Wideband Low-Cost Hybrid Coupler for mm-Wave Frequencies

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***Abstract*—In this paper a new realization of a wideband waveguide hybrid coupler is proposed, which can be realized as a low-cost metallized injection-molded component. A key requirement for low costs is a split-block suited design approach. For that reason, the waveguide ports are stacked in the E-plane. The coupling mechanism is explained in a narrowband approach. By expanding the coupling region in the H-plane, the approach is optimized concerning bandwidth. At 160 GHz a measured bandwidth of 23% is achieved with an isolation better than 20 dB and a very low insertion loss.**

***Index Terms*—hybrid coupler, wideband coupler, rectangular waveguide coupler, mm-wave frequencies.**

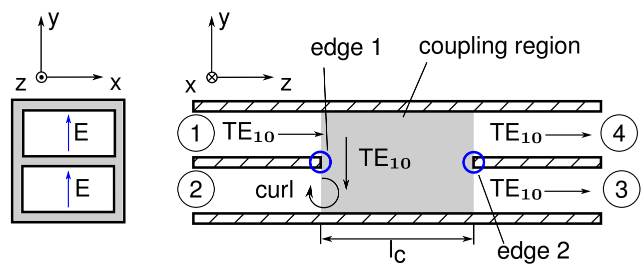


Fig. 1. Schematic cross-sections of the simplified waveguide coupler.

I. Introduction

High absolute bandwidth is one of the key requirements for many radio frequency (RF) and millimeter wave (mm-wave) systems. For communication networks, like 5G, high absolute bandwidth allow high data rates, many channels, and a robust communication. In radar sensors the range precision and resolution are directly proportional to the absolute bandwidth. For that reason the operating frequencies of the systems are being increased because many RF and mm-wave designs provide only limited relative bandwidths. With the technical progress of transistor speeds [1] systems above 100 GHz are feasible [2]. Many of these systems operate in transmit (Tx) and receive (Rx) mode simultaneously. A Tx-Rx-coupler is required when only one radiating element can be realized due to a lack of space or cost reasons.

Several technologies for hybrid couplers are available. Chip-integrated components are cheap but suffer from high insertion loss and limited isolation [3]. Printed circuit boards (PCB) implementations require RF suitable laminates and also suffer from losses and tolerances in the high mm-wave frequency range. For that reason, the rectangular waveguide is a precise and low-loss alternative. A low-cost technology for rectangular waveguide components is the split-block design with metallized injection-molded half-shells.

In the literature, waveguide couplers are often split in the H-plane, like in [4]. This positioning is disadvantageous for realizations in two half-shells since H-plane cuts are more sensitive to contact tolerances because of the currents, which have to pass between the half-shells. In other approaches small parts, like slot structures in [5] or thin separation walls in [6], are required that complicate a split-block design.

In this paper, a compact hybrid coupler is proposed, which is suitable for a low-cost realization with a simple split-block design. In Section II the operation principle is explained, followed by the simulation results in Section III. The fabrication options are discussed in Section IV before the measurement results in Section V.

II. Functional Principle

The proposed hybrid coupler is based on two rectangular waveguides, which are stacked in the E-plane, as depicted in Fig. 1. The wall between the two rectangular waveguides is removed in the coupling region so that TE_{10}-modes are able to propagate not only in x-direction but also in y-direction. The edge 1 is a strong discontinuity for the incident wave at port 1, resulting in a curl of the electric field at port 2. The E-field of the curl has the opposite orientation compared to the E-field, which is reflected at edge 2 at the other side of the coupling region. This leads to destructive interference and consequently port 2 is decoupled of port 1. This principle works only in a very limited bandwidth. Additionally, the wall between port 1 and 2 has to be assumed to be infinitely thin.

