Low-loss compact MEMS phase shifter for phased array antennas

A.S. Abdellatif ✉, A. Abdel Aziz, R.R. Mansour and S. Safavi-Naeini

A compact and low-loss MEMS-based phase shifter is proposed for microwave/millimetre-wave phased array antenna systems. The proposed phase shifter is an alumina-based CPW line, loaded with a variable series capacitor. The phase shifter uses an electromagnetic MEMS actuator to change the capacitor value. A simple three-mask surface micromachining process has been developed for device fabrication. The measurements at 26 GHz show a phase shift of 20°. The overall size of the phase shifter (including the actuator) is 0.5 × 1.5 mm. The measured average insertion loss is 0.75 dB with a variation of 0.4 dB for different phase shifts across the band from 24.5 to 26.5 GHz.

Introduction: The microwave/millimetre-wave range of frequencies makes it feasible to realise phased arrays with a large number of elements in a reasonable size [1]. Millimetre-wave phased arrays are being considered for a number of emerging applications, such as satellite communications, automotive radar and high-speed 5G cellular communication. Phased array antennas provide a beam steering capability with high efficiency and in a relatively compact form [2]. However, the integration of a high-performance, low-cost phase shifter in large phased array systems is challenging in the high frequency range. High-performance phase shifters should consume minimal DC power and provide a low average insertion loss and low insertion loss variation for the full range of phase shift over a wide frequency range. In addition, the optimal phase shifters should be compact in size in order to fit within the antenna element footprint.

Owing to their low loss and simple integration, CPW-based phase shifters have been preferred in microwave/millimetre-wave applications [3]. Loading a CPW line with a variable capacitor is one practical approach. This simple but efficient idea has been implemented in the microwave/millimetre-wave range using various techniques [4, 5].

This Letter introduces a CPW-based MEMS microwave/millimetre-wave phase shifter. The proposed structure is essentially a series variable capacitor phase shifter. The phase shifting is performed by perturbing the propagation constant of a CPW line by virtue of a variable series capacitor. A simple low-cost three-mask fabrication process has been developed and used to fabricate the proposed phase shifter.

Design and operation: As illustrated in Fig. 1, the phase shifter is a CPW line with an actuated section of the signal line (connected to the input) that overlaps with another extended section (connected to the output) such that the overlap area between the actuated and extended signal line sections provides the variable series capacitance that allows varying the phase shift accordingly.

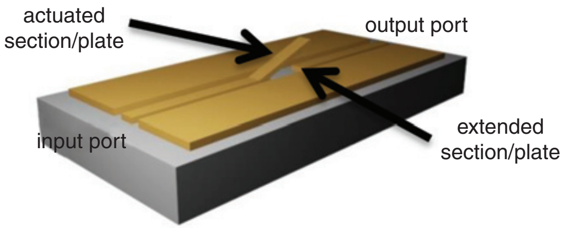

Fig. 1 *Illustration of architecture of proposed phase shifter*

The CPW line has been optimised for 50 Ω matching at 26 GHz on an alumina substrate with a thickness of 25 mils. Moreover, the structure has been optimised to have a minimal mismatch for the maximum phase shift. A HFSS–finite-element method solver along with its built-in optimiser has been used for the RF design and optimisation. The simulation results are shown in Fig. 2.

The actuation of the suspended section of the signal line can be performed electrostatically and/or electromagnetically depending on the actuation air gap (between the actuated and extended signal line section) and the power consumption restrictions [6]. In electromagnetic actuation, the presence of small electric currents in the suspended and stationary current loops can be employed (see Fig. 4). However, for large out-of-plane deflections of the actuated section, which are typically due to residual stresses of a few megapascals (especially if the length of the actuated section is relatively long), only a suspended current loop can be utilised in conjunction with a strong magnet. Placing a commercial (~1.2 T) permanent magnet on the backside of the substrate is more feasible than placing it at a certain height on the front side of the substrate where the device lies, as well as all the required probing and characterisation for the testing. The placement of the permanent magnet is shown in Fig. 3.

