Switchable microwave circuits using the EADS low-complexity RF-MEMS process

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Abstract – This article illustrates the ongoing RF-MEMS development at EADS Innovation Works in Germany from the basic drivers for the use of RF-MEMS in aeronautic and space systems to the major results achieved so far. It discusses in detail the EADS low-complexity RF-MEMS in-house process and highlights the demonstration of several switchable microwave circuits like phase shifters, filters and patch antennas.

Index Terms – RF-MEMS, switch, switchable filter, switchable antenna, low-complexity, technology

1. Introduction – Why using RF-MEMS?

Next generation radar and communication systems in the aeronautic and space domain will operate over larger frequency-bands or multiple frequency-bands compared to current operational systems. Looking for example at future airborne radar system applications, the radar itself has to fulfill a variety of different tasks spanning from multi-beam searching and tracking to advanced features like synthetic aperture radar and jamming. To achieve all these very different tasks with one radar system, it is necessary to make use of broadband and frequency-agile (changing between frequency-bands or adjusting the bandwidth) RF-technologies. RF-MEMS are prone to realize such kinds of components, since the monolithically integrated tunable varactors [1], tunable inductors [2] and switches can be used to realize these circuits with excellent RF-performance. Examples of the circuits needed are, among others, tunable filters [3] for the frequency-band selection or variable matching networks [4] to optimize the load impedance of broadband solid-state amplifiers.

Regarding next-generation airborne communication and radar systems, both of them will have the need for low-profile or conformal antennas, which impose the use of electronically steerable antennas (ESA). This kind of antenna is becoming more and more important when it comes to the integration of larger antenna apertures for broadband satellite communication in Ku-band on commercial airplanes [5] or smaller apertures for side-looking radars in fighter aircrafts. These ESA have therefore depending on their application different performance and integration requirements and thus several possibilities of realization. But the key driving factor besides the maximum performance achieved with active ESA is mostly cost, which in turn leads to the implementation of passive ESA structures. The key element of these passive antenna systems are the phase shifting devices, since they are used directly in front of the low-noise amplifier in the receive path and consequently their RF-performance is critical for the signal-to-noise ratio of the receiver. If used in phase shifters, RF-MEMS exhibit advantages in terms of low insertion loss compared to their counterparts PIN diodes or FETs, while offering at the same time similar isolation values and much lower DC-power consumption.

Turning the focus to space applications, satellite payload developers can also greatly benefit from the use of RF-MEMS components. Besides the already mentioned frequency-agility of filters onboard the satellite, another important functionality, the switch-matrices, could be greatly reduced in terms of size and weight [6]. In this case, the existing co-axial mechanical parts could be replaced by small and light-weight RF-MEMS.

This variety of possible implementation of RF-MEMS components in aeronautic and space electronic systems led to the development of a low-complexity RF-MEMS process at EADS Innovation Works in Germany. The paper first reviews the advantages of this RF-MEMS technology and shows some recent results on the core building block of the switchable circuit, the RF-MEMS switch itself. But besides realizing RF-MEMS based circuits like phase shifters by implementing single switches, the subsequent paragraphs illustrate some of the switchable circuits realized by using a further simplified version of the low-complexity process. Finally, an outlook is given on further ongoing developments and ideas.

2. RF-MEMS technology description and its benefits

The low-complexity RF-MEMS technology was developed to minimize the technological challenges associated with complex RF-MEMS processes, while taking advantage of several inherent benefits described in more detail later in this paragraph. Furthermore, the low complexity of the fabrication process will greatly enhance the chances for a successful technology transfer into mass production.

The principle topology of the RF-MEMS switch is shown in Fig. 1. The fabrication starts with the thermal oxidation (1) of a high resistivity silicon substrate (2). The oxide is used as a dielectric layer for the electrostatic actuation. The next step is the implantation and the subsequent annealing of the p-type doping material (3) within the switching area of the RF path. Then, a 100 nm thin sacrificial layer is deposited and patterned. On top of the sacrificial layer, the aluminum alloy sandwich is deposited with a compressive stress in the lower half (4) and a tensile stress in the upper half (5). The geometry is defined by contact photolithography and wet etching. The backside of the wafer is metallised (6). After removal of the sacrificial layer the released cantilever structures bend up with a constant radius, pre-defined by the stress gradient of the two aluminum layers and the thickness of the sandwich. At last, the devices are released in a critical point drier.

