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This is the accepted version of a paper presented at *2017 Asia-Pacific Microwave Conference (APMC)*.

Citation for the original published paper:

Malmqvist, R., Gustafsson, A., Svedin, J., Beuerle, B., Shah, U. et al. (2017)
A 220-325 GHz Low-Loss Micromachined Waveguide Power Divider.
In: *Proceedings of the 2017 Asia-Pacific Microwave Conference (APMC)* IEEE

N.B. When citing this work, cite the original published paper.

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<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-217909>

A 220-325 GHz Low-Loss Micromachined Waveguide Power Divider

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Abstract—A J-band (220-325 GHz) silicon micromachined waveguide power divider based on a tee-shape topology is presented. To characterise the power divider a test circuit was designed with one output path connected using a low return loss 90° multi-stepped bend while the other output path uses an on-chip matched waveguide load filled with an absorbing material. The power divider is fabricated using a micromachined waveguide technology employing a double H-plane split which results in low losses. Measured transmission and reflection coefficients are equal to $-3.5 \text{ dB} \pm 0.4 \text{ dB}$ at 231-330 GHz and between -10 dB and -20 dB at 220-320 GHz, respectively. A good agreement between the simulated and measured data was obtained by taking the microfabrication sidewall profile (undercut) into account in the simulations. To the best of our knowledge, this is the first time a low-loss micromachined power divider of this type is characterised within this frequency range.

Keywords—Micromachining; micromachined waveguide; waveguide power divider; millimeter-wave; submillimeter-wave

I. INTRODUCTION

Recent advances in MMIC technology have made development of communication and radar systems operating well into the submillimeter-wave (sub-MMW) spectrum a reality. For wireless communication and active/passive imaging applications such systems have the potential to meet the demand for higher bandwidths. For short-distance radar applications such as security screening, millimeter-wave and submillimeter-wave systems make high-resolution imaging sensors possible, also at safe stand-off distances. For a complete sub-MMW system many required subcomponents, such as low-loss power dividers, feed networks and antenna arrays cannot easily be integrated on an MMIC chip in a cost-efficient way. To this date, many of these waveguide components are still manufactured in mechanical workshops using CNC milling and manual assembly, based on split-block designs. The cost for a system built in this way is very high due to the serial nature of the manufacturing process and the attainable fabrication accuracy is insufficient in many cases, in particular for frequencies into the sub-MMW region.

Micromachining offers a significantly better manufacturing accuracy and flexibility compared to CNC milling. As it is a highly parallel process, fabrication tolerances are very accurate and micromachining offers the potential for low-cost volume production with high uniformity, very small features down to micrometer sizes, and even the integration of microelectromechanical (MEMS) reconfigurable devices up to 750 GHz, such as switches and phase shifters [1-2]. Design, fabrication and characterisation of micromachined hybrid couplers have been reported up to at least WR-1.5 band [3-8]. Wideband and narrow-band micromachined waveguide power divider designs implemented at 75-105 GHz and at 300 GHz were reported in [3] and [9], respectively. A 200-270 GHz 16 way power splitter/combiner module with an insertion loss of 4 dB back to back was presented in [10]. In this paper, we report on the design, manufacturing and characterisation of a J-band (220-325 GHz) power divider. The power divider was manufactured using a silicon micromachined waveguide technology developed at KTH [11] that comprises two H-plane splits to enable reduced waveguide losses. Two-port measurements of the manufactured device have been made possible by the use of an on-chip matched load [12].

II. DESIGN OF J-BAND POWER DIVIDER

Fig.1 depicts the topology used for the J-band silicon micromachined waveguide power divider. The input port (port 1) is connected to the output port (port 2) via a tapered tee-shape topology and a multi-stepped matched corner (90° bend) which enables improved performances in terms of reduced reflection losses over a wide bandwidth [13]. An integrated micromachined waveguide absorber [12] acting as a matched load is also used (connected to the right arm of the power divider) to enable two-port measurements of the fabricated device. An initial design of the J-band power divider was made based on a previously reported approach used for a W-band power splitter [3]. This design was optimised for the desired frequency band to obtain a final design for manufacturing. The used goal function involved minimising the losses of a symmetrical structure before adding the load and stepped bend.

