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Micromachined Gap Waveguides for 100 GHz Applications

Sofia Rahiminejad*, Hasan Raza†, Ashraf Uz Zaman†, Sjoerd Haasl‡, Peter Enoksson*, and Per-Simon Kildal†

*Department of Microtechnology and Nanoscience, Chalmers University of Technology
Gothenburg, Sweden, Email: rahimine@chalmers.se
†Department of Signals and Systems, Chalmers University of Technology
Gothenburg, Sweden
‡Royal Institute of Technology, Stockholm, Sweden

***Abstract*—**
The present paper demonstrates groove gap waveguides at around 100 GHz, fabricated on Gold-plated micromachined silicon. Three different groove gap waveguides have been manufactured and measured: a resonator for determining Q-factor and thereby attenuation, a straight waveguide, and a waveguide with two 90 degree bends.

***Index Terms*—Groove, Gap Waveguide, Micromachining, Bed of nails, High-frequency, Waveguide**

I. Introduction

During the past few years, gap waveguides were introduced [1] in three different basic varieties named ridge, groove and microstrip gap waveguides [2]. The functionality is based on creating a stopband for normal parallel-plate modes between two conductive surfaces by using a texture in one of these surfaces in terms of pins or other sub-wavelength periodic elements [3]. The ridge gap waveguides were demonstrated to work at $10 - 20$ GHz in [4] , and thereafter different gap waveguide components like filters [5] were realized and gap waveguides were used for packaging of microstrip circuits [6], microstrip filters [7] and MMIC amplifier chains [8]. All these demonstrators were realized by conventional milling techniques for different frequency ranges between 10 GHz and 38 GHz. Milling is expensive and not accurate enough at high frequencies, however, above about 100 GHz micromachining becomes an interesting alternative, offering tolerances on micrometer level. The first micromachined gap waveguides were designed for $220 - 325$ GHz [9]. The purpose of the present paper is to demonstrate gap waveguides designs for operation at around 100 GHz realized by micromachining.

The present paper presents groove gap waveguides for demonstrating performances at $90 - 140$ GHz (F-band). The parallel-plate stopband is created using metalized pins which are easy to realize with micromachining. The demonstrators are a straight groove gap waveguide, a groove gap waveguide with two $90°$ bends and a groove gap resonator.

We are in the process of realizing a small linear slot array fed by a corporate feed network in ridge gap waveguide technology, with a transition to a groove gap waveguide so that we can use the same measurement equipment. The slot array is actually almost the same in terms of wavelengths as that realized by milling and presented in [10] and measured at 13 GHz.

We hope to present also results from this micromachined gap waveguide antenna in the oral presentation.

II. Structure and Design

All micromachined circuits have used a bed of nails surface to confine the wave [3]. All nails (pins) have a height of 750 μm, but the width of the pins varies depending on the purpose and the components. Different widths can easily be realized by micromachining, whereas a new height requires a new step in the processing. All three test circuits have a metal lid placed above it for the groove waveguides to work, as shown in as seen in Fig. 1 .

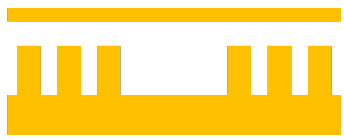

Fig. 1. Drawing of the groove waveguide and metal lid above it.

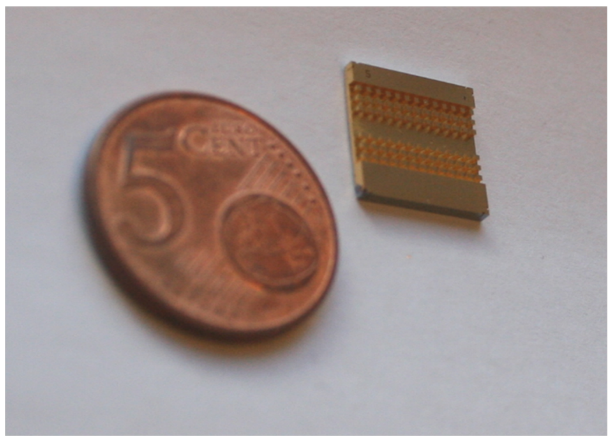

Fig. 2. Photo of the straight groove gap waveguide

The first circuit (fig. 2) is a groove gap waveguide, the groove is 2.03 mm wide. On both sides of the groove, three rows of pins are used to confine the wave. Each pin has a 450 μm wide square cross section. The length of the waveguide is 12.75 mm.

