A LOW-LOSS 20 GHz MICROMACHINED BANDPASS FILTER

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ABSTRACT

We report on the results of a state-of-the-art planar interdigitated bandpass filter at K-band by using micromachining techniques. In this design, a microwave model was first built at 850 MHz to simulate the K-band filter, and the 20 GHz micromachined filter was fabricated based on the 850 MHz microwave model. Excellent agreement has been achieved between the microwave model and the 20 GHz filter. The micromachined filter exhibits a return loss better than -15 dB within the passband and a 1.7 dB port-to-port insertion loss at 20.3 GHz. A grounded coplanar waveguide with a micromachined mouse-hole shielding structure has also been carefully examined. The grounded coplanar waveguide structure is used in the micromachined filter as the input/output feeding line and exhibits a return loss better than -20 dB up to 32 GHz.

I. INTRODUCTION

The purpose of this work is to develop a new technology which can be used to build a small, light weight, low loss and low cost K-band and Ka-band filter for use in satellite receiver systems and future personal communication systems. A planar interdigitated filter topology with a quarter-wave resonators is chosen for compactness. Interdigitated filters are symmetrical, exhibit low insertion loss and have very sharp roll-off rejection response. Another advantage of these filters is that the second passband occurs at three times the bandpass frequency. Interdigitated filters have been widely used in the lower microwave range [1,2]. However, as the frequency increases, the machining of interdigitated resonators becomes increasingly difficult and costly.

The problems associated with mechanical machining have been solved by applying micromachining techniques to the design of planar interdigitated filters. The micromachined interdigitated filters are very compact (about 1 cm-square at Ku-band) and lightweight (about 0.4 grams). Micromachined filters, suspended on thin dielectric membrane, do not suffer from dielectric loss and from dispersion. Also, with the advantage of the MMIC fabrication process, batch fabricated micromachined filters can have nearly identical responses at Ku-band. A 40% and 5% interdigitated micromachined filters have been fabricated and are presented in [3,4]. Details of the fabrication process are also presented in [3,4] (see Fig. 1). The measured responses in [3] show a shift from the design frequency, and this shift becomes larger as the number of sections in the filter increased. This problem is caused by the design procedure used in [1,2] which neglects the mutual coupling between non-adjacent resonators. Also, the higher order modes from the micromachined cavity can disturb the performance of the filters especially if the cavity becomes larger than a half-wavelength long at the passband frequency. In order to eliminate these design uncertainties, a microwave model approach is proposed. First, a microwave model is built and tuned at low frequencies, and then a 20 GHz K-band micromachined filter is fabricated and tested. Excellent agreement is achieved between the microwave model and the 20 GHz micromachined filter.

Grounded coplanar waveguide transmission lines (GCPW) with micromachined mouse-holes are used in the micromachined filters as the feeding structures. These lines are carefully examined in this paper. A 178 μm wide, 2.6 mm-long GCPW built on a 350 μm thick high resistivity silicon wafer is measured from 2 to 40 GHz. The results show a very good performance up to 32 GHz with a return loss better than -20 dB and an insertion loss less than -0.3 dB at 20 GHz.

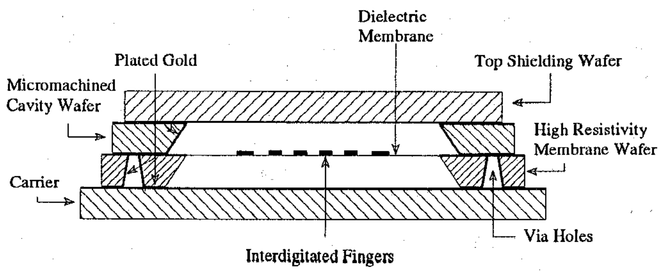

Figure 1: A cross-section view of the micromachined interdigitated filter.

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II. MICROWAVE MODEL OF THE 20 GHz BANDPASS FILTER

The design procedure of an interdigitated filter has been developed by Matthaei [1,2] and Cristal [5]. In this work, only the coupling between adjacent resonators has been considered in the admittance/impedance matrices, and a bandwidth correction factor is needed to compensate for neglecting the mutual coupling between the non-adjacent resonators. Also each resonator needs to be shortened to compensate for the open-end effect. This correction, of course, preserves the correct center frequency. These problems become a challenge for the design of micromachined interdigitated filters, with non vertical sidewalls. Numerical techniques, although well developed for microstrip circuits, are not accurate for micromachined circuits.