To enhance the bandwidth, the coupling region is expanded in the H-plane. Thus, TE_{20}- and TE_{01}-modes can be excited in x-direction. The symmetrical expansion of the coupler is shown in the 3D schematic view in Fig. 2. Because of the increased height of the coupling region h_c, the three modes have different phase velocities. This leads to mutual coupling of the modes and creates a degree of freedom to adjust the position of the curl. A further improvement is achieved by slightly decreasing the width of the coupling region w_c. The distance between port 1 and 2 and port 3 and 4 causes undesired reflections of the electromagnetic wave. A reduction of these distances is realized by decreasing the wall thickness from g to t_w in front of the coupling region with a linear taper of length l_{taper}.

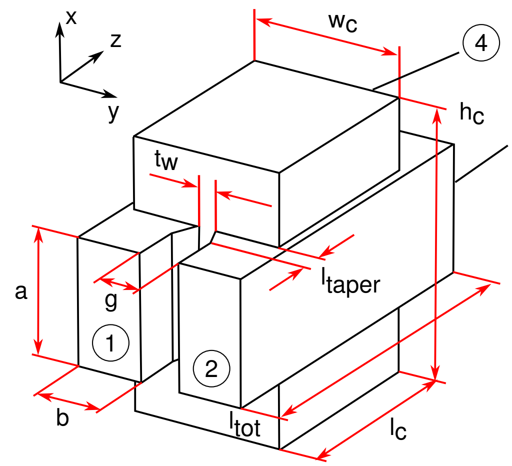


Fig. 2. 3D schematic view of the complete coupler with its parameters.

TABLE I
DIMENSIONS OF THE 160 GHZ WAVEGUIDE COUPLER.

parameter	length in µm	parameter	length in µm
a	1251	b	626
l_{tot}	3369	l_c	1897
w_c	1463	h_c	2676
g	385	t_w	193
l_{taper}	241		

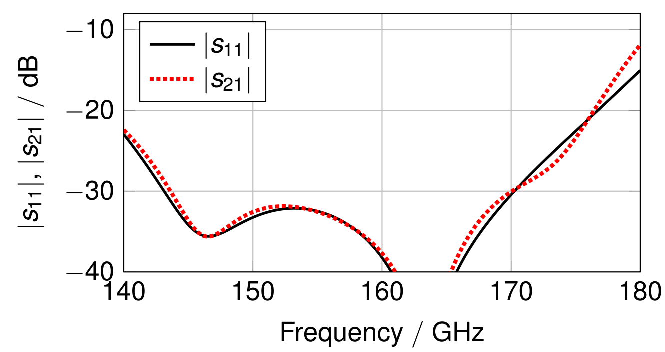
III. SIMULATION

Based on the explained principle the coupler was simulated and optimized leading to the dimensions listed in Tab. I. The critical port separation was reduced from 385 µm to 193 µm, which is realizable due to the wedge-shaped tapering structure.

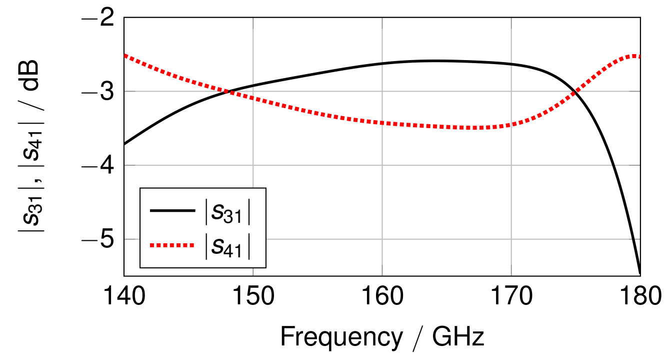
The simulated lossless S-parameters are depicted in Fig. 3. The transmission coefficient emphasizes the wideband performance of 35 GHz with an amplitude imbalance below 1 dB. The reflection coefficient of the coupler is below -20 dB from 140 GHz to 176 GHz. The isolation to the decoupled port is above 30 dB between 144 GHz and 170 GHz, which confirms the suitability of the coupler as Tx-Rx-coupler.

