MEMS CONTROLLED PHASE-SHIFT ELEMENTS FOR A LINEAR POLARISED REFLECTARRAY

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1. SUMMARY

No technical solution is available today for antenna reconfigurability at a competitive cost, although it is a desirable feature, particularly requested by space telecommunication operators. The reflectarray antenna with MEMS control is an appropriate answer to this need.

Two missions requesting reconfigurability were identified for space antennas :

- As a scanning antenna, a reflectarray in Ka-band used for high-rate data transmission between nano satellites flying in formation in the frame of a scientific mission ;
- As a reconfigurable antenna, a telecommunication antenna in Ku-band with a reprogrammable contoured beam ;

Phase shift elements with MEMS switches have been previously developed for missions with circular polarisation [1]. The objective is now to develop a phase shift element with MEMS devices operating on linear polarisation.

2. DESIGN OF THE PHASE SHIFT ELEMENT

2.1 SPECIFICATIONS

The following stringent requirements were selected for the design of the phase shift element :

- low loss, lower than 0.5 dB
- phase quantisation better than 3 bits,
- large bandwidth (7% in Ku band),
- 0.6 λ array lattice,
- low cross-polarisation,
- low cost for industrial manufacturing,
- robustness with respect to the manufacturing tolerances

The following frequency bands were selected :

- For the telecommunication applications, the application which benefits the most from reconfigurability is DBS TV. The band is 11.7-12.5 GHz, which gives a 6.6 % relative bandwidth ;
- For data transmission, the allocated band is set to 50 MHz, which can be allocated anywhere within a 500 MHz range (26.15 – 26.65 GHz).

2.2 Phase Shift Element Design

The design of the active phase shift element is an extension of the work carried out by IETR and ALCATEL SPACE on passive phase shift elements [2].

In this concept, we observed that by changing simultaneously the patch and the slot length, is was possible to achieve a phase shift range greater than 360°, and to have smooth variation of the phase shift with frequency.

The main interest of this phase shift element is that it combines simultaneously a low Q factor, i.e. a large frequency bandwidth, and manufacturing simplicity, since only one layer is required, instead of 2 of 3 layers for a phase shift element with similar performances [3].

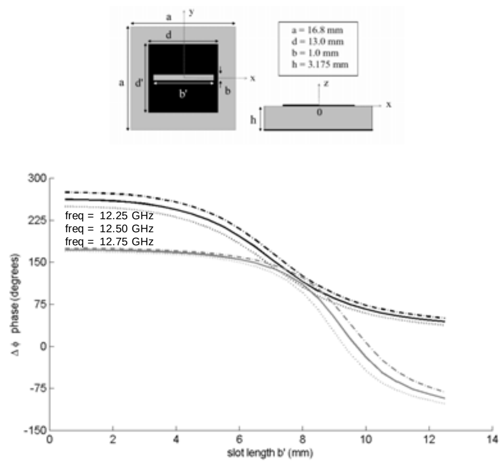


Figure 1 : Concept of a phase shift element based on a patch loaded with a slot. Corresponding Phase

variations versus slot length for two patch length, at 12.25, 12.5, 12.75 GHz.

We then devised the extension of this concept for active phase shift elements, with MEMS control. We came up to the design of a phase shift element, which consists in three patch sections separated with 0.5 mm gaps, as presented in Figure 2. These patch sections can be interconnected to each other by MEMS switches, distributed along the gaps.

When the MEMS located in the edges of a gap are in down position, the gap is then converted into a slot.

Depending on the MEMS up and down positions, the active length of the slot varies, as shown in the following figure. It is then possible to have a phase shift element, which can consist of a patch section, a long patch with two slots, a shorter patch with one slot closed to a patch section, etc.

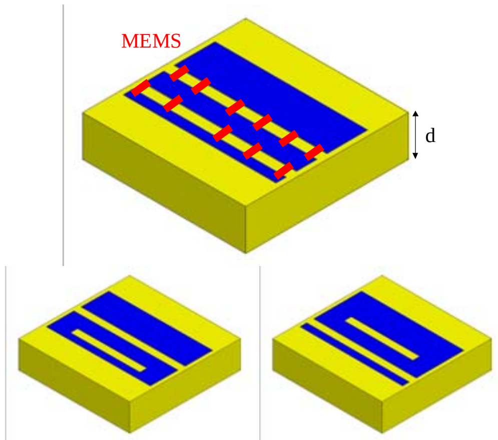


Figure 2 : Active Phase shift element with MEMS switches. Example of equivalent phase shift elements which can be obtained.

