Micromachined 60 GHz Air-filled Interdigital Bandpass Filter

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Abstract

A 4-pole interdigital filter has been demonstrated at 60 GHz with a bandwidth of 10 %, it is made using micromachining and a multi-layer bonding. The filter is an air-filled three-dimensional structure. It is formed of five layers which are bonded together. Each layer is micromachined SU-8 based, 200-μm thick, and finished with 1.5 μm gold coating. The resonators are thick stripline-like and enclosed in a cavity. The input and output are transitions from a coplanar structure to a rectangular coaxial line, which are then coupled into the cavity. The filter is only 3.7 mm by 2.0 mm in size and 1.0 mm in height. The measured insertion loss is 1.1 dB and the return loss is below -9 dB. The bandwidth of the tested filter is broadened due to fabrication imperfections, which have been identified by modelling and discussed in the paper.

1. Introduction

The increasingly crowded microwave spectrum coupled with the demand of high-speed large-volume data transfer and communications has revitalised the studies of millimetre wave (mm-wave) frequencies, which had been largely reserved for military applications [1]. At these frequencies, waveguide and coaxial based three-dimensional (3D) devices are usually adopted if very high performance is required. Whereas planar circuits are often resorted to as far as integration and miniaturisation is concerned, at a cost of higher losses. The advancement of micromachining techniques has rendered new possibilities to realise low loss mm-wave devices while maintaining their compactness. Such efforts have targeted both planar and 3D-structure filters. Micromachined planar filters are mainly implemented in membrane structures [2], where a micron-thick dielectric membrane is used to suspend microstrip or coplanar line resonators in a cavity constructed of multiple wafers. Micromachined 3D-structure filters are in the form of substrate integrated waveguides [3], air-filled waveguides/cavities [4, 5], coaxial lines with dielectric supported centre-conductors [6], or self-supported air-filled structures [7, 8, 9].

This paper presents a self-supported air-filled interdigital filter with 3D resonator structures. Compared with cavity filters, an interdigital filter occupies a smaller footprint by virtue of capacitively loaded λ/4 resonators. A 3D micromachined comb-line filter [7] has been demonstrated before, using a process based on sequential deposition of multiple metal layers [10] to form three-dimensional structures. In this process, a dozen or more layers were used as the thickness of each layer is often limited by the plating or deposition process to be much less than 100 μm. Also, to remove the sacrificial materials, release holes have to be implemented. This put some restrictions on the design and the achievable performance. In our work, a simpler and potentially low-cost fabrication process has been used. The device was made of only five layers which are bonded together, as shown in figure 1. Each layer is of 200 μm thick SU-8 photoresist, plated with gold coating. A single 4-inch wafer can be used to produce all required layers. The SU-8 is patterned by ultraviolet photolithography. The process is simple and no expensive equipment is required [11]. SU-8 has been widely used in MEMS and has been used as the construction materials of waveguide/cavity structures [5, 12]. To our best knowledge, this is the first demonstration of using SU-8 in a coaxial structure filter.

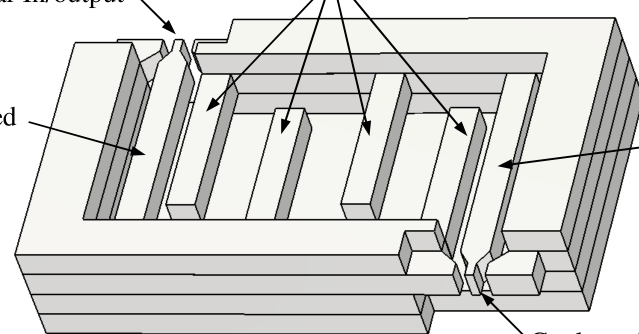

Figure 1. Diagram of the interdigital filter, with the top layer removed to assist viewing.

