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A 170 GHz 45° Hybrid for Submillimeter Wave Sideband Separating Subharmonic Mixers

Peter J. Sobis, *Student Member, IEEE,* Jan Stake, *Senior Member, IEEE,* and Anders Emrich

Abstract—We present a 135°/45° phase shifter hybrid intended to be used in subharmonic sideband separation mixer schemes at submillimeter-wave frequencies. The design consists of an increased height 90° 6-arm branch guide coupler with a three stub loaded differential line 45° phase shifter at the output. The device has been implemented at G-band in an E-plane WR-05 splitblock design with a center frequency of 170 GHz and 15% bandwidth. Measured S-parameter are in good agreement with simulations showing an isolation and return loss better than 20 dB and an amplitude and phase imbalance within 0.4 dB and 2° respectively.

***Index Terms*—Millimeter wave directional couplers, millimeter wave phase shifters, power dividers, rectangular waveguide filters, terahertz waveguide couplers**

I. Introduction

THE Branch Guide Coupler (BGC) is a general component with a wide range of applications (eg. power monitoring, divide-combine networks, beamforming networks etc.). Its development originates from early work on military radar systems during World War II, which operated at frequencies up to about 300 MHz, see [1] for a historical review of microwave couplers. More recently it has also been used at submillimeter wave frequencies as an LO/RF hybrid in various sideband separating receivers employing fundamental SIS mixers [2]-[4].

In an attempt to develop the first submillimeter-wave subharmonic sideband separating Schottky mixer [5], we present a 135°/45° phase shifter waveguide hybrid operating at 170 GHz. The development of this novel waveguide hybrid intended to be used as an LO hybrid is motivated by the fact that subharmonic sideband separation mixers that utilize quadrature LO feeding require half the phase difference for the LO signals compared to their corresponding fundamental sideband separation mixer schemes, see [6] and [7].

The design consists of an increased height 90° 6-arm branch guide coupler with a three stub loaded differential line 45° phase shifter at the output and has been implemented in the WR-05 waveguide standard, see [8] and [9] for the theory and optimum design method for this type of fixed tuned phase shifter hybrids.

Moreover it has been designed with relatively large dimensions keeping the depth to width aspect ratio (using standard E-plane splitblock fabrication) below 1:2.12. A sensitivity study has been performed showing that the design can be scaled up in frequency by at least a factor of three, using modern high precision milling systems. Further scaling up in frequency would be possible using DRIE processing techniques [10].

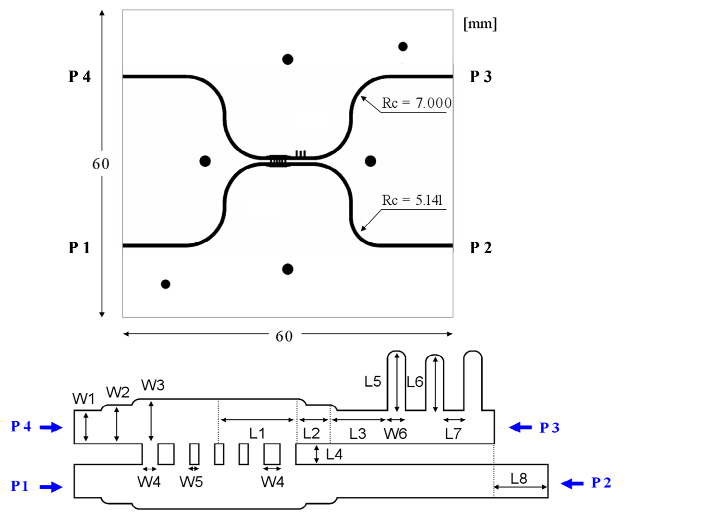

Fig.1. Block layout (top) with a symmetrical position of the input and output ports and detailed drawing of the phase shifter design (bottom), the radius of all inner corner features is 150 um.

TABLE I
DESIGN DIMENSIONS

Parameter	Length (mm / λ_g)	Parameter	Width (mm / λ_g)
L1	1.499 / 0.646	*W1*	0.648 / 0.279
L2	0.583 / 0.251	*W2*	0.758 / 0.327
L3	1.094 / 0.471	*W3*	0.868 / 0.374
L4	0.400 / 0.172	*W4*	0.300 / 0.129
L5	1.161 / 0.500	*W5*	0.166 / 0.072
L6	1.082 / 0.466	*W6*	0.340 / 0.146
L7	0.380 / 0.164		
L8	0.798 / 0.344		

Table 1. Parameter values of the BGC drawing found in Fig.1, the wavelength λ_g at 170 GHz is 2.321 mm in a WR-05 standard height waveguide.

