Novel Waveguide 3 dB Hybrid with Improved Amplitude Imbalance

Hawal Rashid, Denis Meledin, Vincent Desmaris and Victor Belitsky, Senior, IEEE

***Abstract*— We present a new design concept for a 90° waveguide hybrid and its implementation. This novel hybrid design is based on a multiple branch waveguide hybrid. The primary feature of this quadrature waveguide hybrid is the introduction of a controllable ripple in the operational band for achieving a better overall amplitude imbalance. This design concept is verified by implementation of a 90° waveguide hybrid for the 166 – 208 GHz band and can be used for waveguide hybrids up to several THz. Our simulations indicate that the amplitude imbalance of the designed hybrid is better than 0.11 dB over the most of the 166 - 208 GHz band with a phase imbalance better than ±2.3°. Experimental verification of the hybrid shows excellent agreement with simulations with an amplitude imbalance better than 0.15 dB and phase imbalance of ± 2.5° over most of the band being achieved.**

***Index Terms*— Waveguide hybrid, Millimeter and sub-millimeter component, THz component, Directional coupler**

I. Introduction

DIRECTIONAL couplers have been studied since the 1940s, resulting in a variety of design techniques for both waveguide and substrate-based components. While most of the theoretical foundation was developed during the 1960s, branch line couplers, such as that shown in Fig.1 (in the case when a=0) remain a pertinent research topic today [1]. Branch line couplers have attained much attention due to their simplicity and ease of fabrication. The multiple branch waveguide 90° hybrid (referred to as a waveguide hybrid throughout) [2], [3] has proven to be a very suitable type of coupler, especially for high frequency (mm wave to THz wave) applications such as radio astronomy instrumentation [4], [5], [6], [7].

The classical waveguide hybrid design [2], [3] allows for very good directivity, return loss and phase imbalance (usually better than ±1°**)** within the operational bandwidth. Amplitude imbalance on the other hand is typically approximately 1 dB or worse for broadband operation [8]. Furthermore, the maximum amplitude imbalance occurs at the designed center frequency, which is depicted with the dashed line in Fig.2. This is an undesired feature in many applications, especially in receiver systems that employ a Sideband Separation (2SB) layout [4]. Since all components in a 2SB receiver chain (except the waveguide hybrid) perform optimally at the center frequency, a waveguide structure that allows for controllable ripples in the operating band, similar to substrate based multi-section hybrids [9], is desirable.

Manuscript received on July 12, 2013, Revised October 7, 2013 and Accepted November 26, 2013. The authors are with the *Group of Advanced Receiver Development* (GARD) at Chalmers University of Technology,Gothenburg,Sweden.(email:Hawal@chalmers.se)

The work presented here concerns design and development of a novel waveguide 90º hybrid, which is different from predecessors by introducing controllable amplitude ripples within the operating bandwidth.

A typical design condition of a waveguide directional coupler is a maximized directivity / isolation. We introduce a design concept whereby relaxing this condition for maximum isolation, the layout of the hybrid is modified such that interleaved ripples are introduced into S21 and S31 (cf. Fig.1), thus yielding minimum amplitude imbalance within the operating frequency band. Such a modified hybrid is a trade-off between the controllably degraded return loss and the improved amplitude imbalance. Furthermore, the presented design is not limited to the waveguide implementation: the same technique could be applied to any multi-section branch-line-coupler, including stripline or microstrip line based couplers.

II. Hybrid design

According to [2], a periodical coupler exhibits optimal performance for an even number of sections. Hence, an eight branch periodical waveguide was designed to achieve as low amplitude imbalance as possible over 166-208 GHz, approximately 22.5% fractional bandwidth. This operation band was selected in order to measure the hybrid performance with existing in-house Vector Network Analyzer (VNA) extension modules, which operate from 140 GHz to 220 GHz.

Figure 1 shows the cross section for the proposed layout of the eight-branch waveguide coupler, where the dashed line indicates the symmetry plane in the structure. The coupler properties can be calculated either with even and odd mode analysis, similar to [3], or by employing numerical analysis methods [10].

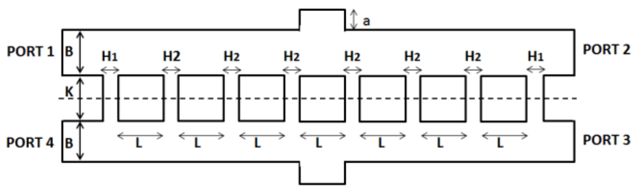

Fig.1. Cross section of the eight branch hybrid. The dashed line shows the symmetry plane.

