Hybrid Integrated RF-MEMS Phased Array Antenna at 10GHz

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***Abstract*— In this paper, a one-dimensional electrically steerable RF-MEMS phased array antenna for operation at 9.5GHz is demonstrated. The antenna itself is a four by eight patch antenna array realised on low-loss Teflon substrate and the feed network made out of the same substrate is a one-to-four corporate feed network. The phase shifting necessary to steer the main beam of the antenna in the H-plane of the aperture is achieved by four 3bit RF-MEMS phase shifters, which are integrated in a hybrid fashion between the antenna and the feed network. The paper describes the integration of the different elements in a stand-alone phased array antenna demonstrator. The design of the 3bit RF-MEMS phase shifters is presented and validated by very good measurement results. Finally, the measured radiation characteristic of the complete phased array antenna is shown for different switching states of the phase shifters.**

I. INTRODUCTION

Phased array antennas are pivotal components of millimetre-wave front-ends offering huge opportunities in the field of communication and sensors. Driven by the always increasing need of such devices for emerging millimetre-wave applications like automobile collision avoidance radar, the last decade has seen the development of new antenna concepts and technologies, making the realisation of electrically steerable antennas possible. Rotman lenses [1], active T/R modules [2], PIN diode or transistor based phase shifters have been implemented and some front-ends using these technologies are produced in large series and regularly commercialised. However, in many cases these realisations are handicapped by high fabrication costs or unacceptably high insertion loss. To improve on this situation, some alternative solutions based on ferro-materials or RF-MEMS phase shifters have been developed and demonstrated [3]. Because they implement very low-loss phase shifters and are cost effective to fabricate, RF-MEMS phased antennas are becoming more and more attractive. The different issues dealing with the practical implementation of RF-MEMS technology like reliability and packaging are on their way to be solved and some working RF-MEMS phase shifters have been demonstrated with excellent performance [4]; and even complete RF-MEMS phased array antennas have been demonstrated [5,6]. Nevertheless, these realisations are often based on a monolithical integration of the phase shifters, and the trend is now to evolve toward the use of RF-MEMS phase shifters as stand-alone chips, packaged and diced, that could be used as hybrid integrated components in a larger system. In this paper, a four by eight one-dimensional electrically steerable phased array antenna at 9.5GHz is demonstrated. The antenna uses RF-MEMS phase shifters integrated in a hybrid fashion between the feed network and the antenna, both realised on soft Teflon substrate. In the following sections, the design of the different elements including the feed network, the antenna and the phase shifters as well as the way they are integrated in a stand-alone demonstrator is presented. Finally, the completely integrated phased array antenna is assessed by measurement.

II. ARCHITECTURE OF THE PHASED ARRAY ANTENNA

The phased array antenna is realised with a patch antenna array and a microstrip feed network manufactured on 787µm (31mil) thick Rogers RT/Duroid 5880 substrate (ε_r=2.2, tanδ=0.001), and with four 3bit RF-MEMS phase shifters. The phase shifters are fabricated in silicon technology on a 300µm thick high resistivity silicon dielectric. The antenna itself is formed by four serially fed patch antenna sub-arrays containing eight patches each and connected in parallel by a corporate feed network. The RF-MEMS phase shifters are placed between the feed network and the antenna and are connected to them using Au RF-bond wires. Two cross-sectional views showing the integration of the elements are shown in Fig. 1.