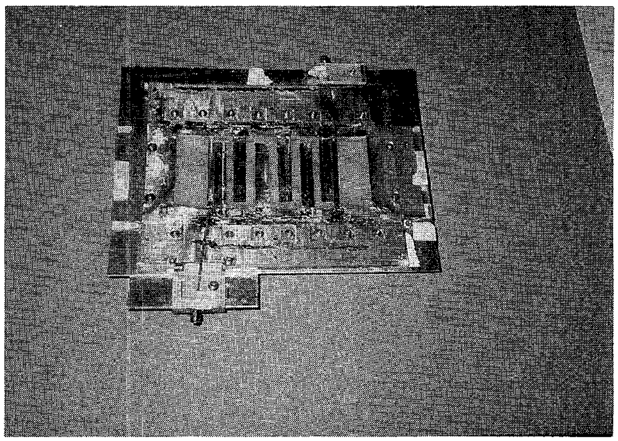
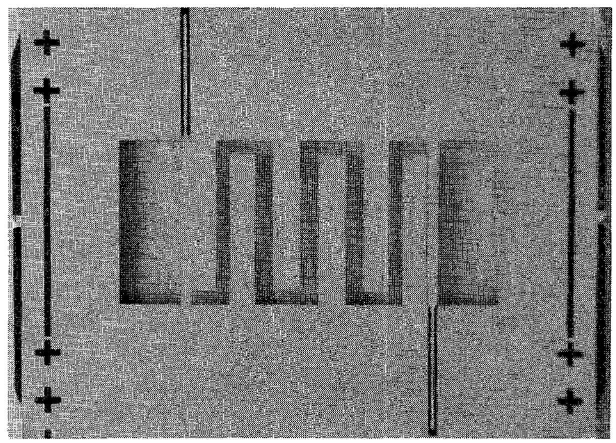


Figure 2: The 850 MHz microwave interdigitated filter. This filter has an insertion loss around 0.8 dB and return loss better than -15 dB in the passband range.

The micromachined interdigitated filter is built on a very thin dielectric membrane (1.5 μm thick) and suspended in air as shown in figure 1. This results in a pure TEM propagation mode. Because of the pure TEM mode, a microwave model can yield accurate simulation of the performance of the 20 GHz filter. Based on this concept, an 850 MHz microwave model is built with a scaling factor of 23.7. In this microwave model, a 152 μm thick polyethylene sheet is chosen to simulate the 1.5 μm thick dielectric membrane. An 8.4 mm thick plastic glass is used to support the polyethylene membrane layer and provides the proper spacing for the top and bottom ground planes. This plastic glass behaves similar to the 350 μm high-resistivity silicon wafer in the micromachined filters. The resonators and ground plane in the microwave model are made of copper tape. Screws are used to insure that both the top and bottom ground planes have a good DC and RF short. In order to achieve a 50 Ω input/output feeding impedance in the microwave model, two coaxial cables were used and connected right at the ends of the first and last fingers (Fig. 2). Matthaei's equations [1] were first used as a starting point and then the lengths, widths and gaps of the eight finger-resonators were adjusted experimentally until the design requirements were achieved. The measured results of the microwave model show a center frequency of 856 MHz and a 3-dB bandwidth of 140 MHz. This translates into a center frequency of 20.28 GHz with a 3-dB bandwidth of 3.3 GHz for the micromachined filter. A picture of the 20 GHz micromachined interdigitated filter is shown in figure 3.



K	$s_{k,k+1}(\mu m)$	K	$w_k(\mu m)$	$L_k(\mu m)$
0, 6	22.9	0, 7	228.6	3373.1
1, 5	284.5	1, 6	502.9	3111.5
2, 4	370.8	2, 5	528.3	3101.3
3	375.9	3, 4	576.6	3086.1
K: finger number			w_k: finger width	
$s_{k,k+1}$: gap between fingers			L_k: finger length	

Figure 3: A picture of the 20 GHz interdigitated membrane filter and its physical dimensions. The clear area on this picture is the dielectric membrane.

III. MICROWAVE MEASUREMENTS

A. Grounded Coplanar Waveguide Feeding Structures

Grounded coplanar-waveguide transmission lines (GCPW) are used as shielded feeding structures for the interdigitated filter. The interdigitated filter is quite sensitive to the input/output loading impedance, and a test of the feeding structure to insure a good 50 Ω feed-line is necessary before any other filter measurement is performed. The total length of the GCPW line is 2.6 mm with a 50 μm gap and a 75 μm wide center conductor. This line is compatible with a 150 μm-pitch CPW-based $Cascade^{TM}$ probe. A fabricated

20 GHz membrane filter was broken intentionally and only the two feeding lines were left on the wafer. The reason of doing this is try to preserve the same environment of the feeding structures. The measurement system is calibrated from 2 to 40 GHz using a SOLT (Short-Open-Load-Thru) on-wafer calibration routine. The GCPW line is measured first without a shielding structure. Next, a mouse-hole shielding cavity is added on top of this line. The mouse-hole cavity has a channel about 1.5 mm long, 1 mm wide and 250 μm high. It is found that both lines have very good microwave characteristics. The measured return loss and insertion loss for the shielded and unshielded GCPW lines are shown in figure 4. Both lines exhibit a return loss better than -20 dB up to 32 GHz. The insertion loss of the GCPW line with a mouse-hole cavity is less than -0.3 dB at 20 GHz which is around 0.1 dB/mm at 20 GHz and comparable to published results [6].