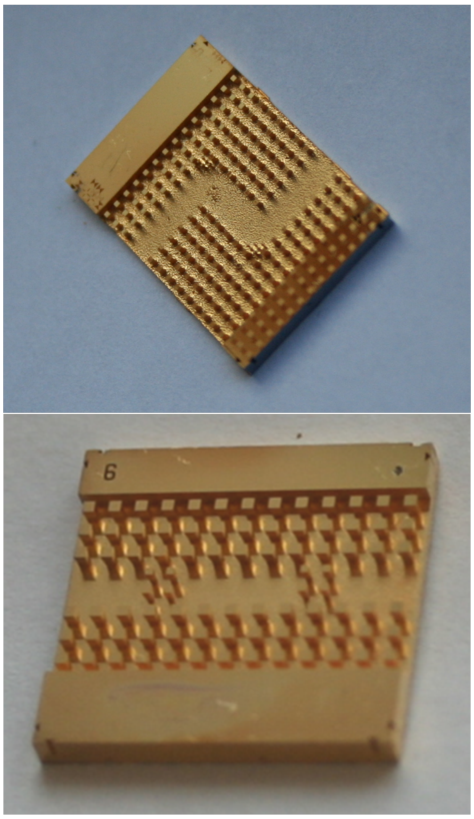

Fig. 3. Photos of the lower plate of the groove gap waveguide with two 90° bends (upper photo) and the groove gap resonator(lower photo). The upper plate is smooth and does not need to be in conductive contact with the lower plate, so simple mechanical spacers are sufficient.

The second circuit is a groove gap waveguide with two 90° bends (fig. 3). The width of the groove is the same as for the straight waveguide and there is a minimum of three rows of square pins on each side. The pins have a width of 470 μm. In the corners there are triangles of thinner pins. The purpose of these latter pins is to smoothen the corners to reduce reflections, known in conventional waveguides as mitered corners. The thinner pins are 150 μm wide. The total length from edge to edge is 11.062 mm.

The third circuit is a resonator (fig. 3) to measure Q-factor and losses. It has the same dimensions as the straight waveguide except for the input and output coupling sections, each with two rows of pins with thinner 300 μm width. These pin rows define the resonance cavity and the coupling to it.

III. Fabrication process

All three devices have the same pin height thus they were all processed at the same time.

The substrate is an SOI (Silicon on Insulator) wafer, where a 750 μm thick Si layer is on top of an insulator, a 1.5 μm oxide layer and a 500 μm thick carrier layer. The substrate is covered with a 1 μm Al layer hard mask and then patterned with photoresist. The structures are then etched all the way down to the oxide layer which stops the etching process and achieves a pin height of 750 μm. Afterward the Al is stripped of the wafer and the components are diced out of the wafer. The components are first sputtered with Ti/Au and then electroplated with Au to achieve a 1 μm thick conductive surface.

IV. Simulated and Measured Results

The simulations of the 100 GHz straight line and the 90° bend groove gap waveguide were done in CST Microwave studio; whereas the simulation for the resonator was done in HFSS.

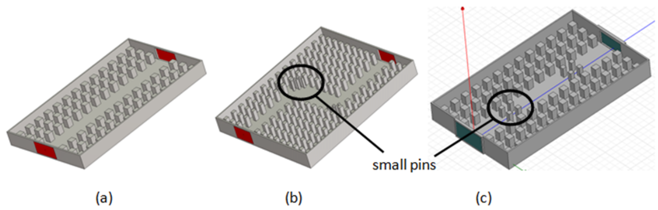

Fig. 4. The simulated designs of the groove gap waveguides a) straight waveguide, b) waveguide with the two 90° bends and c) resonator.