Fig. 1. a) Topology of the 220-325 GHz silicon micromachined power divider with a multi-stepped bend and a 5 mm long tapered load filled with an absorber [12] to enable 2-port measurements of the fabricated waveguide device and b) top view of the power divider with a stepped bend (wo the load).

The following dimensions were obtained for the optimised tee-junction and subsequently used for fabrication: $h = 285 \mu\text{m}$, $w = r = 864 \mu\text{m}$, $t = 70 \mu\text{m}$, $l = 1000 \mu\text{m}$. $d = 900 \mu\text{m}$. The design parameters h and w denote the waveguide height and width, t is the septum thickness, l corresponds to the length of the tapered input section and d is the distance between the septum origin and the 90° corners. The left arm of the tee-junction was connected to the output port using a low return loss multi-stepped bend [13] to enable the input and output ports to be placed on the opposite sides. Due to a limitation with the RF probe positioners used in our s-parameter measurement set-up (excluding the possibilities of using a 90° angle between the waveguide ports), the device structure shown in Fig. 1a was used to experimentally validate the micromachined J-band power divider network. The optimised dimensions for the multi-stepped bend were found using the optimum distances for H-plane corners [13]: $s_1 = 225 \mu\text{m}$, $s_2 = 544 \mu\text{m}$ and $s_3 = 752 \mu\text{m}$. The effect of different septum thickness t was reported in [3] for a W-band power splitter design and it was found that the input matching will improve if this distance is reduced. Fig. 2 shows simulated s-parameters of the micromachined power divider against frequency with different septum widths. Compared with a more narrow septum ($t=10 \mu\text{m}$), a $70 \mu\text{m}$ thick septum will result in worse input matching if the waveguide sidewalls are assumed to vertical (without undercut). A higher return loss is obtained if a $70 \mu\text{m}$ thick septum with non-ideal sidewalls is used in the simulations ($22 \mu\text{m}$ is used as a nominal value of the undercut).

Fig. 2. Simulated s-parameters of the micromachined J-band power divider against frequency using different septum widths ($10 \mu\text{m}$ and $70 \mu\text{m}$) and with and without including a sidewall undercut ($22 \mu\text{m}$) in the simulations.

III. FABRICATION AND ASSEMBLY

The J-band power divider was fabricated in a low-loss micromachined waveguide technology developed at KTH [10], consisting of a silicon-wafer triple stack, i.e. comprising two H-plane splits. The central wafer is $285 \mu\text{m}$ thick which results in a 66% waveguide height as compared to the standard height for WR-3.4 of $432 \mu\text{m}$. The reduced height should only result in minor increase of waveguide losses, which is compensated by the better surface roughness control on the sidewalls for reduced etching depth. The central wafer is etched by deep-reactive ion etching, using a silicon dioxide mask. The wafers are metallized by gold sputtering of $1 \mu\text{m}$ metal thickness and the assembly is made on chip scale by thermo-compression bonding in a tailor-made chip-bonding chamber. The double H-plane split provides a waveguide concept with close to ideal surface roughness of the bottom and the roof of the waveguide, as only the sidewalls are affected by the silicon etching. This comprises a significant advantage over single H-plane split micromachined waveguides as for instance employed in [3], which is a major reason for the low loss of the power divider. Fig. 3 shows SEM images of the fabricated power divider before bonding to the waveguide top and bottom. As can be seen, the sidewall undercut is close to $20 \mu\text{m}$ on each side.

b) Fig. 3. Scanning electron microscope images of the micromachined power divider chip before metallisation and final assembly: a) top view and b) side view of the fabricated septum (the sidewall profile is in the range of 15-25 μm).

