Abstract— in this paper, a new kind of frequency reconfigurable microstrip patch antenna based on MEMS (microelectromechanical systems) technology is proposed. In fabrication of this antenna, a combination of bulk and surface micromachining is used. Thermal actuation is utilized as driving mechanism. The antenna patch is discretized to facilitate vertical displacement of the patch and as a result decreasing power consumption of actuation mechanism. Downward relocation of discretized patch, toward fixed ground plane, reduces the air gap height, and subsequently operating frequency of the antenna. Operating frequency of the antenna can be shifted continuously from 17.387 GHz to 16.812 GHz in the bandwidth of 680 MHz and 645 MHz respectively. The tuning range of 575 MHz is realized by a 2V CMOS compatible voltage and acceptable power consumption. Finite-element analyses show a good microwave performance and mechanical behavior over the tuning range.

Keywords—micromachining; reconfigurable microstrip patch antenna; MEMS; thermal actuator

I. INTRODUCTION

Nowadays, because of rapid promotions in wireless communications systems, significant effort for antenna system designers is to make antennas reconfigurable so that their behavior can adapt with changing system requirements or environmental conditions. The reconfigurable antennas have the ability to modify characteristics such as operating frequency, bandwidth, radiation pattern and polarization in real time condition. Although the reconfigurable antennas have features such as, lighter in weight, lower in price and smaller in dimension incorporating them by MEMS (microelectromechanical systems) technology, ameliorates increasingly these features and adds new profits to them including low power consumption, miniaturization and new tunable properties. To overcome the challenges of multi-frequency operations, MEMS-based frequency reconfigurable microstrip patch antennas with reasonable RF and microwave characteristics and superior mechanical behaviors considered more and more. There are some mechanisms in implementation of frequency tuning in the literature of MEMS-based frequency reconfigurable antennas. In [1] Opening and closing a pair of RF-MEMS switches reconfigures a simple dipole antenna printed on a high-resistivity silicon substrate to operate in one of two frequency bands. Direct integration of RF-MEMS switches provided three separate operating bands with similar omnidirectional radiation characteristics in [2]. In [3] a frequency tunable microstrip patch antenna where a CPW stub loaded with MEMS fixed-fixed beam capacitors was used. The electrical length of the stub adjusted as the MEMS capacitors controlled via dc actuation voltage. This variable stub provided a frequency shift of 300 MHz with a tuning voltage in the range of 0–11.9 V. In [4] a frequency tunable microstrip patch antenna used a micromachined reconfigurable ground plane membrane. Electrostatic actuation of the membrane away from the antenna patch substrate introduced a Controllable air gap thickness between the substrate and the copper ground plane, which results a tuning range of 1.02GHz for a ground plane deflection from 0 to 138µm. In [5] an electrostatically actuated MEMS-based circular microstrip patch antenna by tuning range of 270 MHz is demonstrated. This antenna tunes from 16.91 GHz at 0 V to 16.64 GHz at 165 V.

In this paper, we present a novel micromachined frequency reconfigurable microstrip patch antenna. The idea of this paper in implementation of frequency tuning is controlling of the air gap height. Thermal actuation is used as a driving mechanism to meet required deflections in discretized patch. Operating frequency of antenna can be tuned from 17.387GHz to 16.812 GHz. The Tuning range is 575 MHz, which is attained by a CMOS compatible tuning voltage in the range of 0–2V. RF and microwave performances of the antenna are sufficient and its bandwidth in 0V and 2V applied driving voltage is 680 MHz and 645 MHz respectively.

The paper is organized as follows: in Section II configuration, operational mechanism and actuation mechanism of the antenna is described. Section III presents fabrication process. Simulation results are discussed in Section IV and Last Section concludes the presented work.

II. CONFIGURATION AND OPERATIONAL MECHANISM OF THE MICROMACHINED ANTENNA

A. Configuration

The configuration of proposed antenna is presented in Fig. 1. It encompasses a RF-module chip (500µm) which over it a micromachined silicon chip is mounted. The micromachined chip is formed through a process combination of bulk and surface micromachining. Bulk micromachining is used in forming silicon membrane, which then structured to create discretized patch substrate, cold arms of thermal actuator and twisty springs in the thickness of 4µm. Hot arms are founded over silicon membrane via surface micromachining process.
The Proximity coupling is used as feeding method in the antenna configuration, so a 50Ω microstrip line stooded over RF-module chip. Microstrip line radiation couples to discretized patch through 104µm thick air gap layer and 4µm thick suspended silicon membrane. The patch is a 4×4mm² discretized square of golden layer which covered silicon membrane (\(\varepsilon_r=11.9\)).

**Figure 1.** schematic of the micromachined frequency reconfigurable microstrip patch antenna

### B. Operational mechanism

The patch antenna was designed based on the equations from the transmission line model (TLM) approximation. This approximation states that the operating frequency of the patch antenna is given by [6]

\[
f_r = \frac{V_0}{2(L + \Delta L)\sqrt{\varepsilon_{eff}}} \tag{1}
\]

Where \(V_0\) is the velocity of the light in the free space, \(L\) is the length of the antenna, \(\Delta L\) is a parameter that takes into account the fringing effect which causes the antenna look some larger than its physical dimensions and \(\varepsilon_{eff}\) is the effective dielectric permittivity.