The optimisation of the phase shift element was first carried out at IETR with HFSS. The phase shift element was simulated assuming an incident plane wave on an infinite array of similar elements. Periodic boundary conditions were then used for HFSS.

The phase shift element was first simulated at three frequency points of the Ku band (central frequency and band edges) for various size of the slots. MEMS were not first considered.

As shown in Figure 3, the results indicated that the full range 0-360° was achievable. A desired phase shift can also be achieved with a number of combination of the length of the two slots. This gives an opportunity to select the best couple of slot lengths which fit the best to the desired variation of the phase shift within the frequency band.

In the design stage, the parameters of the phase shift elements were varied (substrate thickness, position of the slots, …), and those leading to the smoothest curves (phase shit vs slot lengths) were selected for the final optimisation.

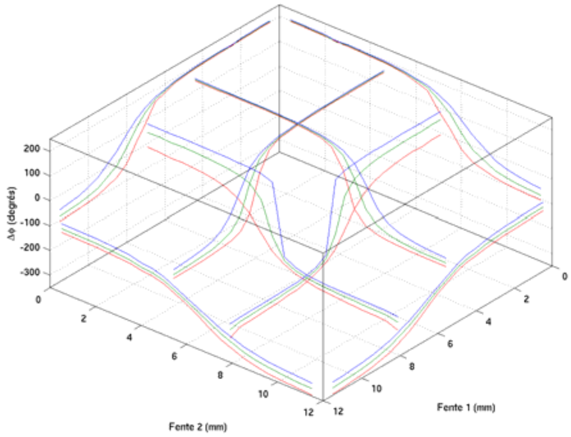


Figure 3 : Variation of the equivalent passive phase shift element (in ordinate) with the variation of the two slot lengths (in abscissas). No MEMS is considered here.

Once the parameter of the phase shift element were set, the phase shift element was simulated with MEMS switches. 5 MEMS were distributed over each slot. For the first iteration, pure short and open circuits were considered for the load when the MEMS is in down or in up position.

Specific cases were simulated. Comparison with the passive phase shift element was performed, assuming the slot length equal to the maximum distance between MEMS in down position. The discrete points showed a satisfactory comparison between the equivalent passive element and the active element with MEMS switches.

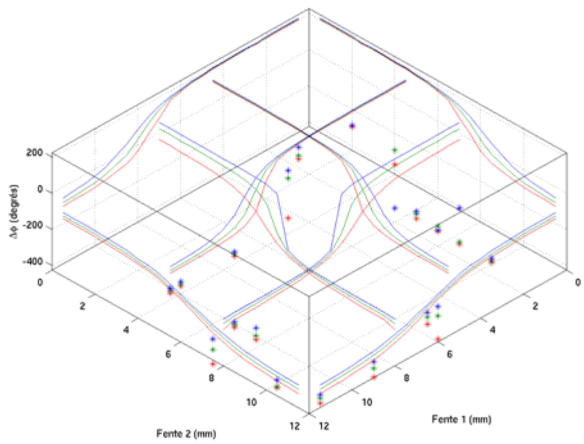


Figure 4 : Comparison of phase shift with MEMS with the equivalent passive phase shift element. The equivalent slot length is equal to the distance between MEMS switches.

It has to be mentioned that due to the diversity of scale, and to the requested meshing in HFSS, simulation were altered by convergence problems.

2.3 Simulation of the phase shift states

Now the phase shift element has been designed, the question is : Is it possible to simulate all the different phase states resulting from the various combination of the positions of the MEMS ?

The phase shift element includes 2 slots, each slot being loaded with 5 MEMS. We imposed the two opposite MEMS to be on the similar state (for the sake of reducing the cross polarisation). Then, $2^5*2^5 = 1024$ phase states can be achieved. It is of course not possible to simulate all these states with HFSS.

A specific electromagnetic modelling tool was then developed by ENSEEIHT [4-5], which could manage the high diversity of scales within the antenna (the phase shift element, the MEMS circuits), and which could be extended in the future to the scale of the array.