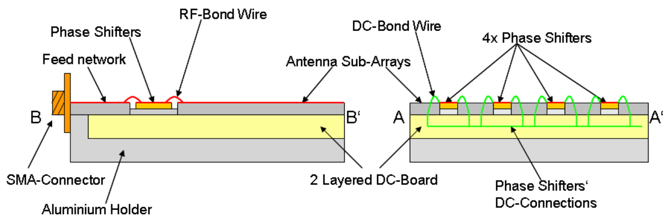

Fig. 1 Architecture of the antenna

The feed network, the antenna, and the phase shifters are placed on a DC-control board using conductive epoxy in the way described in [7]. The DC-control board is made out of a multilayer FR4 substrate. It contains the DC-control lines allowing for the actuation of the phase shifters. The difference in thickness between the silicon chips and the Teflon substrate of about 500µm implies the use of 700µm long RF-bond wires, which, thanks to the relatively low operating frequency, does not influence the matching of the antenna to a large extend. Additionally, in order to keep the broadside pattern of the antenna close to 0° in the H-plane, the length of these bond wires has to be kept quite similar. The chips are packaged using a glass lid placed on top of the Rogers substrate of the antenna and feed network. In order to maintain a gap between the RF-bond wires and the lid, a cavity is realised on the back side of the glass cover. A photograph of the fabricated antenna is shown in Fig. 2.

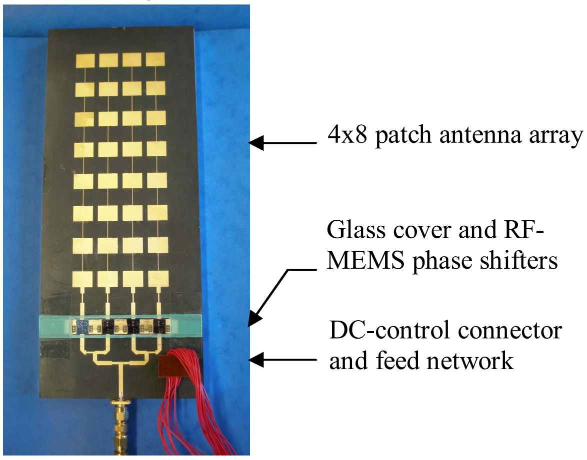

Fig. 2 Photograph of the four by eight phased array antenna

The photograph shows the different elements of the phased array antenna integrated together on a rigid aluminium holder. The patch antenna array and the corporate feed network are shown on the upper and lower parts of the photograph, respectively. In between and under the glass cover, the four RF-MEMS phase shifters are the areas in dark. The 24-pin connector on the right-hand side of the feed network is the DC-control connector allowing for a connection of the phase shifters to a LabView controlled switch matrix. The RF-interface is realised with a SMA-connector.

III. Design and Measurement of the Phase Shifters

The phase shifting necessary to steer the beam is achieved by four 3bit RF-MEMS phase shifters. The different bits 45°, 90° and 180° are all implemented in switched-line topology. The different transmission lines are switched either by two SP2Ts (Single Pole Double Throw) RF-MEMS serial switches for the 90° bit or by two SP4Ts (Single Pole 4 Throw) for the 45° and 180° bits. The parallelisation of the 45° and 180° bits imply the use of a 225° bit to overcome the fact that the two bits can not be added as in a standard serial configuration. This configuration of the phase shifter presented in [8] allows for miniaturisation of the chip. The fabricated phase shifter is shown in Fig. 3.

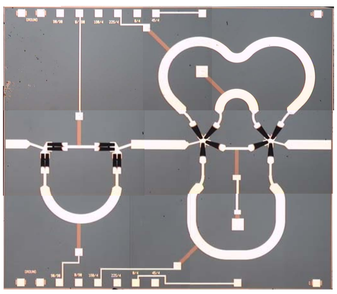

Fig. 3 Photograph of the 3bit RF-MEMS phase shifter

The RF-performance of the phase shifter has been measured with an Agilent E8363B PNA. The phase shift corresponding to the eight switching states of the phase shifter is plotted in Fig. 4. The return loss and the insertion loss corresponding to the eight switching states are shown in Fig. 5.

