Laser Machined Microsystems for Active Frequency Selective Surfaces

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***Abstract* — This paper presents the large scale integration of laser machined cantilever switches onto frequency selective surfaces for pass-band switching. A sheet of aluminum is patterned through laser cutting and attached by point laser welding to a frequency selective surface. The switch cantilever positions are adjusted by local thermal laser heating. As a result the response of the FSS can be shifted by electrostatic actuation of the switches. The design is verified by measurements on a 100 element active FSS at X-Band.**

***Index Terms*—Frequency Selective Surface, RF MEMS, Tunable Filters, Laser Beam Cutting**

I. Introduction

Active frequency selective surfaces (FSS) are capable of shifting their resonant frequency through an array of integrated switching devices. In the past, research groups presented several different approaches for active FSS. Implementations use either mechanical movements of layers, pin diodes [1], ferroelectric materials [2] or MEMS switches [3], [4]. Whereas the mechanical approach is bulky and slow, the PIN diode and ferromagnetic approach suffers from high losses. MEMS switches perform better; however, the MEMS integration onto a substrate is limited by the size of the microstructuring system. Another limiting factor is the small capacitance variation due to the small size of MEMS.

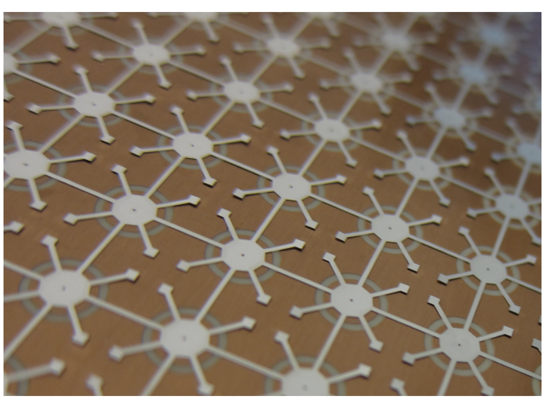

Figure 1. Photograph of the assembled FSS with the cantilevers in UP-State.

Laser machined switches overcome these problems. In terms of losses they perform comparably to MEMS switches. In contrast to MEMS switches laser machined switches are much bigger in size and allow more capacitance variation. The laser machined switches can be patterned, placed, fixated on the FSS and adjusted in two comparable simple manufacturing steps. The FSS size is only limited by the range of the laser table. In the field of microwaves engineering laser machining is already successfully engaged in the LTCC production[5], the tuning of filters [6] and manufacturing of mm-wave structures. For our application we cut, weld and bend the actuators of our FSS by laser machining.

II. Laser Machining Concept

The active FSS consists of two metal layers separated by a dielectric layer. The lower static layer is a wet etched 17 µm copper layer on an RO4003c substrate. The upper active layer contains the movable cantilever switches, which can be electrostatically actuated. We use a laser cutting system to manufacture the active layer out of thin metal sheets. Figure 2 and 3 are illustrating this process.

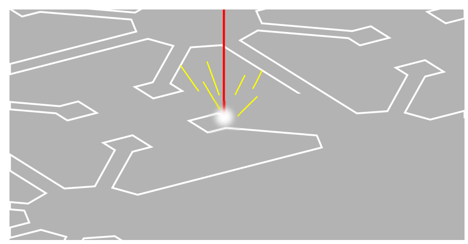

Figure 2. The laser cuts the structure out of a thin metal sheet.

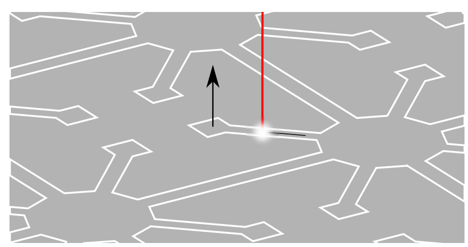

Figure 3. Some elements may be adjusted by local thermal bending

We use sheets of aluminum and stainless steel in our studies. Both materials have advantages and disadvantages from operational as well as processing point of view. Since stainless steel absorbs more laser-light than aluminum, less power is needed for cutting. The surrounding materials, like the supporting layer, suffer less damage from excessive laser-light. Although we observed smoother cutting edges with stainless steel, the residual stresses are much higher, resulting in uncontrollable deformations of the patterned structure.

Aluminum has less uncontrollable residual stress and a lower Young's modulus, which converts to lower actuation voltage for the electrostatic actuation. The yield strength of aluminum is also low, making it a sensitive material during the process flow as well as during operation.