The structure is modelled by considering separately, at different level, the cell, the 3 patches, and the MEM switches (fig. 5). Scaling is modeled by N-ports (computed by using a integral equation technique) and the cascade of multiple N-ports allows the electromagnetic analysis of the whole multi-scale structure.

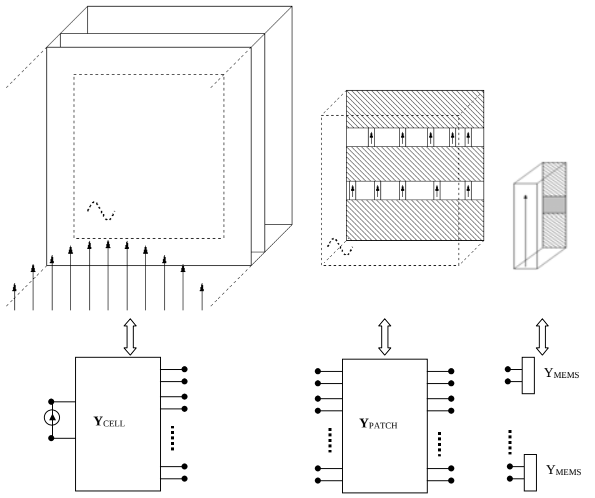
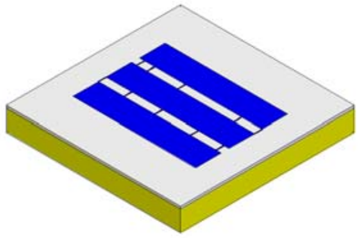


Figure 5 : General diagram of the scaling technique

The one-port network is equivalent to a surface impedance model and may be used for a first rapid design of systems containing a great number of MEMS switches. Next, the number of ports may be increased in order to improve the accuracy of numerical results.

The proposed model offers a substantial reduction in computer time and memory over many direct full-wave methods. The tool has been successively benchmarked with HFSS. The computation of all phase shift states can be computed quasi immediately with a post processing varying successively the impedance of the MEMS.

Scanning these 1024 states shows that a very regular phase distribution in the 0-360° range can be achieved (Fig 6). The average phase quantization step is very low. Dots in blue correspond to configurations which have been crossed checked with HFSS.



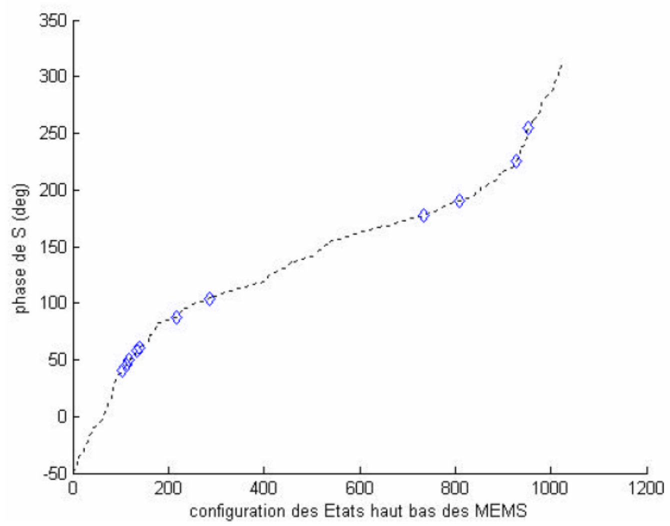


Figure 6 : Phase shift for the 1024 possible states resulting from the combinations of MEMS in up and down position.

The tool can be also used to identify the required value of the capacitance, as shown in Figure 7. Characteristics of the phase shift elements can be simulated assuming MEMS are represented by capacitances C_{down} and C_{up} instead of ideal short circuit or open circuit loads.

The objective is to preserve a similar behaviour for the phase shift elements, with capacitances achievable by the MEMS technology.

The phase shift element with MEMS switches are still compared with an equivalent passive phase shift element with variable slot lengths, as shown in Figure 7. For the comparison, the slot length of the passive element is set to the maximum distance between two MEMS in a down position. The MEMS of the active element are actuated only for one slot, all the MEMS being in up position on the other slot. With a proper actuation of MEMS, we are then able to simulate the following lengths: b=[3.5 5.5 6 6.6 7.5 8.5 9 9.5 10.5 11.5] mm. That thus corresponds to 10 MEMS configurations.