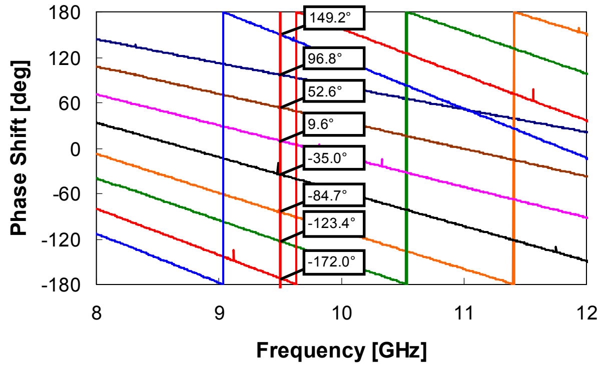

Fig. 4 Measurement of the phase shift for the eight switching states of the phase shifter

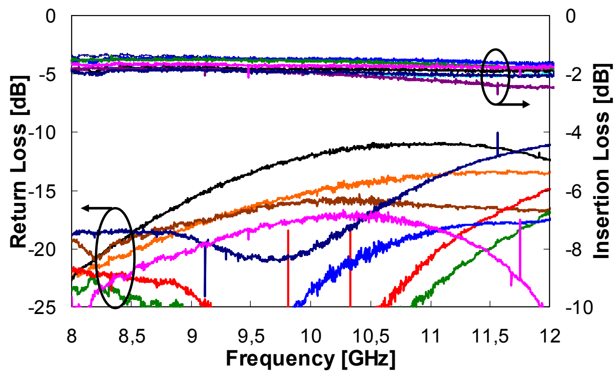

Fig. 5 Measured return loss and insertion loss for the eight switching states of the phase shifter

The insertion loss is below -2dB at the design frequency and the return loss is better than -13dB for any switching states of the phase shifter. The insertion and return loss show a satisfactory behaviour over a large band up to above 12GHz. Due to the discrete phase shifts from 0° to 315° achievable with a 3bit phase shifter, the ideal linear phase gradient required to steer the beam in a given direction cannot be exactly achieved [9]. For an ideal 3bit phase shifter, the mean phase deviation between the ideal phase gradient and the achievable phase shift is 13°. The phase deviation of the phase shifter is plotted over frequency in Fig. 6 as well as its mean insertion loss. The phase shifter has a phase deviation of less than 14° from 9GHz to 10.5GHz with a minimum of 13.1° at 9.66GHz. The variation of the phase deviation of the phase shifter versus frequency is expected and due to the true time delay switched line topology chosen to design the bits. 14° phase deviation corresponds to an equivalent number of bits of 2.89, a pointing accuracy of 6.07°, a side lobe degradation of -17.40dB and a quantisation loss of -0.26dB. For an ideal 3bit phase shifter the pointing accuracy is 5.63°, the side lobe degradation is -18.06dB and the quantisation loss is -0.26dB. This situation can only be overcome by implementing phase shifters having more than 3 bits or by using active or ferro-electric material based analogue phase shifters at the price of higher cost and/or higher insertion loss.

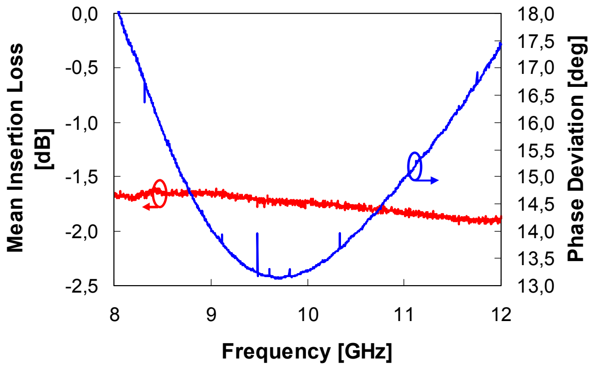

Fig. 6 Measured performance of the 3bit phase shifter: Mean insertion loss (red, graduated on the left Y-Axis) and phase deviation (blue, graduated on the right Y-Axis)

On the left Y-axis of Fig. 6, the mean insertion loss over the eight switching states is calculated from the measurement. It is below -2dB up to 12GHz and better than -1.7dB at the design frequency.