IV. FABRICATION AND ASSEMBLY

A key advantage of the proposed coupler is its simple fabrication due to lack of irises, slits, holes, or pins. It is realizable as a split-block design, which can be processed in two technologies. For fast prototyping the two half-shells are milled out of an aluminum block. A suitable low-cost production process is injection molding of the two half-shells with subsequent surface metallization. Compared to pure metal blocks, the elasticity of the metallized plastic materials improves the conductive contact between the two half shells because surface roughness, small air gaps, and scratches at the contact area are better compensated with the plastic parts. The alignment of the two half-shells is achieved with alignment pins. One half-shell of the prototype is depicted in Fig. 4 with



(a) Simulated reflection coefficient and transmission coefficient to the decoupled port.



(b) Simulated transmission coefficients of the coupled ports.

Fig. 3. Simulated S-parameters of the lossless coupler.

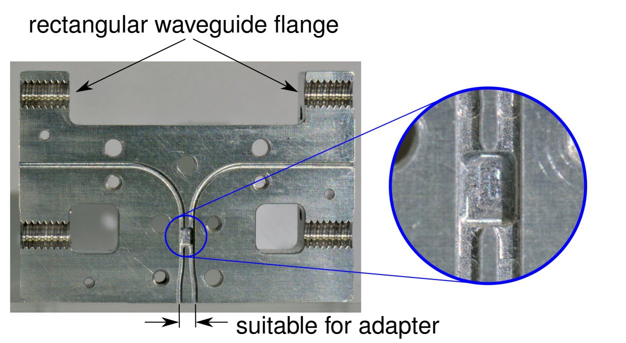


Fig. 4. One half-shell of the aluminum prototype with an enlargement of the coupling region.

an enlargement of the coupling region. The upper two ports are connected with standard waveguide flanges. The lower two ports are guided in parallel to the lower edge, where a suitable measurement adapter can be attached, which has the same shape as the coupler aluminum block but without the coupler.

V. MEASUREMENT RESULTS

The measurement setup for the scattering parameter s_{41} is shown in Fig. 5, where the rectangular waveguide absorbers are connected to the other two ports of the coupler. In a preliminary measurement the reflection loss of the absorbers was measured to be higher than 30 dB. For this S-parameter measurement two H-plane waveguide bends were required

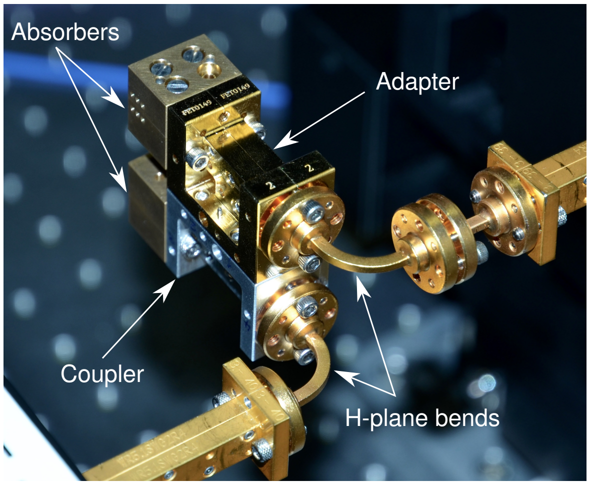
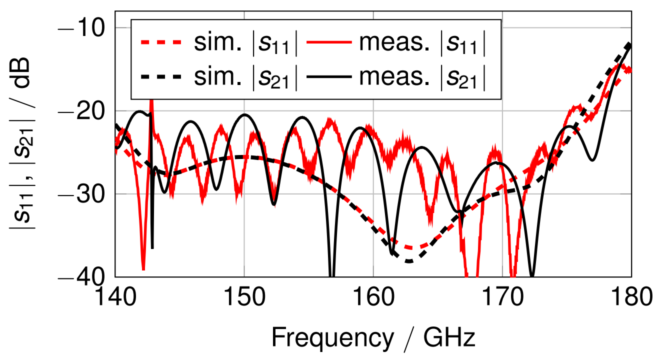
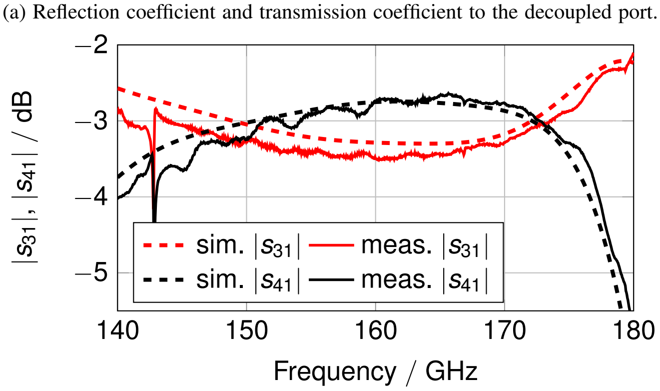