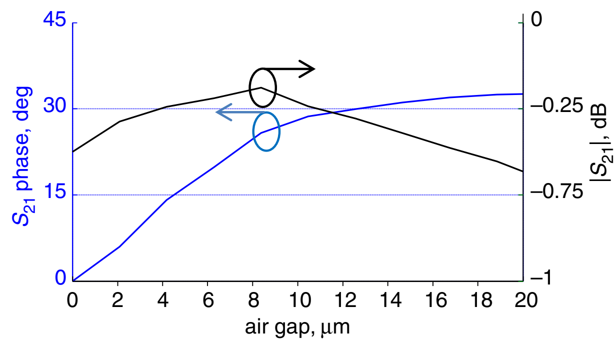

Fig. 2 *Simulated phase and insertion loss variations against air gap at 26 GHz*

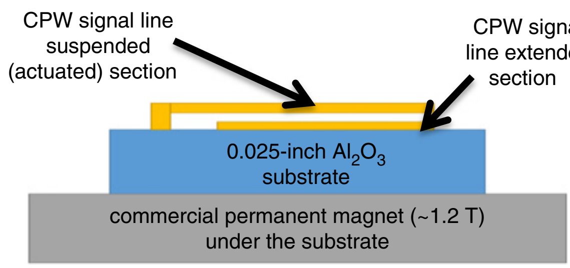

Fig. 3 *Cross-sectional view of series capacitor with permanent magnet under MEMS actuator, allowing suspended section to become in-plane if appropriate current is applied*

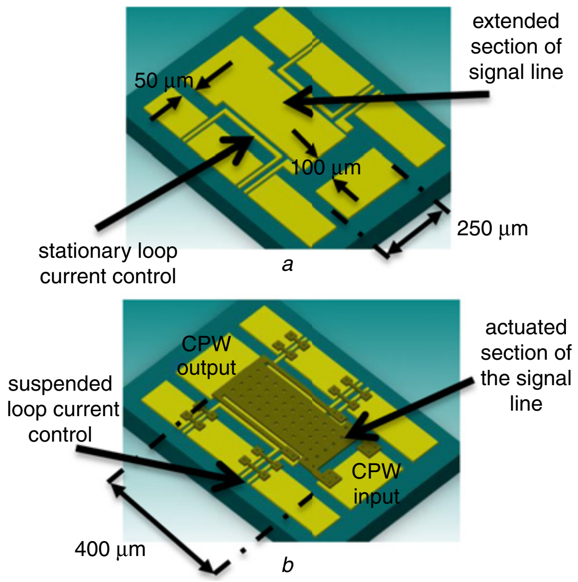

Fig. 4 *3D illustration of main fabrication steps of phase shifter*

a After patterning first gold layer
b After patterning second (structural) gold layer

In fact, using the permanent magnet with a suspended and stationary current loop allows the most reliable operation, and the voltage difference between the two loops can be used for electrostatic holding of the actuated section (and power saving) [6]. For the large initial deflections of the actuated section, the suspended current loop connected to the plate and the permanent magnet is used to restore the suspended structure in-plane. Then, the suspended and stationary current loops can be used for further controlling the position of the actuated plate relative to the extended section of the line using electromagnetic and/or electrostatic actuation (e.g. holding voltage). In the proposed design, a commercial permanent magnet is used to overcome the residual stresses, whereas the suspended and stationary current loops are used for the electromagnetic actuation as discussed in the 'Results and discussion' Section below.

Fabrication: The phase shifter was fabricated using the UWMEMS process [7]. The process employs seven photolithographic masks on 0.025-inch-thick polished alumina substrate with a relative permittivity of 9.9 and loss tangent of 0.0002 at 1 MHz. Only three masks are enough to build the phase shifter, namely, the first electroplated gold layer (2 μm) that is used to build the CPW line and the low-frequency electrically decoupled circuit, the anchor layer in the 2.5 μm-thick polyimide sacrificial layer and the second electroplated gold layer (2 μm) that is the structural layer used to build the movable plate of the capacitor. Fig. 4 demonstrates the 3D architecture of the phase shifter, where Fig. 4*a* shows the device after the microfabrication of the first gold layer whereas Fig. 4*b* shows the complete device after all the microfabrication steps are performed. An SEM picture of the fabricated device is displayed in Fig. 5. The picture is zoomed on the actuation part.