2. Filter design

A 2-pole cavity filter has been demonstrated before using similar fabrication process at 38 GHz [5], showing an insertion loss of 1 dB. The measured quality factor of a single cavity resonator was 343. Here, an interdigital filter has been designed at 60 GHz based on coaxial line resonators. As shown in Figure 1, the four interdigital fingers, as the resonant elements, are self-supported with a cross-sectional area of 200 μm by 200 μm. The input and output are shorted stubs which are coupled to the first and fourth resonators. All these are defined in the middle layer of the device. The rest of the four layers form the cavity enclosing the resonators. Transitions are made to a thick coplanar waveguide (with the strip and slot widths of 60 μm and 80 μm) to facilitate measurements using on-wafer probes. Some dimensions of the circuit are given in Figure 2. The fingers are $0.22{\cdot}\lambda$ long. The filter is 3.7 mm by 2.0 mm in size and 1.0 mm in height. The filter is a 4-pole Chebychev type, with a specified ripple of 0.1 dB. Its low-pass prototype has $g_1 = 1.1088$, $g_2 = 1.3061$, $g_3 = 1.7703$, $g_4 = 0.8180$, $g_5 = 1.3554$. The fractional bandwidth is 10%. This requires the external quality factor to be $Q_{e1} = Q_{e2} = 11.088$, and the coupling coefficients between resonators to be $k_{12} = k_{34} = 0.0831$, $k_{23} = 0.0658$.

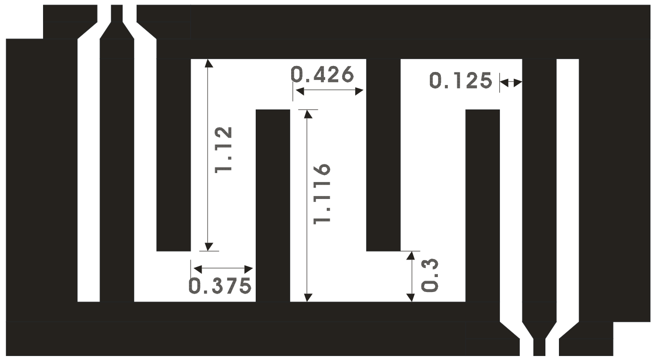

Figure 2. Some dimensions of the middle layer of the filter. Dimensions in millimetres.

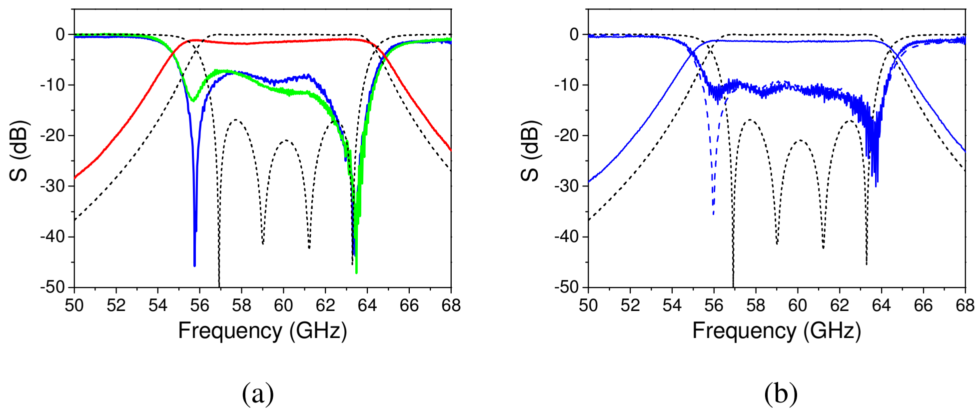

Figure 3. Measured and simulated filter responses. (a) The initially assembled device. (2) The device after a compression resulting in its height reduced from 1.095 mm to 1.085 mm.