The capacitance for the up position is set to 15 pF, which is achievable. The question is now : What is the minimal value for the capacitance in down position ?

Technologically, achieving a ratio C_{down}/C_{up} of 30 is reasonable. A ratio of 100 is challenging.

The objective was then to set these required values so that they are not over-specified, and the design works nominally.

As shown below, this minimal ratio between Cdown and Cup is around 30, which is achievable technologically.

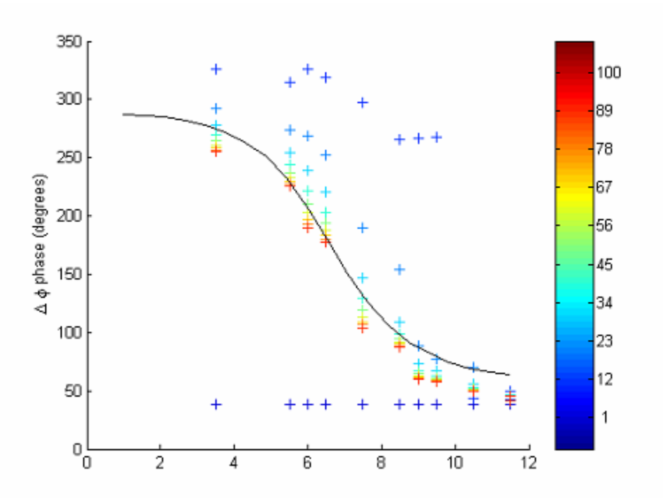


Figure 7 : (+++) C_{up}=15pF, the ratio C_{down}/C_{up} is given by the colorbar,(___) Equivalent phase shift elements, versus slot length at 11.7GHz.

3. FABRICATION OF THE PHASE SHIFT ELEMENT DESIGN

Two designs were derived:

- In Ku band, for a GEO telecom mission with flexible coverage, pseudo-active phase-shift elements (MEMS frozen Up or Down) are manufactured by Thales R&T on alumina ;
- In Ka band, for high data rate transmission between satellites, active phase-shift elements on micro-machined silicon are built by LAAS ;

3.1 PHASE SHIFT ELEMENT IN KU BAND

Alumina is chosen as the substrate used for the MEMS and the patch element. The main interest of this material is its low loss tangent. A suspended approach is selected, consisting in a thin layer of Alumina substrate suspended on an air spacer layer. This approach permits to keep the effective permittivity for the phase shift element as close as possible to the permittivity of the air.

Another advantage is the availability of Alumina substrates with filled via holes. This technology does not exist when using silicon wafers which are standard substrates for MEMS. These vias are though required in a full scale demonstrator for routing the control signals to the MEM switches.

As a first run, the decision was taken to have MEMS frozen in up or down states. This is a 5 mask levels process without packaging. The layout includes command lines and electrodes even though the switches are placed in fixed UP or DOWN configurations. This ensures the same electromagnetic behaviour as for a fully active antenna pattern.

The technology demonstrator on alumina proved to be difficult to realise due to the combination of specific requirements not present before:

- Alumina substrate required flatness: for the MEMS process a very good flatness is required, as can be found on regular silicon wafers (mirror finish) ;
- Substrate thickness: in order to meet the RF performances we chose the thinnest available alumina substrates. Even though 254 µm remains a standard thickness, the substrates are highly fragile and prone to breaking. Substrate fragility is considerably increased by the presence of 1000 via holes per plate.
- Hole pitch: metal bridge appears between two vias at the end of the electrolysis process used to fill the vias with metal; these bridges create stresses during the subsequent polishing process that leads to breakage of the substrate ;

At the time this paper is issued, despite these difficulties, the manufacturing of the phase shift elements has been finished.