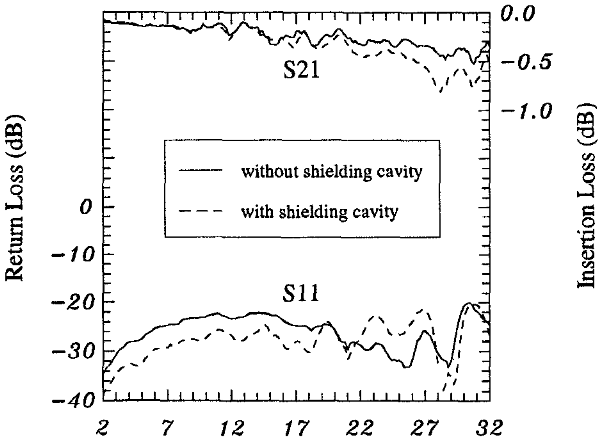


Figure 4: Measured insertion loss and return loss for the GCPW lines.

B. Membrane Filters

A 20 μm diameter gold wire is bonded across the first finger at the membrane-GCPW transition to equalize the two ground planes. The bonding wire is important for this filter because it forces a symmetrical field distribution at the transition and provides a 50 Ω feeding impedance at the GCPW line. The required bonding wires can be built using an air-bridge technology in future designs.

A micromachined cavity wafer with a mouse-hole channel is stacked on top of the membrane wafer using silver epoxy and this creates the top cavity for the filter. Another carrier wafer is stacked at bottom of the membrane wafer to form the bottom cavity. The bottom carrier wafer has four micromachined V-shape grooves on the surface. The purpose of the four grooves is to provide a gas-escape channel for the bottom cavity. This avoids any pressure building up on the membrane layer after the bottom cavity is sealed. Both the top cavity and bottom carrier wafer are electroplated with gold to obtain a good RF ground plane. This filter is measured from 2 to 40 GHz and no tuning is attempted during the measurements. The results show a 1.7 dB port-to-port insertion loss at 20.3 GHz (including a 0.3 dB loss from each of the GCPW line) with a 3-dB bandwidth of 3.1 GHz (Fig. 5). The return loss is better than -15 dB in the passband. As can be seen, excellent agreement is achieved between the 850 MHz design and the 20.3 GHz results due to the TEM nature of the micromachined filter (i.e. no dispersion).

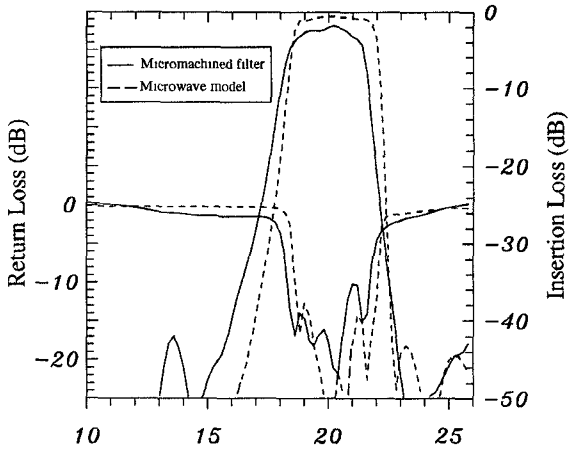


Figure 5: Measured results of the 20 GHz micromachined filter and the scaled response for the 850 MHz microwave model. In this figure, the frequencies for the 850 MHz filter have been scaled up by a factor of 23.7.

In order to show the significance of the bonding wires, the same filter without the bonding wires is measured again. Without the bounding wire, the feeding impedance can vary around 50 Ω and change the passband response. The measured response for this filter is shown in figure 6, along with the response from the previous filter for easy comparison. As predicted, return loss has dropped to -5 dB in some passband frequencies and the insertion loss is not flat anymore. It is also found that cavity modes start to appear at around 30 GHz. A possible way to eliminate the cavity modes is to reduce the length of the cavity and make it smaller than a half wavelength at the highest operating frequency. This can be done by either choosing a thinner wafer which reduces the length of the cavity, or keeping the same wafer thickness but dividing the cavity into two smaller sub-cavities.

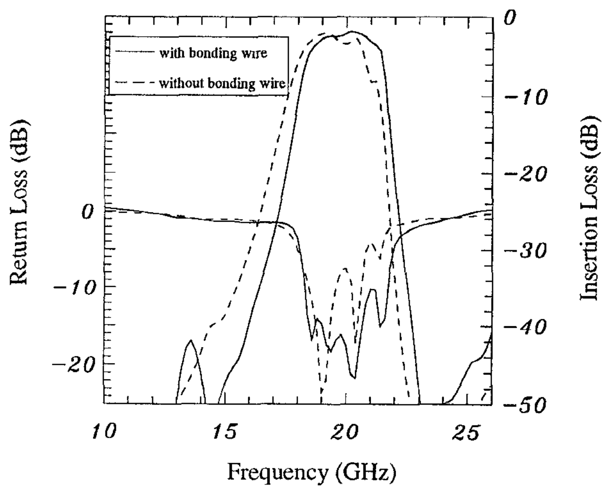


Figure 6: Measured results for the 20 GHz micromachined interdigitated filters.

ACKNOWLEDGEMENTS

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