IV. Measurement of the Phased Array Antenna

The 3bit phase shifters are placed between the feed network and the antenna in order to feed the four sub-arrays with a controlled phase shift that results in electronic scanning in the H-plane of the aperture. For phased array antennas realised with 2π-phase shift range phase shifters as it is the case here, the maximal scanning angle is limited by the apparition of grating lobes in the antenna pattern and by the anisotropic radiation of a single radiating element. The antenna array presented in this paper is designed with a radiator-to-radiator spacing of 15.8mm, which corresponds to half a wavelength at the design frequency of 9.5GHz. This spacing prevents the apparition of grating lobes for a scan angle up to 90°. However, due to the anisotropic radiation characteristic of the patches used to implement the antenna array, it is not possible to steer the main beam of the antenna up to 90° and the radiation pattern of the antenna will be distorted for large scan angles. The phased array antenna has been realised and integrated as described in section II and it has been measured in an anechoic chamber.

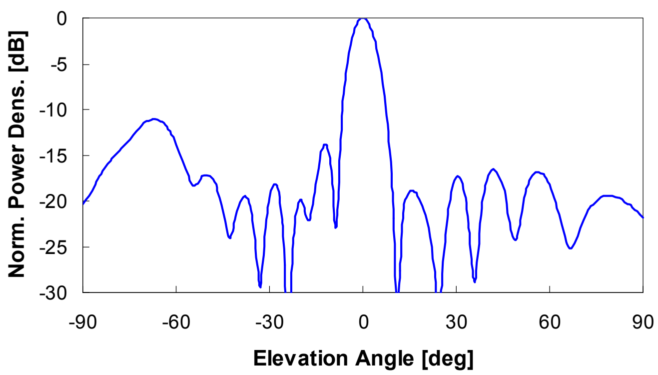

Fig. 7 Measured E-plane radiation characteristic of the phased array antenna

In the E-plane (Fig. 7), the main beam is exactly centered on the broadside, which means that the different patches of the serially fed sub-arrays are all fed in phase. The pattern has a -3dB beam width of 8.3° and the side lobe level is measured at -11dB.

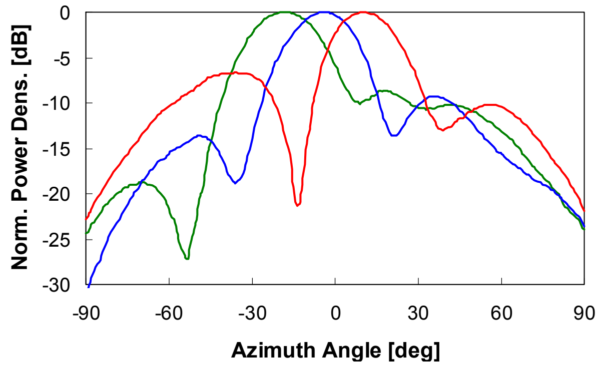

Fig. 8 Measured H-plane radiation characteristic of the phased array antenna corresponding to the three states -15°, 0° and +15°

Fig. 8 shows the measured H-plane radiation characteristic of the antenna for three switching states of the phase shifters (-15°, 0°, and +15°). The depicted patterns assume well-formed scanned main beams in the -17°, -2° and +12° directions of the H-plane. The side lobe level is about -8.8dB, -9.2dB and -6.7dB for the -17°, -2° and +12° oriented radiation characteristic, respectively. These relatively high side lobe levels as well as the slight asymmetry that can be observed for the different patterns and especially for the broadside one can be explained by different factors. The first reason is the quantisation error due to the digital nature of the phase shifters, which is further pronounced by the slight deviation of the phase shifters from ideal behaviour. A second reason may be an inaccuracy in the integration of the phase shifters.