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II. Design Methodology and Fabrication

A. Design Considerations and Approach

There are numerous examples of branch guide coupler designs, see [2-4], [9]. Many of the 3-dB couplers use relatively narrow branches in standard height rectangular waveguide configuration. To simplify machining and make the design scaleable up in frequency, the coupler branch width should be large enough to be able to use standard tools that typically have an aspect ratio of less then 1:3. To achieve this, an increased height WR-05 branch guide coupler design had to be used, similar to the design presented in [4]. The design layout is described in Fig. 1 with the accompanying block dimensions presented in Table 1. Starting from a scaled version of the WR-10 standard waveguide height coupler described in [3], the coupler input waveguide height has been tuned step by step followed by stepwise increases of the coupler branch widths to exactly 0.3 mm, which was the available tool diameter dimension at the time. In addition, a single section transformer to standard waveguide height was added to all four coupler ports. The stub-loaded phase shifter was then designed separately keeping the stub waveguide height also larger than 0.3 mm. Finally both the coupler and phase tuner were merged and fine tuned in a full 3D-EM simulation.

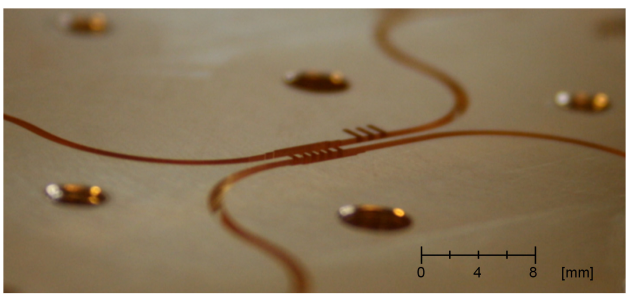


Fig.2. Photograph of the WR-05 waveguide phase shifter hybrid manufactured in an E-plane split block.

B. Simulation Method

Both the coupler and the phase shifter have been designed using the finite element method 3D-EM solver HFSS from Ansoft, implementing complete parametric models of the 3D structure. In order to speed up the simulations, H-plane symmetry of the fundamental TE_{10} waveguide mode has been used. For the three stub phase shifter design, a combination of *S*-parameter data of EM-simulated waveguide T-junctions of different heights together with ideal waveguide elements in the ADS circuit simulator from Agilent were used as a complement to the 3D-EM modeling.

For the 3D-EM simulations of the complete phase shifter hybrid, a mesh size larger then 30000 tetrahedrons was typically required in order to achieve good convergence.

C. Splitblock Layout and Fabrication

The final split block layout measured 60 mm by 60 mm and had relatively long waveguides leading to the device approximately 9 mm by 4 mm in size. In order to get a symmetrical position of the waveguide flange interfaces and at the same time obtain the correct phase difference between the outputs, a different size radius was used in one of the output bends, as shown in Fig.1. The symmetrical layout and the large spacing between the waveguide interfaces simplify the connection of external flanges, but also make it possible to use the block in backward direction as a 90° hybrid.

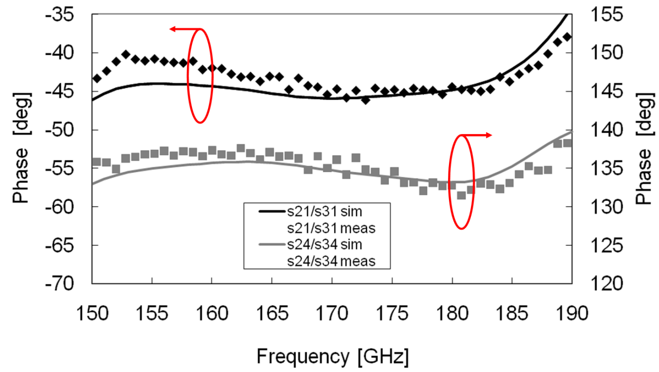


Fig.3. Simulated (solid) and measured (dot) phase imbalance.

The block was manufactured in a KERN Evo NCR micro milling system with a 0.3 mm diameter 1 mm long cutter tool and was machined out of a brass block and goldplated to a thickness of approximately 1 µm, a photograph of the block can be seen in Fig.2.

III. Results

The x-y dimensions of the manufactured splitblock, see Fig.1, were verified to be within 5 µm, using a digital camera microscope. A more precise verification method must be used to see if the expected machining tolerances of 1 µm were reached. Due to a configuration error in the machining program, the final depth of the two main waveguide channels including the widened profile and the three waveguide stubs, was increased by 30 µm, whereas the coupler arms had the correct waveguide depth. This error could easily be corrected in the future, expecting no depth variations in between the different features of the waveguide component.