Figure 4 shows an outline of our proposed process flow. The first step (1a) is to cut the desired structure out of a 13 µm thick aluminum sheet. During the machining the sheet is supported by a 5 mm thick PMMA block, which appears nearly transparent for the laser light used (YAG-Laser, 1060 nm wavelength). In order to maintain the sheet flat during cutting, a thin film of water is deposited onto the PMMA causing a flat adhesion of the aluminum sheet. The water evaporates during cutting. As a result, the delicate patterned structure, having a size of 80 mm x 80 mm, can be peeled of the PMMA easily after cutting.

The precise adjustment of the upward bends of the cantilevers is also performed by the laser. Through local heating of certain cantilever locations the residual stress of the metal is altered.

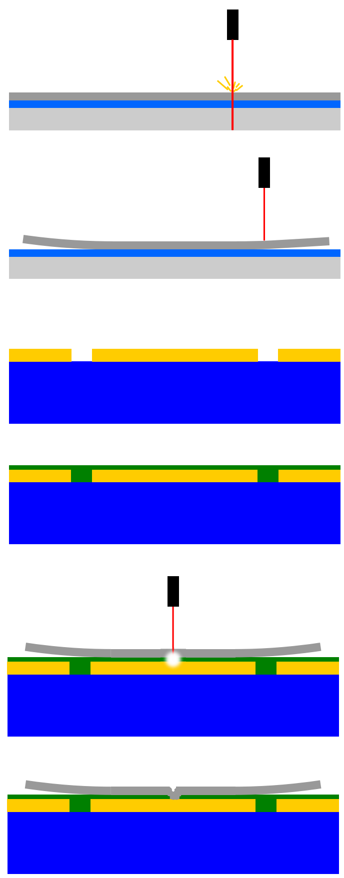

Figure 4. Outline of the laser-machining process flow

The static patterned substrate (2a) is now prepared by spray coating (2b) a dielectric layer to avoid electrical contact. In an alternative approach, we omit the dielectric layer and anodize the aluminum to grow a thin film of oxide as dielectric layer on its surface, which will also increase the yield strength of the aluminum.

In Step (3) the prepared aluminum sheet is placed on top of the substrate and then anchored by point laser welding. For the combination of copper and aluminum it is challenging to get reproducible results, due to different melting points and absorption rates. Higher yields are produced by laser-drilling small holes in the aluminum sheet at the anchor points of the active layer. In a final step the dielectric layer is dissolved at the drill holes. After drying (4), the two structures are mounted together at a small area around the hole. The junction also provides a galvanic contact between the layers. Using this process we are able to reliably produce large thin metal laser machined structures with integrated switches, and selectively anchor them to the substrate.

III. Frequency Selective Surface

For the bandpass FSS design we employ a loaded circle unit cell as depicted in Figure 5(b). The dimensions are 8mm $\times$ 8mm. In order to make the frequency response reconfigurable, we cover the cells with the second active conducting layer, shown in Figure 5(a). As discussed, the two layers are DC-isolated from each other at the four cantilever arms, which act as electrostatic actuators. By varying the loading of the unit-cell resonators the frequency response of the FSS is shifted in frequency.

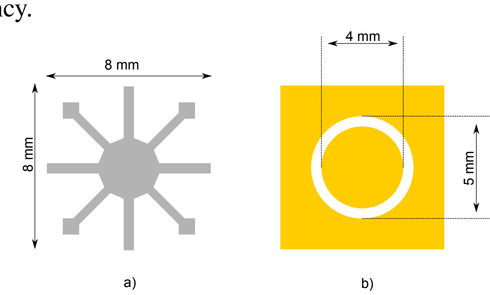

Figure 5. Unit cell of the DC-isolated FSS layers

The active structure consists of 10 by 10 unit cells with a total of 400 cantilever switches.

The periodic structure is insensitive to polarization due to the 90° rotation-symmetry. Depending on the initial loading, controllable by the geometry of the cantilevers and their distance to the subjacent layer, an initial UP-state resonant frequency is being set. After applying a sufficient DC-voltage between the conducting layers, the cantilevers are attracted by the copper layer, and get pulled down to the dielectric.

We studied two different versions of this FSS, only differing in initial heights of the cantilever beams. A “medium”-voltage version was designed with an initial cantilever height of about 98 µm distance to the dielectric layer at the end of the cantilever. The pull-down voltage was expected to be around 200 V. A “high”-voltage version was designed to have cantilevers with a distance of 210 µm to the dielectric layer, having a higher pull-down voltage of about 350V. First tests on single switches suggest that the actuation voltage can be reduced to less than 100 V for optimized switch designs.