The benefits of this technology are manifold. At first, it is easy to fabricate. Only 3 photolithographic masks are necessary to fabricate the whole RF-MEMS device. The single 2.5µm thick aluminum layer is used for the transmission lines as well as for the switching element. Furthermore, no additional bias electrodes are needed to actuate the switch: the actuation voltage is applied between the backside metal and the RF-lines on the front side. This is possible, because silicon acts as a dielectric for the...
RF-signal and as a series resistor in the DC actuation path. Hence, the entire electric field drops between the silicon oxide and the air gap resulting from the sacrificial layer. Due to the spherical bending, the air gap is very small at the anchor point of the movable part and the beam starts to be pulled down in a rolling fashion. This effect leads to a considerably high restoring force, which pulls the switch back up against capillary forces and parasitic charges. This can also be seen in the high release voltage of about 80% of the actuation voltage, which makes the switch less sensitive to stiction. The reliability tests performed up to now confirm this assumption with 10^7 switching cycles achieved without failure with 50% duty cycle under ambient atmosphere and no packaging or inert gases.

The actuation voltage can be tailored to the application by choosing the appropriate stress and thickness of the cantilever. Generally, a practical actuation voltage of 30 V to 40 V is used, which leads to an actuation path of about 20 µm at the tip of a 300 µm long cantilever structure.

Another advantage of the illustrated RF-MEMS switch concerns its RF-power handling capability. The large restoring force due to the thickness of the metal layer together with the big actuation path gives this technology also the potential of handling high RF-power e.g. in the transmit path of an antenna. First tests were performed at 12 GHz with a RF-power of several Watts at the RF-MEMS device (limited by the measurement setup). The device was actuated with the RF-power being on (hot-switching) and neither the insertion loss in the down state, nor the isolation in the up state changed [7].

Another major advantage of the single-clamped cantilever structure made with one metallization layer is the temperature handling capability. The switch was tested well above 100 °C for several hours without any indication of shape change or performance changes [8].

3. RF-MEMS switches

Since the RF-MEMS switch is the key building block for a variety of RF-MEMS based circuits, the first focus was on realizing all kinds of switches (shunt or series configuration) in different transmission line configurations (microstrip and coplanar) and for various frequency bands. Some of the microstrip line switches, which were designed for operation in Ku-, K- and Ka-band, are illustrated in the Figure 2. The upwards bended parts of the cantilevers appear in black colour due to the reflection of the microscope light. Further developments are currently ongoing to extend the frequency of operation up to W-band [9].

RF measurements were performed up to 40 GHz with a network analyzer using on-wafer TLR calibration for the de-embedding of the microstrip access lines. In the following graph, the measurement results of the series switch design for K-band are presented (Fig. 3). The K-band series switch consists of one 600 µm long trapezoid switchable cantilever with an overlap length between the switchable and the fixed part of 120 µm.

The measured series switch has an actuation voltage of 60 V. The insertion loss is between –0.3 dB at 18 GHz and –0.33 dB at 30 GHz with a corresponding isolation in the up-state between –22 dB and –17 dB over this frequency band. The switch is matched with S21 < –20 dB in the whole measurement range (not shown here).

4. RF-MEMS phase shifters

The switches presented in paragraph 3 were used as building block for the realization of phase shifting circuits. The first phase shifters were designed for the use in a Ku-band reflect array antenna for satellite communication on aeronautic platforms [10]. Therefore, the configuration of the circuit depicted in Fig. 4 is of reflective nature.

The SP3T switch in this design is based on a miniaturized and optimized version of the Ku-band switch of Fig. 2 (top left). The multi-throw switch is used to address three reflective states, while the forth state is activated with all switches in the upstate position. High-resistivity bias-lines are added to the process for the DC-voltage supply of the switches in the circuit.

The RF-performance of this circuit was measured over the frequency-band of interest from 10.7 GHz to 12.75 GHz, which is the receive channel for commercial SatCom services. The RF-parameters were analyzed for all four states and are summarized in Fig. 5 in terms of mean insertion loss and phase standard deviation.
On both sides 160 µm of the length of the patch were switchable. The far-field radiation patterns of the antenna in both states are performed for the matching frequency of the patches, in down-state at 35GHz (red and thin) and in the up-state at 38GHz (black and thick).

The mean insertion loss is smaller than -1.1 dB and the phase standard deviation is less than 27.3°. This compares favourably to the theoretical value of 26° for a 2-bit phase shifter and results in an equivalent number of bits of 1.93.

In addition to the reflective phase shifters, also transmit type phase shifters were designed and fabricated with a total insertion loss of less than 2.9 dB at 35 GHz for a 3-bit phase shifting circuit [11].