Fig. 5. Measurement setup with coupler and adapter, open coupler ports are terminated with absorbers.



(a) Reflection coefficient and transmission coefficient to the decoupled port.



(b) Transmission coefficients to the coupled ports.

Fig. 6. Simulated with milling radii and measured S-parameters of the coupler.

because the respective flanges are located at the same side.

A network analyzer with two converter modules from 140 GHz to 220 GHz was used for the S-parameter measurements. In Fig. 6 the measured S-parameters are compared to the simulation data taking into account the milling radii.

The milling radii slightly decrease the simulated return loss and isolation in Fig. 6a. However, both curves are above 25 dB over a bandwidth of 30 GHz. Compared to the simulation, the measurement curves are superimposed with ripples caused by reflections from the rectangular waveguide flanges. Due to the sensitivity of the measurement setup above 140 GHz, these reflections cannot be avoided completely. In a radar or communication system the transmitter, the receiver, and the antenna, e.g. a horn antenna, can be integrated in one split-block component or one metallized injection-molded part together with the coupler to minimize these reflections.

Despite the ripples the simulated and measured curves show a very similar behavior. A return loss of over 20 dB was achieved in the measurement up to 175 GHz. Similarly, the isolation is better than 20 dB up to 175 GHz.

The agreement of the simulated and measured transmission coefficients from port 1 to the coupled ports in Fig. 6b is obvious. In the measured curves the losses of the feeding waveguides are deembedded. The ripples in the measurement data are caused by reflections from the waveguide flanges. The losses in the coupler itself are only about 0.1 dB to 0.2 dB due to the low-loss rectangular waveguide technology.

VI. Conclusion

In the proposed coupler design the requirements concerning wideband, low losses, and high isolation can be realized in a low-cost technology, like metallized injection molded parts. By removing the sidewall between two waveguides stacked in the E-plane, the coupling region is created. The expansion of the coupling region in the H-plane generates two degrees of freedom, which are used to enhance the coupler's bandwidth. Due to the consciously chosen positioning of the waveguide ports in the E-plane, the coupler is realized as a split-block design with an E-plane cut. The measured performance matches well with the simulations and confirms the proposed coupler design. In comparison to the state-of-the-art listed in Tab. II, the compact hybrid coupler only requires two split-block half-shells, which are stacked in the tolerance insensitive E-plane. No metal pins or substrate parts are necessary emphasizing the simple approach.

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TABLE II
OVERVIEW OF REALIZED RECTANGULAR WAVEGUIDE HYBRID COUPLERS

Property	This work	[4]	[7]	[8]	[9]	[6]
Center frequency	160 GHz	94 GHz	100 GHz	250 GHz	440 GHz	12 GHz
Relative bandwidth	23%	17%	32%	8%	25%	30%
Size in wavelength	1.27	2.02	1.29	1.06	2.73	0.88
Cutting plane	E	H	E	E	E	E
Number of elements	2	2	2	2	8	3
# of pins / # of non metal parts	0 / 0	0 / 0	3 / 0	3 / 0	0 / 6	1 / 0

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