IV. Simulations and Measurements

We performed measurements to verify our proposed laser machined structure. Since the cantilevers are large in size, one can easily detect bad performing cantilevers. We were able to achieve a yield of around 90% for the medium-voltage version and around 98% for the high-voltage version. In the shown prototype we observe still a slight variation of the heights of the cantilevers, which should have a significant impact on the performance of the FSS. The optimization of our process should eliminate these defects.

To obtain the insertion loss S_{21} for the FSS, we assembled the structure between two horn antennas as shown in Figure 6. The space between the antennas is separated by a large

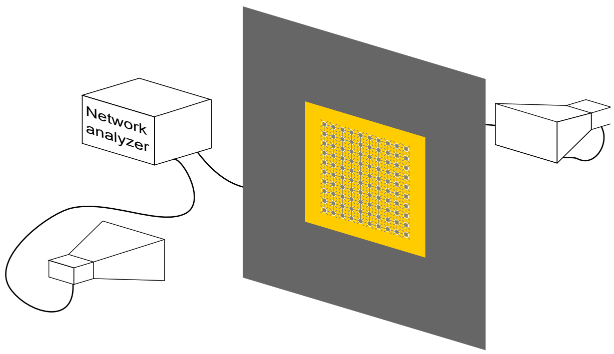

Figure 6. Simplified measurement setup to obtain S_{21} of the FSS

metal sheet with an opening for the FSS. We used a simple calibration, where we normalized the transmission to 0dB for the open window in the sheet without the FSS.

The results of the medium-voltage design are shown in Figure 7. For the UP-state, the resonance frequency is at 10.47 GHz and has an insertion loss of 9.2 dB. At 210V, all working switches move to the down state and we observe an insertion loss of 35.62 dB at 10.47 GHz, following an UP-state to DOWN-state difference of 25 dB. We can see, that the resonance frequency shifts to around 5 GHz, but the insertion loss at the peak is about 20dB. An explanation for this might be, that the bandwidth is very small and thus the variation of the cantilever heights have a significant impact on the frequency response.

The results of the high-voltage version are shown in Figure 8. We observe improved results, especially for the insertion loss at the UP-state resonance frequency, here 4.3 dB at 13 GHz. In DOWN-state, the insertion loss increases to 30 dB, resulting in an UP-state to DOWN-state difference of around 25 dB, as well.

V. Conclusions

Laser machined microsystems open up new design options for large scale integrated actuated microwave circuit. They may be an alternative to conventional MEMS design. Initial designs on FSS provide a switched attenuation of 25 dB. We expect an even better attenuation and almost perfect yield with an optimized design and process. The concept may also be applied to frequency agile periodic planar filters or even loaded waveguide filters.

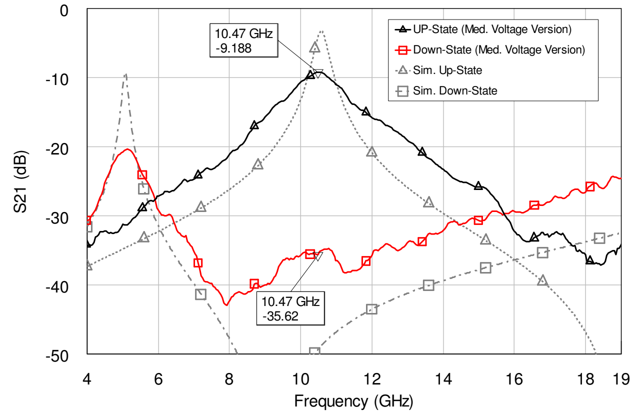

Figure 7. Comparison of the insertion loss between UP- and DOWN-state shows a 25 dB difference.

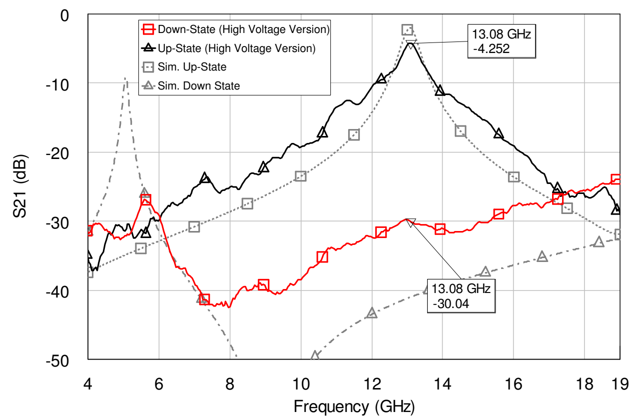

Figure 8. A lower UP-State insertion loss about 4.3 dB was observed for the high-voltage version.

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