At both ends, the gap waveguide is terminated by waveguide ports of standard W-band rectangular waveguide dimensions. The dimensions of the pins, the distance between two pins and the gap between the top metal plate and the pins have been chosen to produce a stop band from 90 GHz to 140 GHz. The smaller pins (see fig.4) in the resonator and, especially in the 90° bend waveguide were chosen based on parametric studies which gives the best S-parameters for these 100 GHz groove gap waveguides. The simulated results show that the S11 for the case of straight line and 90° bend is below -20 dB between $90-130$ GHz. The groove gap resonator in simulations shows two resonance peaks at 99.75 and 119.9 GHz within the stopband.

The measurements were performed using a HP 8150C VNA from 75 to 118 GHz. The groove gap devices were connected via two WR-10 waveguide flanges. The setup was calibrated with a standard 2-port TRL calibration for W-band ($75-110$ GHz) using Hewlett Packard's WR-10 calibration kit. The groove waveguide, however, was designed for F-band ($90-140$ GHz), and therefore there is some mismatch between the flange opening and the groove waveguide opening. The reason for this is simply due to the waveguide flange nonconformity, that is we could not get access to an F-band VNA.

The straight groove gap waveguide shows a return loss below -10 dB between $90-118$ GHz (fig. 5a). The groove gap waveguide with two 90° bends has return loss below

$-15\ dB$ between $100 - 118\ GHz$ (fig. 5b). The graphs show some reduction in the transmission coefficient, and even some resonances appearing at 95.64 and 115.6 GHz. The groove gap resonator shows resonance peaks both in measured and simulated curves (fig. 5c). The corresponding Q-values have been read from the curves and are shown in table I. We believe that the downwards shift of the measured resonances are caused by the pin widths being smaller at the bottom than at the top. This effect will be larger at low frequencies where closer to cutoff.

TABLE I
SIMULATED AND MEASURED QS

	Q1	Q2
Simulated	$760(99.75\ GHz)$	$2000(119.90\ GHz)$
Measured	$1210(95.64\ GHz)$	$1160(115.60\ GHz)$

Table II shows both measured and simulated S21 at 100 GHz and 110 GHz for both the the straight waveguide and the waveguide with the two 90° bends. The difference between the simulated and the measured values for both cases are large. The losses obtained from the Qs has better accuracy (that is why we measure small losses in transmission lines by using resonators), but does only include the losses in the transmission line itself, and not the transitions. The losses calculated from the Qs are included in the table as well, by using Eq. (1) of [11], which for our case then becomes for a transmission line length L (we have assumed a TEM transmission line so the result are approximate).

$$\alpha = \frac{\beta}{2Q_u} \tag{1}$$

TABLE II
ATTENUATION IN STRAIGHT WAVEGUIDE AND WAVEGUIDE WITH TWO 90° BENDS

	Straight waveguide ($L = 12.8 \cdot 10^{-3}\ m$)		90° bend waveguide ($L = 13.7 \cdot 10^{-3}\ m$)	
Frequency	100 GHz	110 GHz	100 GHz	110 GHz
Simulated $\|S21\|$ of waveguide:	0.03 dB	0.03 dB	0.05 dB	0.04 dB
Measured $\|S21\|$ of waveguide:	0.56 dB	0.62 dB	0.38 dB	0.42 dB
Frequency	95.64 GHz	115.60 GHz	95.64 GHz	115.60 GHz
Estimated from measured Qs of resonator:	0.09 dB	0.10 dB	0.12 dB	0.12 dB
Corresponding per wavelength from Qs:	0.022 dB	0.024 dB	0.022 dB	0.024 dB