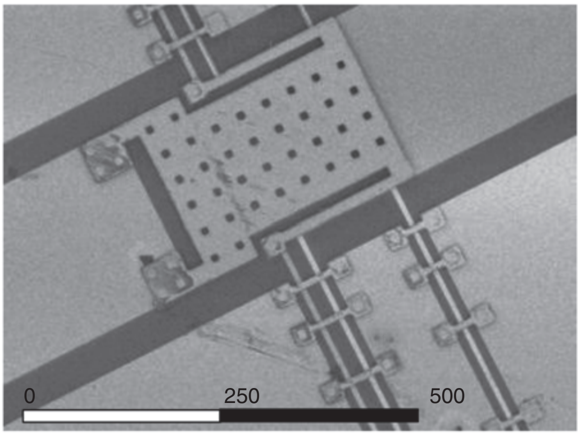

Fig. 5 *SEM picture of fabricated phase shifter*

Results and discussion: The first measurement was performed on the initial profile of the released MEMS phase shifter, and a WYKO NT100 optical interferometry profiler was utilised. The profiling result is shown in Fig. 6, where the tip deflection due to residual stress is around 17 μm for the devices with 400 μm-long actuated sections. The large initial out-of-plane deflection is suppressed by applying the appropriate current magnitude and direction to the suspended current loop. With the commercial magnet under the MEMS phase shifter chip, the current needed was around 50 mA at a voltage of 0.1 V.

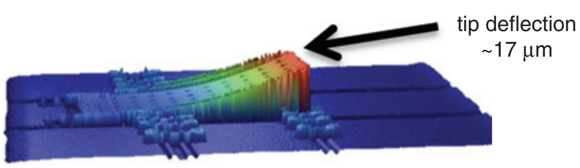

Fig. 6 *Profile of actuated section using WYKO NT1100 optical interferometry profiler*

The second set of measurements is the RF measurement conducted using the Cascade probing station and Agilent PNAX network analyser. The frequency ranges from 24.5 to 26.5 GHz. Fig. 7 shows the magnitude measurements of S_{21} and S_{11} for both the up-state and the down-state of the actuator. The insertion loss variation between the two states is ≤0.4 dB across the measurement band while the average insertion loss is 0.75 dB. As shown in Fig. 8, the measured phase shift is linear across the band and has a value of 20° at 26 GHz.

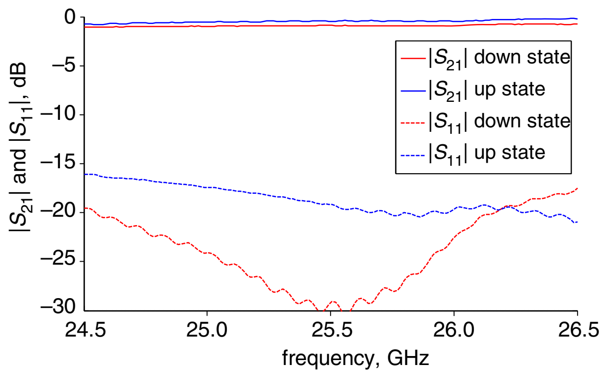

Fig. 7 *Measured $|S_{21}|$ and $|S_{11}|$ against frequency*

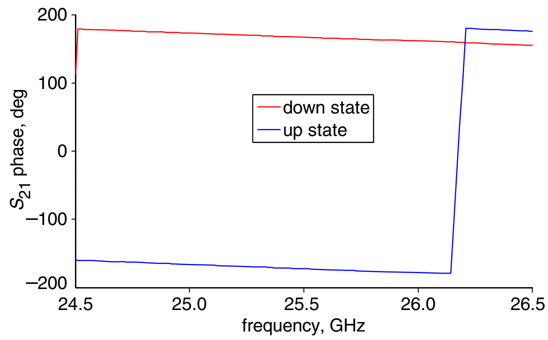

Fig. 8 *Measured S_{21} phase against frequency*

Conclusion: Proposed is a MEMS-based microwave/millimetre-wave phase shifter. The phase shifter uses CPW technology for easy integration. The MEMS actuation is essentially loading the CPW line with a MEMS-based variable capacitor based on the measured phase. The proposed phase shifter has been fabricated and tested. A simple low-cost three-mask process has been used. The measured phase shift at 26 GHz has a value of 20°. The average insertion loss is 0.75 dB with a variation of 0.4 dB for all the phase shifts across the band from 24.5 to 26.5 GHz. The length of the phase shifter cell is 0.5 mm.

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One or more of the Figures in this Letter are available in colour online.

A.S. Abdellatif , A. Abdel Aziz, R.R. Mansour and S. Safavi-Naeini (*Electrical and Computer Engineering Department, University of Waterloo, Waterloo, ON, Canada*)

✉ E-mail: aabdella@uwaterloo.ca

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