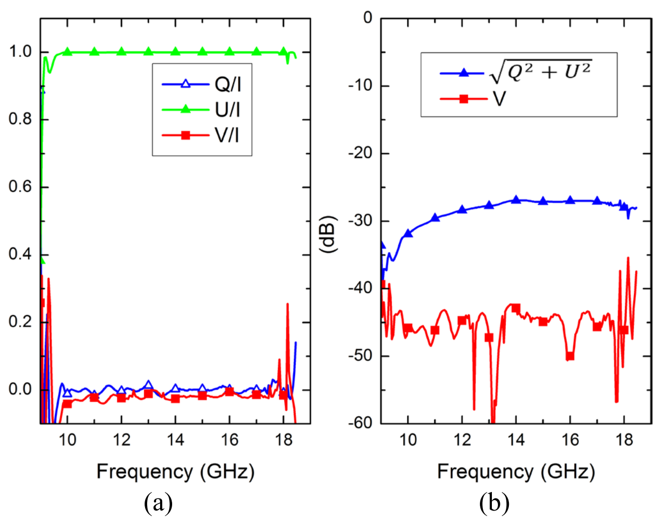

Fig. 12. (a) Normalized Stokes parameters for two in-phase signals with the same amplitude applied to the coupler calculated with coupling parameters measurement. (b) Measured $\sqrt{Q^2+U^2}$ and V components.

The obtained Stokes parameters show that injected in-phase signals and with same amplitude produce a linearly polarized wave of 99.9% with an angle of polarization of 45º and below 2% of circular polarization. A different angle of linear polarization is obtained when the amplitude of the two injected signals is different. Moreover, circular polarization can be obtained with two injected signals with the same amplitude and 90º out of phase. Finally when both the amplitude and phase of the injected signals are different, an elliptically polarization is obtained. Therefore, the presented coupler allows to generate the three linearly polarized waves and a circular polarized wave needed to calibrate the four parameters of a fully polarimetric radiometer. In the case of the CMB it is considered that the parameter V is cero since the CMB has no circular polarization, then with three linearly polarized waves a polarimetric radiometer intended to measure the CMB could also be calibrated with the proposed coupler.

IV. Conclusion

A new double waveguide coupler to square waveguide targeted for polarized calibration is presented. This waveguide coupler is designed to couple the two orthogonal modes TE_{10} and TE_{01} in a square waveguide through rectangular waveguides, obtaining a known elliptically polarized wave. This subsystem can be placed after the antenna of a polarimetric radiometer, injecting signals that are coupled to the square waveguide to produce at least four brightness temperatures for polarization calibration and measurement of Stokes parameters. The double square waveguide coupler is composed of four E-plane split-block waveguide parts, which are easy to manufacture, and they are assembled in two blocks rotated 90 degrees. Both simulated and measured performances show very good agreement in terms of S-parameters. The measured results demonstrate a full-band double coupler from 10 to 18.9 GHz with average coupling of around 31dB and cross polarization better than 50 dB.

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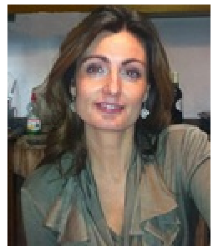

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