Three different designs of an eight-branch periodical waveguide hybrid where evaluated using the analysis techniques provided by [2] and [3]. Design 1 considers the classical design in order to find the hybrid properties and its limitations. Design 2 reveals the possibility of introducing the ripples in the operational band and the limitation of such a design. Design 3 implements the findings from the former

designs together with a modification in the waveguide structure in order to improve performance considerably.
The geometrical parameters shown in Fig.1 and overall performance for the three designs are given in Table 1.
The bandwidth is usually determined by the operational band ripple amplitude. However, in this case, the simplest and the most straightforward approach for comparing the performance between the different designs is to compare a combination of parameters: reflection, isolation, amplitude, and phase imbalance for a fixed frequency band i.e., 166-208 GHz.

TABLE I
WAVEGUIDE HYBRID PARAMETERS FOR THREE DIFFERENT DESIGNS WITHOUT CORRECTIONS (ΔA IS THE AMPLITUDE IMBALANCE, Δφ IS THE PHASE IMBALANCE, AND RL IS THE RETURN LOSS)

Design	H_1/H_2	a	L	RL	ΔA	Δφ
1	0.8	0	λg0/4	<-25 dB	0.5 dB	± 0.2°
2	1.56	0	λg0/4	<-20 dB	0.5 dB	± 1°
3	1.33	80 um	λg0/4	<-16 dB	0.1 dB	± 2.3°

Design 1: The classical eight branch waveguide hybrid

The analytically calculated amplitude and phase imbalance performance of the reference hybrid design is depicted with dashed lines in Fig. 2. Furthermore, analytical analysis reveals the relationship between bandwidth and amplitude imbalance; specifically the wider the bandwidth the greater the amplitude imbalance becomes.

Design 2: Generating ripples across the operation band.

One of the synthesis conditions in [2, 3] is perfect directivity. As a consequence of this condition, the input and output branch impedance (H_1) must be substantially smaller than the remaining branch impedances (H_2). However, in order to generate ripples in the operation band, the condition required for perfect directivity needs to be relaxed by allowing the H_1 branch impedance to be noticeably larger than H_2. This design provides ripples within the operation band and a slightly increased bandwidth. The magnitude of the ripples can be amplified by further increasing H_1 at the cost of rapid degradation of both phase imbalance and the return loss. Furthermore, this hybrid design does not provide better overall performance as compared to Design 1.

Design 3: *Modified eight-branch waveguide hybrid*

The amplitude imbalance and ripple amplitude is considerably improved when both the branch height (H_1 and H_2) and the introduced increase in the waveguide height (*a)* at the center section i.e. the center point between the fourth and fifth branch (cf. Fig.1) is increased .The solid lines in Fig.2 illustrate the amplitude and phase imbalance for the proposed Design 3 and demonstrates the optimum performance over the whole bandwidth. This design not only improves the amplitude imbalance substantially, but it also has the lowest imbalance at the center frequency. The performance enhancement comes at the cost of slightly degraded phase imbalance. Similarly, the impedance mismatch between the center section and the adjacent sections deteriorates the return loss and isolation (cf. RL in Table 1). The larger the center section (a), the larger the ripple amplitude becomes, thereby increasing the bandwidth of the waveguide hybrid. However, the gain in bandwidth comes at the cost of further impedance mismatch and degradation of the phase imbalance.
Design 3 was simulated in the 3D electromagnetic structure simulator Agilent EMPro [11]. The design parameters calculated from theoretical analysis [2], [3] were slightly tuned in order to match the simulated and theoretically calculated performance. The waveguide hybrid dimensions (cf. Fig.1) are, B= 630 µm, K= 383 µm, H1=183 µm, H2=118 µm, a=80 µm, L=394 µm. The hybrid was fabricated in the in-house workshop with a KERN CNC milling machine [12], which has ± 2 um accuracy. A tolerance analysis was made using Agilent EMPro, where both the classical periodical hybrid and design 3 was compared. The tolerances of the two hybrids are very similar. According to simulations, the main guide width (**K)** has a tolerance of better than ±10 um and a small deviation such as ± 2 um has negligible effect. However, when the entire branch height (**H)**, deviates simultaneously by the same amount from the design value, this would result in approximately 0.1 dB imbalance (for ± 2 um).