5. RF-MEMS switchable filters and antennas

The presented low-complexity RF-MEMS process can not only be used to replace existing technologies in circuits like phase shifters but enables also the realization of components enabling new functionalities like switchable filters or switchable antennas. These innovative components can be fabricated by even omitting a process step in the process described in Fig. 1. It is only necessary to use the thermal oxidation of the wafer, the sacrificial layer and the front-side and back-side metallisation. No coupling implantation is needed.

The idea behind these components is to use the bending of the front-side metallization not for the realization of a switch but rather lifting parts of transmission lines or resonators in the air. By implementing this effect, the effective dielectric constant of a transmission line or of a resonating structure can be altered and thus the electrical length of the structure is varied.

This principle is applied to the ladder filter structure in Fig. 6.

The measured insertion loss in Fig. 7 of the coupled line band-pass filter is -1.7 dB (1.5 dB) in the up-state (down-state). The center frequency shifts from 37.2 GHz to 31.2 GHz, about 20 % of the operation frequency (for 80 V actuation). For less bending and lower actuation voltage the frequency shift is 3.8GHz. The 3dB-bandwidth is 5.5 GHz (5 GHz). The ripple height is below 1.1dB.

Besides the switchable band-pass filter, this idea of controlling the effective dielectric constant was also applied to microstrip patch antennas [12] and phase shifting circuits [11]. A photograph of the switchable patch antenna is shown in Fig. 8 with a coplanar probing topology on the left side of the microstrip line. On both sides 160 µm of the length of the patch were switchable.

Fig. 6: Switchable band-pass filter at Ka-band using the very low-complexity RF-MEMS technology.

The black parts are bended upwards and the DC-voltage is applied through thin lines RF-decoupled by radial stubs.

Fig. 7: Measured band-pass characteristic of the switchable Ka-band filter

The far-field radiation patterns of the antenna in both states are shown in Fig. 9 at the corresponding matching frequencies of 35 GHz in the down-state and 38 GHz in the up-state. The field distribution in the H-plane as well as in the E-plane (not shown) of the patch does hardly change whether the ends are bending up or are switched down to the substrate (black to dashed and grey to dotted). This is favorable for the design of antenna arrays using these frequency agile elements.

Fig. 8: Switchable patch antenna at Ka-band using the very low-complexity RF-MEMS technology.

The measured directivity in Fig. 9 of the coupled line band-pass filter is -1.7 dB (1.5 dB) in the up-state (down-state). The center frequency shifts from 37.2 GHz to 31.2 GHz, about 20 % of the operation frequency (for 80 V actuation). For less bending and lower actuation voltage the frequency shift is 3.8GHz. The 3dB-bandwidth is 5.5 GHz (5 GHz). The ripple height is below 1.1dB.
From the design point of view, an optimum between the insert feed depth and the length of the switchable parts on both sides of the patch have to be found for an optimum matching in both states. A good compromise is an insert feed depth of 370 µm with a matching better –20 dB for both states (Fig. 10).

In this configuration, the antenna exhibits a centre frequency in the up-state of the patch of 38.3 GHz and switches to 35 GHz in the down-state position. It can also be seen that the antenna can act as a first filter for the separation of the two bands by being hardly matched with less then -1.7dB in the opposite frequency band.

![Fig. 10: Simulated and measured reflection coefficient with asymmetric switchable lengths of 160 µm on the feed side and 80µm on the opposite side.](image)

6. Summary and outlook

This paper described and illustrated the low-complexity RF-MEMS technology developed by EADS Innovation Works Germany and its benefits. Several applications in the aeronautic and space domain were discussed and the possible implementation of RF-MEMS components was highlighted. The low-complexity process was used for the realization of a variety of microwave circuits spanning from switches and phase shifters to enabling approaches like switchable filters and switchable patch antennas.

Based on these components, the next steps will be to demonstrate the successful integration of RF-MEMS circuits in various prototype systems like passive phased array antennas up to the W-band [13] and tunable matching networks and to proof their benefits. At the same time, the high-power handling capability of the switches will be investigated in detail.

References


This work was supported by the German Ministry of Education and Research BMBF in the project “Radarauge” under the granted contract # 16SV2227 and by the European Commission in the project “RETINA” under the granted contract FP6-2003-AERO1 #516121. Website: http://www.radarauge-project.com/ Website: http://dolomit.ijs.si/RETINA/

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(Received on July 01, 2007) (Revised on July 08, 2007)