A sensitivity analysis of the design, in which the design parameters were varied by 10 µm, showed a maximum change in the amplitude and phase imbalance of 0.3 dB and 0.5° respectively. Variations in the coupler branches had the largest impact on the amplitude imbalance, while variations in the phase shifter stubs seem to have the largest effect on the phase imbalance.

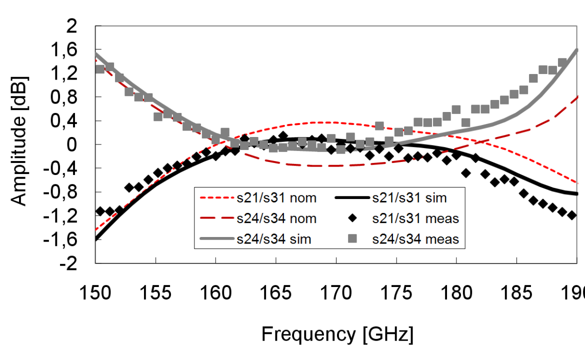
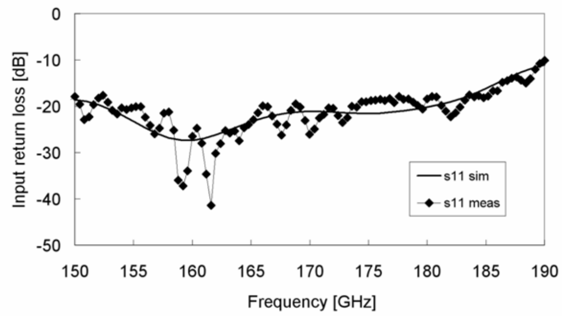
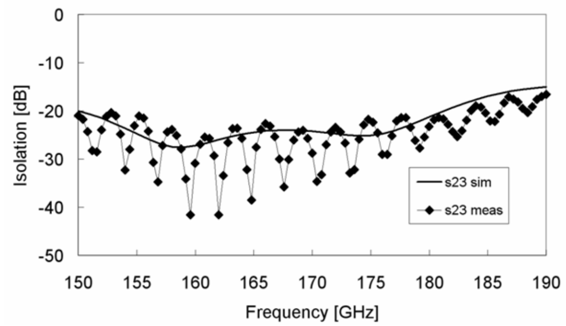


Fig.4. Simulated (solid/dashed) and measured (dot) amplitude imbalance.



(a)



(b)

Fig.5. Simulated (solid) and measured (dot-solid) input return loss (a) and isolation (b).

The device was tested using the Agilent 8510C vector network analyzer together with a WR-05 OML frequency extender, in a test setup configuration with additional RF and LO synthesizers (HP 83651A and HP 83621A) and a millimeter wave controller unit (HP 85105A). Since semi rigid waveguide bends prove to be a source of very large through phase variations, only rigid waveguides were used in the test setup. Instabilities of the test setup added noisy ripples to the test data with a magnitude of approximately 0.2 dB and 1°.

S-parameter measurements of the device are presented in Fig. 3-5, and compared to simulated results for which the effect of the increased waveguide depth is included. The insertion loss through the block was measured to approximately 1 dB. The increase in waveguide depth resulted in approximately 0.25 dB lower coupling and a 2 GHz shift down in frequency with minor changes in the coupler phase and input return loss and isolation characteristics compared to the nominal design. This is in line with the results from the sensitivity analysis.

Moreover, the device characteristics of the S_{11} and S_{23} data seen in Fig.5 suffer from ripples with a 2.8 GHz periodicity. The half wavelength at 2.8 GHz coincides well with the total waveguide length of 78 mm across the block, pointing towards a mismatch between the block and the external waveguide flange connections. This mismatch could partly be due to the wrong waveguide depth in the manufactured block, but it is more likely to originate from the calibration itself or from poor waveguide interface connections.

It also proved to be difficult to determine the correct phase shift, and extra care had to be taken in the alignment and fastening of the flange connections.

IV. Conclusions

A 170 GHz 45° phase shifter hybrid with a 15% bandwidth, and with a phase and amplitude imbalance of 2° and 0.4 dB respectively has been demonstrated. A sensitivity analysis of the design shows that it can tolerate variations of $\sim\lambda_g/200$, keeping the amplitude and phase imbalance within 0.3 dB and 0.5° respectively from nominal. Consequently the design can be scaled to at least 0.6 THz with a machining tolerance of 3 µm. S-parameter measurements proved to be challenging and showed through phase variations in the order of several degrees.

Further evaluation of this hybrid is needed, as a first step it will be used in an experimental modular subharmonic sideband separating 340 GHz mixer, and at a later stage it will be integrated into a single sideband separating subharmonic mixer block minimizing transmission losses and eliminating any phase errors caused by the waveguide flange interfaces.

Acknowledgment

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