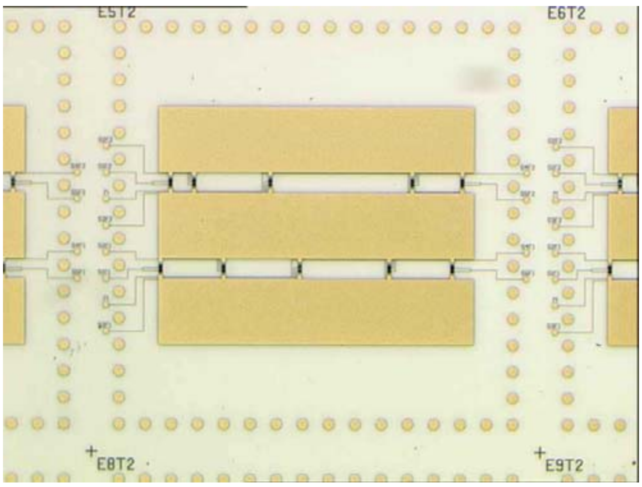


Figure 8 : Phase shift element in suspended alumina in Ku band

3.2 PHASE SHIFT ELEMENT IN KA BAND

Silicon Substrate is selected for the substrate of the phase shift element in Ka band.

A major issue is to reduce the losses. A material with high loss tangent leads to high losses, when the phase shift element has a very resonant behaviour.

In order to decrease the losses, the substrate is then locally micromachined under the location allocated to the patch, as shown in Figure 9.

The slotted patch has then to be etched on a very thin dielectric membrane. As the membrane surface was set to few square millimetres, a new membrane process was developed in order to obtain a more reliable membrane. The membrane is made with PECVD SiOxNy which allow up to 5µm thick layers, as compared to a 1.4 µm thickness with the previous process (based on SiO2/SiNx).

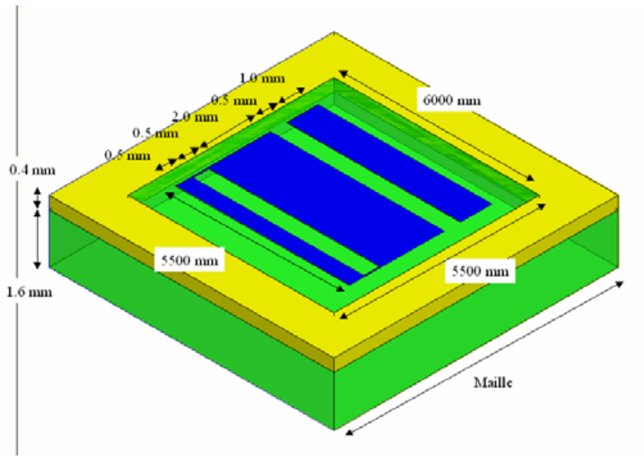


Figure 9 : Phase shift element in micromachined Silicon in Ka band

The new SiOxNy membrane was developed, and benchmarked with the SiO2/SiNx membrane for the case of a transmission line. The losses were measured very low and comparable for both membranes. This membrane could then be used for the phase shift element.

After the study of several potential design with microwave designer, we have chosen to fabricate antenna with 5 and 4 active MEMS for each slot. Several passive structures with MEMS on down position and without MEMS have been selected in order to evaluated the optimal characteristic and the parasitic effects. Switches have been also designed to evaluate the MEMS capacitance in the down position and mechanical tests structures have been implemented to control the technological parameter. Figure 10 shows an example of active cell with 5 MEMS for each slot and with tests structures around the active part.

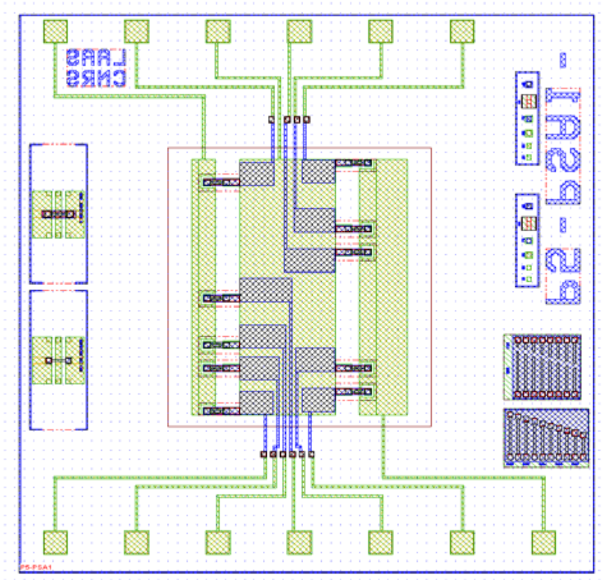


Figure 10 :Mask of a phase shift element in micromachined Silicon

The detail of the switch is presented below.