3. Fabrication and performance

SU-8 is a negative photoresist, which is sensitive but transparent to the UV i-line (365 nm in wavelength). It is capable of forming structures as thick as 2 mm, and of an aspect ratio up to 1:50 [13]. A standard photolithography process can be used to expose and develop the resist. In order to form a durable structure, at least three controlled baking steps are required, following the resist dispersion, the exposure, and the development respectively. The patterned SU8 pieces are released from a silicon handle wafer and coated with a 1.5-2.0 μm gold layer by evaporation, covering all surfaces including the side walls.

The five layers are bonded on top of each other using a flip-chip bonder. For many materials like silicon, no extra adhesion layers are required to achieve good bonding strength, subject to pressure and relatively high temperature. For SU-8, however, high temperature may cause deformation of some structures, particularly when the SU-8 slice is thin, or the features are narrow and long. It is the case for this 60 GHz filter, where the SU-8 used is 200 μm thick and the resonator fingers are prone to thermally induced deformation. In order to lower the required bonding temperature, an adhesion layer is used between layers by spreading minimal amount of silver epoxy. A drawback of the extra adhesive is that it effectively increases the layer thickness. It is observed that the height of the assembled filter is increased by 95 μm from the nominal 1.0 mm. This is likely to be the main reason for the increased bandwidth and worsened matching in the measured filter responses, as seen from Figure 3(a). The return loss is -7 dB, much higher than the designed -17 dB. By re-compressing the assembled device under the bonder, the device height is reduced by 10 μm. It is evident that the return loss is improved from -7 dB to -9 dB, as shown in Figure 3(b). Simulation results shown in Figure 4 indicate that an increase of 20 μm in the thickness of each layer could cause the amount of bandwidth increase observed in the measurement. However, this does not fully account for the increased return loss. Other contributing factors include the slight misalignment between layers after bonding, which will affect the external coupling. In the interdigital topology, the mutual couplings between resonators are not sensitive to inter-layer misalignment. If deep reactively etched silicon is used in place of SU-8, it is expected the height of the device will be better controlled, as no adhesion layer is required for compressively bonding two gold-coated silicon slices. However, silicon based devices are prone to higher conductor losses due to larger surface roughness on the sidewalls [5]. Another way to improve the height control is by taking the adhesive into account and offsetting the thickness of the SU-8 layers.

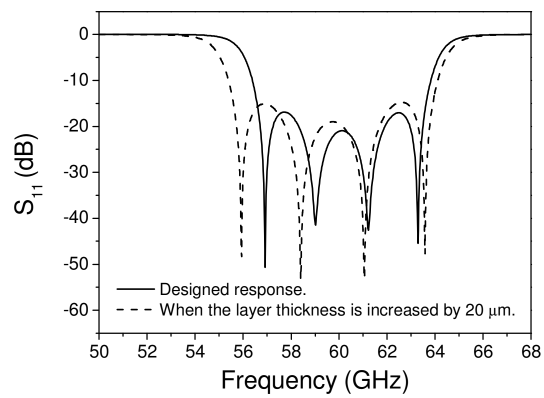

Figure 4. Modelling of the contribution of possible fabrication errors to the filter responses.

The measured insertion loss of the interdigital filter is 1.1 dB. The quality-factor of the interdigital resonator is estimated to be 197. A loss of 2.4 dB has been reported for a micromachined comb-line filter at 55 GHz and with a bandwidth of 13.6 % [7]. Considering the comb-line filter is smaller in size, the performances in terms of losses are on a comparable level for the two filters.

4. Conclusions

This paper reported one of the smallest 3D-structure filters at V-band, enabled by a micromachining and bonding technique. This approach to form air-filled devices using multi-layer structures can be applied to many other transmission-line resonator filters with self-supporting features [14]. Due to the small volume of the device, it has been identified that the height control during the fabrication is critical. To overcome this, a silicon based device not requiring adhesive in the bonding process and an offset of the SU-8 layer thickness taking the adhesive into account are being investigated. The quality factor of the resonators is expected to have scope to improve and the insertion loss of the filter further reduced.

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