V. CONCLUSION

We have presented the design and measurements of three test circuits for micromachined groove gap waveguides for use at 90-140 GHz. Unfortunately, we could only measure it up to 118 GHz, and with reduced accuracy above 110 GHz (end of W-band). The measured Q-values of the resonator, and the performance of the straight and double-bent waveguides indicate low losses and suitability for making more advanced components above 97 GHz. The agreeability between simulations and measurements at 100 GHz shows the potential that micromachining has for devices above 100 GHz. The S11 performance of the waveguide with two

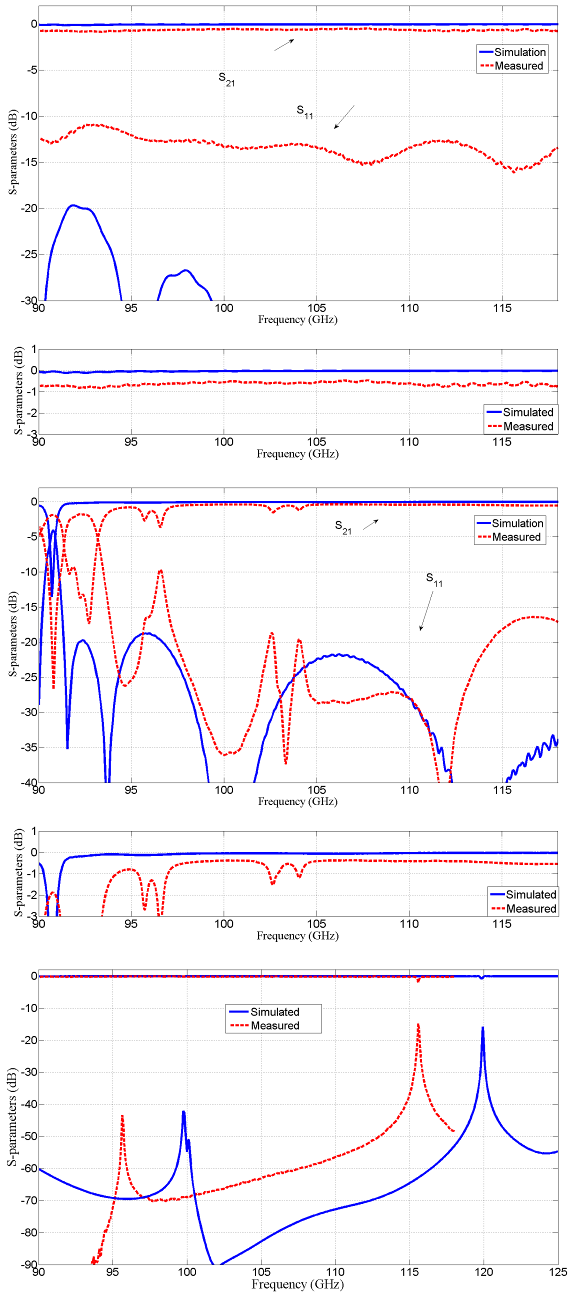

Fig. 5. The parallel-plate stopband is from 90 to 140 Ghz. Unfortunately, we could not measure above 118 Ghz. The graphs shows simulated (solid blue line) and measured (dashed red line) S11 and S21 for the groove gap a&b) straight waveguide, c&d) waveguide with the two 90° bends and e) resonator.

bends is better than the straight waveguide above 100 GHz, which indicates some problems in the transitions from the straight gap waveguide to the measurement equipment. The waveguide with two bends behaves very bad below 95 GHz, so near the start of the stopband of the parallel-plate waveguide modes the performance is not reliable. This can be caused by the pins being shorter than they should be due to tolerances. However, generally the performance look very promising, and we are also in the process of manufacturing a linear slot array in ridge gap waveguide that we hope can be presented at the conference as well.

ACKNOWLEDGMENT

This work has been supported by The Swedish Research Council VR, a project within then VINNOVA funded Chase antenna systems VINN excellence center at Chalmers, Pakistans NESCOM scholarship program, and Chalmers production area of advanced science for funding of the reported work. The authors are grateful to the nanofabrication laboratory at Chalmers University of Technology for their help in the fabrication process and to Mattias Ferndahl for his support with the measurements.

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