In order to assess the discrepancy of the far field radiation pattern, additional 3D electromagnetic simulations corresponding to the cases discussed above have been performed. The simulated far field patterns and the measured radiation characteristic are compared in Fig. 9.

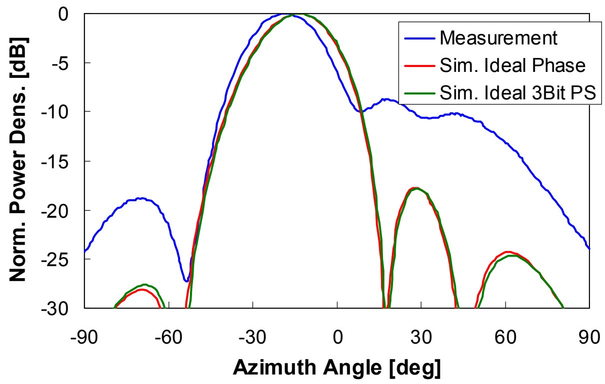

Fig. 9 Simulated and measured H-plane radiation characteristics for the -15° steered beam case

The plot shows the simulated pattern of the phased array for two different phase distributions corresponding to the -15° steered beam: in red the ideal linear phase gradient and in green the phase shift achievable with an ideal 3bit phase shifter. In blue the measured radiation characteristic already plotted in Fig. 8 is redrawn for comparison. A simulation performed with the phase distribution measured on-wafer for the phase shifter presented in section III and not plotted here for better visibility is very close to the result obtained for an ideal 3bit phase shifter. The simulation results obtained for the three phase distributions are extremely close in terms of main beam direction as well as side lobe level.

The graph shows a very good agreement between simulation and measurement in terms of main lobe direction and beam width. The measured pointing direction of –17° is only 3° above the simulated one and the -3dB beam width is measured at 26.5° where the simulated radiation characteristic shows 27.5°. The side lobe level measured at –8.8dB is above the side lobe level observed in the simulated radiation characteristic. As a consequence, it is believed to be due to the difference in length of the bond wires connecting the four sub-arrays and feed network to the phase shifters. Fig. 10 shows the measured return loss of the entire phased array antenna. The matching is better than -10dB between 9.49GHz and 9.8GHz, which corresponds to a relative band-width of 3.3%. It is a satisfactory value for an antenna of this type having eight patch resonators connected in series.

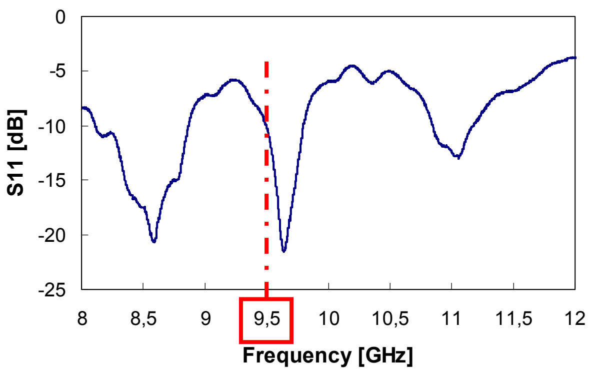

Fig. 10 Measured return loss of the complete phased array antenna

V. Conclusions

In this paper a hybrid integrated RF-MEMS based phased array antenna at 9.5GHz is demonstrated. The 3bit RF-MEMS phase shifters realised in silicon technology are mounted between the feed network and the antenna to allow for a one dimensional beam steering in the H-plane of the aperture. The design of the phase shifter is presented and validated by excellent measurement results. The phase deviation is smaller than 14° from 9GHz to 10.5GHz and the mean insertion loss is better than -2dB at the design frequency. The far field radiation characteristic of the stand-alone phased array demonstrator is also presented for 3 switching states of the phase shifters. The measurements agree quite well with the simulation results especially for the main beam direction. The somehow high side lobe level observed in the measured radiation characteristics is explained by inaccuracies in the integration of the phase shifters.

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