III. MEASUREMENTS

The waveguide hybrid was measured with Agilent two port Vector Network Analyzer (VNA) with OML 140-220 GHz extension transmitter and receiver modules. The VNA was calibrated with the OML standard TRL waveguide calibration kit. Since the hybrid is a reciprocal four-port device, only through, coupled and isolated S-parameters need to be measured in order to fully characterize the hybrid. The reflection coefficient is obtained in any of these measurements. In the first measurement, a pilot signal is excited at Port 1 cf. Fig.1. The pilot signal is measured at Port 2 (through) and input Port 1 (reflected signal) while the remaining ports are terminated with waveguide matched loads from the calibration kit.

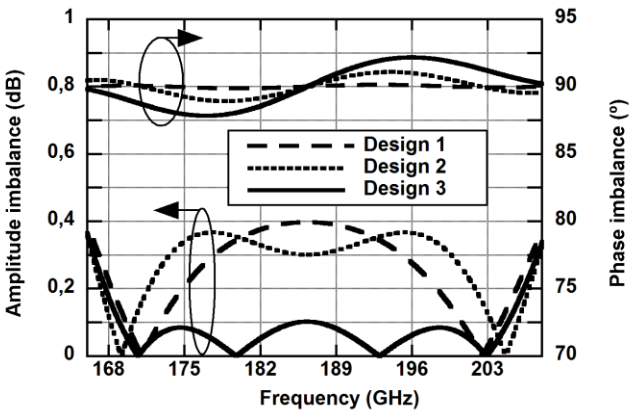

Fig. 2. Theoretical comparison of amplitude and phase imbalance for waveguide hybrid with different designs.

Subsequently, Ports 1 and 3 (coupled) were connected and measured while the remaining ports are terminated. Finally, Ports 1 and 4 were connected and measured while the through and coupled ports were terminated. In order to account for the conductive loss in the leading waveguides, a two port fixture with the exact shape and length as the hybrid through path was fabricated. The S-parameters from the fixture were measured and used to de-embed the losses

(0.015 dB/mm) of the leading waveguides (between the calibration planes at the output of the extension modules to the input of the hybrid structure) from the measured hybrid S-parameters. The insertion loss of the hybrid itself is approximately 0.23 dB (cf. Fig.4).
Fig. 4 and 5 show the time gated [11] measurement performance of Design 3 of the hybrid having eight branches with the impedance step in the middle of the hybrid as depicted in Fig.1.

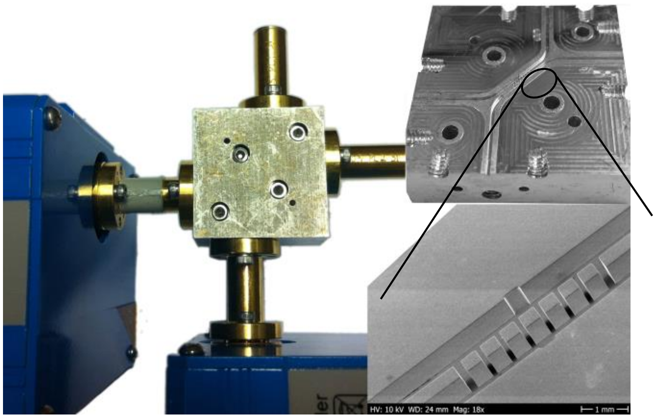

Fig. 3. A picture of the measurement setup including, 140-220 GHz extension modules, the hybrid with an SEM picture of the interior. The port numbers has the same arrangement as in Fig.1.

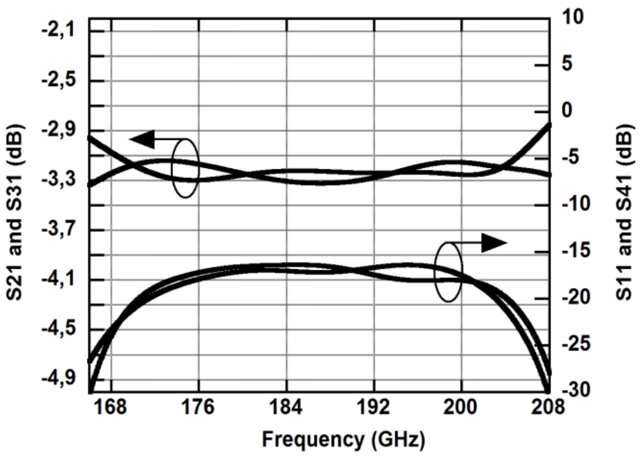

Fig. 4. Measured through, coupled, reflection and isolation performance of the Design 3.