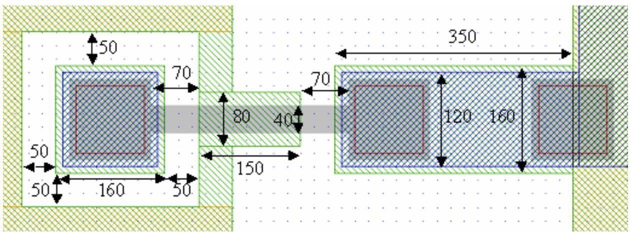


Figure 11 :Topology of the MEMS Switch

The MEMS is perpendicular to the slot. The two anchorages of the bridge are isolated from patch metallization for DC to avoid DC short circuit. And only one anchorage is isolated from patch metallization for RF. The RF short circuit and DC isolation of one anchorage is obtained by thin dielectric layer with high capacitance area.

4. TEST OF THE PHASE SHIFT ELEMENTS

The phase shift elements have not been tested yet. Measurements will be carried out using the Waveguide simulator technique. The test device has been designed and manufactured.

The measurements will first focus on the losses and on comparison between the theoretical and measured RF characteristics.

Reproducibility will be assessed, as well as the effect on losses of the Micromachining process of the Silicon. Phase shift elements with pseudo active MEMS (MEMS in frozen state) will be first tested and compared to the phase shift element will full active MEMS. The effect of the DC lines will be assessed.

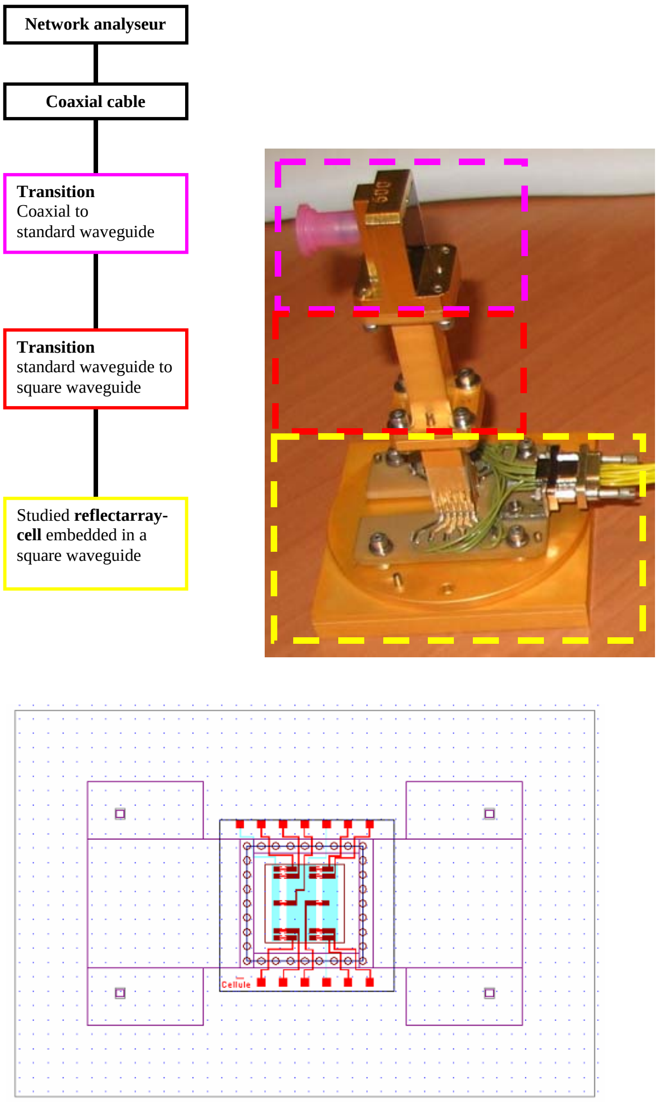


Figure 12 : Test device

5. CONCLUSION

Phase shift elements with MEMS control in linear polarisation have been designed and manufactured in Ku band and in Ka band.

The Phase shift elements indicate low quantization error and large bandwidth. Measurements will be presented at the conference.

6. REFERENCES

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