IV. EXPERIMENTAL RESULTS

The characterisation of the silicon micromachined J-band waveguide power divider was performed using a Rohde&Schwarz ZVZ24 network analyzer with two ZC330 TxRx extenders. A two-tier TRL calibration was carried out, with the first level made using a standard calibration kit and the second level comprising a micromachined calibration kit implemented on the same chip containing the power divider. The micromachined TRL calibration kit is used for de-embedding to reference planes located inside the micromachined rectangular waveguides, i.e. directly adjacent to the power divider input and output ports shown in Fig. 1. A special software was written to enable remote-control of the VNA and for showing the de-embedded results in real time. Since power dividers are three-port devices but only two TxRx extender modules were available for s-parameter characterisation using the network analyser, the third port had to be terminated with a load. This was implemented by the use of a tapered micromachined absorber integrated directly in the power divider design (see Fig. 1), which has a return loss below -15 dB for the whole band, and are described in [12].

Fig. 4a shows measured and simulated transmission coefficients s_{21} and input reflection coefficients s_{11} for the silicon micromachined J-band power divider. The simulated s-parameters are found to be in a relatively close agreement with the experimental data when the effect of a non-ideal sidewall thickness is taken into account in the simulations (the sidewall undercut was assumed to be 22.5 μm based on the corresponding measured sidewall thicknesses shown in Fig. 3). Furthermore, it should be pointed out that our simulations assume ideal matched loads for the input and output ports, whereas the measurements were obtained using a non-ideal micromachined load filled with an absorber as termination for the right arm (third port) in this J-band waveguide test circuit. The measured transmission coefficients are equal to -3.5 ± 0.4 dB at 231-330 GHz and the measured input reflection is between -10 dB and -20 dB in the 220-320 GHz range

(corresponding to a 37% relative bandwidth). The measured transmission coefficients are remarkably close to the ideal value of -3 dB, as is also the uniformity over the large bandwidth of the power divider. The measured and simulated transmission phase responses (between port 1 and port 2) are also found to be in a close agreement as shown in Fig. 4b. Table I summarises the measured results of the J-band power divider fabricated using a micromachined waveguide technology with a double H-plane split which enable low losses. Compared with a W-band design [3], the manufactured J-band power divider results in better performances in terms of lower losses over a wider bandwidth while being realised at a frequency which is approximately three times higher.

b) Fig. 4. Measured and simulated s-parameters of the 220-325 GHz silicon micromachined power divider with a multi-stepped bend and on-chip matched waveguide load filled with an absorber: a) magnitude and b) phase response.

TABLE I. MEASURED RESULTS OF MICROMACHINED POWER DIVIDERS

Ref.	Performance Parameters		
	Frequency band	Transmission Loss	Input Matching
[3]	W-band	≤ 1.2 dB (@ 75-105 GHz)	< -10 dB (BW=27 GHz)
This work	J-band	≤ 0.9 dB (@ 231-330 GHz)	< -10 dB (@ 220-320 GHz)

CONCLUSION

A J-band (220-325 GHz) silicon micromachined -3 dB power divider fabricated in a double H-plane split waveguide design was presented. One output path of the power divider is connected using a 90° multi-stepped bend while the other path uses an on-chip matched waveguide load filled with an absorbing material to enable two-port measurements of the three-port power divider network. The measured transmission coefficients are equal to $-3.5 \text{ dB} \pm 0.4 \text{ dB}$ at 231-330 GHz and input reflection coefficient is between -10 dB and -20 dB at 220-320 GHz. These experimental results display a successful use of the developed double H-plane split, low-loss micromachined waveguide technology. The effect of the waveguide sidewall thickness was studied and resulted in a close agreement between the simulated and experimental data when the sidewall undercut in microfabrication was taken into account in the simulations. Compared with a previous power splitter design made at W-band, the micromachined J-band power divider obtains lower losses and wider bandwidth while being realised at a three times higher operational frequency.

ACKNOWLEDGMENT

This work has been funded by the Swedish Foundation for Strategic Research via the Synergy Grant Electronics SE13-007.

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