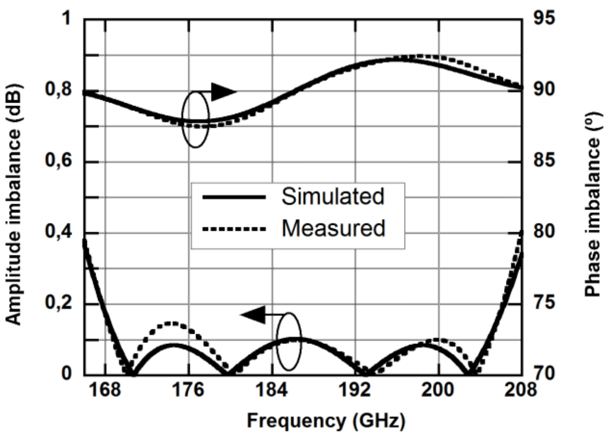

Fig. 5. Measured and simulated amplitude and phase imbalance of the Design 3.

The measured performance of the hybrid demonstrates perfect agreement with simulations.

IV. Conclusions

We have presented a new design concept for 90° waveguide hybrid. The novel hybrid design is based on the multiple branch waveguide design. The primary feature of this hybrid design is the introduction of a controllable ripple in the operational band by changing the width of the outer branches of the structure and introducing an appendix aperture in the point of the hybrid symmetry for achieving better overall amplitude imbalance. This design concept can be used for waveguide hybrids up to several THz. We presented here an implementation of the novel design concept for the realization of 90° waveguide hybrid for 166 – 208 GHz band. Our simulations indicate that the amplitude imbalance of the designed hybrid better than 0.1 dB over the most of the 166 - 208 GHz band with phase imbalance better than ±2.3°. Experimental verification of the hybrid shows excellent agreement with the simulations yielding measured amplitude imbalance better than 0.15 dB and phase imbalance of ± 2.5° (cf. Fig.5) over most of the band.

Acknowledgment

The authors would like to thank Alexey Pavolotsky for fruitful discussions. The authors would also like to thank Sven-Erik Ferm and Mathias Fredrixon for the hybrid fabrication.

References

[1] N. A. Sutton, J. M. Oliver, and D. S. Filipovic, "Wideband 18-40 GHz Surface Micromachined Branchline Quadrature Hybrid," *Microwave and Wireless Components Letters, IEEE,* vol. 22, pp. 462-464, 2012.

[2] G. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*: Dedham, MA: Artech House, 1980.

[3] J. Reed, "The Multiple Branch Waveguide Coupler," *IEEE Transactions on Microwave Theory and Techniques,* vol. 6, pp. 398-403, 1958.

[4] A. website. www.almaobservatory.org.

[5] H. Andoh, T. Minamidani, N. Mizuno, A. Mizuno, Y. Fukui, S. i. Asayama, *et al.*, "Design of Wideband 3dB Branch-line Couplers for ALMA Band 3 to 10.," *ALMA MEMO #468*.

[6] B. Billade, O. Nystrom, D. Meledin, E. Sundin, I. Lapkin, M. Fredrixon, *et al.*, "Performance of the First ALMA Band 5 Production Cartridge," *Terahertz Science and Technology, IEEE Transactions on,* vol. 2, pp. 208-214, 2012.

[7] D. Meledin, A. Pavolotsky, V. Desmaris, I. Lapkin, C. Risacher, V. Perez, *et al.*, "A 1.3-THz Balanced Waveguide HEB Mixer for the APEX Telescope," *Ieee Transactions on Microwave Theory and Techniques,* vol. 57, pp. 89-98, Jan 2009.

[8] S. Srikanth and A. Kerr, "Waveguide quadrature hybrids for ALMA receivers," *ALMA Memo #343,* 2001.

[9] H. Rashid, D. Meledin, V. Desmaris, B. Billade, A. Povolotsky, and V. Belitsky, "Multi-Section Superconducting 4-8 GHz Compact Hybrid Chip for Improvement of Mixer Sideband Rejection," *Transactions on Microwave Theory and Techniques,* 2013.

[10] H. Andoh, S. Asayama, H. Ogawa, N. Mizuno, A. Mizuno, T. Tsukamoto, *et al.*, "Numerical Matrix Analysis for Performances of Wideband 100GHz Branch-Line Couplers," *International Journal of Infrared and Millimeter Waves,* vol. 24, pp. 773-788, 2003/05/01 2003.

[11] http://www.agilent.com.

[12] KERN *http://www.kern-microtechnic.com/upload/media/kern_evo_e.pdf*