Dielectric constants of substrates that can be used for the design of microstrip antennas are usually in the range of 2.2 ≤ \(\varepsilon_r\) ≤ 12. From antennas radiation point of view, using of high values dielectric constant for substrate materials degrades the radiation characteristics of the antennas [6,7]. For good antenna performance thick substrates whose dielectric constant is in the lower end of the range are most desirable. The reason is that they provide better efficiency, larger bandwidth, loosely bound fields for radiation into space, but at the expense of larger element size [6]. To satisfy demands of the antenna system and microwave circuitry perspectives, using the same substrate, micromachining offers an alternative solution. Using the bulk micromachining and forming a cavity in the substrate to introducing an air gap beneath the silicon membrane, puts out same substrate with a lower effective dielectric constant, which possess mentioned profits for the antenna system. Moreover, by controlling the air gap height through actuation mechanisms, effective dielectric constant of substrate can be controlled so that the resonant frequency of the antenna system is adjusted according to (1)[6,7].

In our design, substrate of the antenna system is combination of epitaxial silicon membrane layer, air gap layer and RF-module chip. By controlling the air gap height through thermal actuation mechanism, effective dielectric constant and hence the resonant frequency of the antenna can be adjusted. Variation of the resonant frequency of antenna system versus air gap height is illustrated in Fig. 2. As the figure shows, by decreasing the air gap height, the operating frequency of the antenna shifts downward.

**Figure 2.** Resonant frequency shift of antenna versus air gap height variations

### C. Actuation mechanism

Thermal actuator that is used in this work contains three layers of different materials in a U-shaped structure. First layer, which is formed over silicon membrane through surface micromachining of polysilicon material, contains hot arms. Actuation voltage is applied to the hot arms. Other layer including the cold arms is created through structuring the silicon membrane. These layers are connected to each other by a thin layer of silicon nitride material in place of a shuttle that located on the tip of thermal actuator. An air gap separates them in other places. The silicon nitride layer acts as an electrical insulator between the hot and cold arms. Fig. 3 shows the schematic view of the thermal actuator in actuated mode. Dimensions and Material properties of the proposed thermal actuator are summarized in tables I and II respectively. The Thermal actuators are connected to the silicon membrane by meandered springs. The patch and silicon membrane are discretized to 8 parallel discrete parts and meandered springs are employed to connect these discrete parts to each other. Springs role in actuation mechanism is to ease the downward deflection of the discretized patch. By applying the dc voltage to the hot arms, these hot arms elongate and deflect the shuttle, springs and as a result patch, downward. Fig. 4 gives a plot of distributed meandered spring over the silicon membrane. Our
motivation to discretizing the patch is to achieve more downward deflection in low applied voltage and power consumption. Discretizing the patch cause to have further downward deflections respect to the integrated patch in the same applied voltage. So the desired frequency tuning range can be realized in discretized patch by lower voltages and power consumption respect to integrated patch. Figs 5 and 6 show the downward deflection of the integrated and discretized patch respect to variation of the applied voltage respectively.

![Schematic view of the Thermal actuator when a voltage is applied](image)

**Figure 3.** Schematic view of the Thermal actuator when a voltage is applied

![Distributed meandered springs over the discretized silicon membrane](image)

**Figure 4.** Distributed meandered springs over the discretized silicon membrane

<table>
<thead>
<tr>
<th>Geometrical parameters (um)</th>
<th>Hot arm</th>
<th>Cold arm</th>
<th>shuttle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>430</td>
<td>400</td>
<td>348</td>
</tr>
<tr>
<td>Width</td>
<td>8</td>
<td>12</td>
<td>17.5</td>
</tr>
<tr>
<td>Thickness</td>
<td>2.5</td>
<td>4</td>
<td>4.95</td>
</tr>
</tbody>
</table>

**TABLE I. DIMENSION OF THERMAL ACTUATOR**

<table>
<thead>
<tr>
<th>Material properties</th>
<th>s</th>
<th>Polysilicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus (GPa)</td>
<td>185</td>
<td>169</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td>Density(Kg/m3)</td>
<td>2329</td>
<td>2320</td>
</tr>
<tr>
<td>Thermal expansion(1/C0)</td>
<td>2.6e-6</td>
<td>3.6e-6</td>
</tr>
<tr>
<td>Thermal Conductivity (Wx°C/7m)</td>
<td>149</td>
<td>41</td>
</tr>
<tr>
<td>Resistivity (Ω.m)</td>
<td>1e3</td>
<td>20e-6</td>
</tr>
</tbody>
</table>

**TABLE II. MATERIAL PROPERTIES OF THERMAL ACTUATOR[8-11]**

![Downward deflection of the integrated patch versus applied voltage](image)

**Figure 5.** Downward deflection of the integrated patch versus applied voltage

![Downward deflection of the discretized patch versus applied voltage](image)

**Figure 6.** Downward deflection of the discretized patch versus applied voltage

Produced deflection, thermal distribution and power consumption are important parameters of the thermal actuator. In the proposed antenna, as the downward deflection of the patch increases, the tuning range of the antenna increases too but at the same time the power consumption of the thermal actuator and distributed temperature in the antenna structure enhance. Fig. 7 shows variations of the power consumption of the thermal actuator versus applied dc voltage.

![Power consumption of the thermal actuator respect to applied voltage](image)

**Figure 7.** Power consumption of the thermal actuator respect to applied voltage
The tuning range of 575MHz in the presented work is achieved by downward deflecting the patch about 19µm from up-state position (104µm air gap height) in frequency of 17.387GHz to down-state position (85µm air gap height) in frequency of 16.812GHz by the aid of a 2V applied dc voltage to the thermal actuators. Fig. 8 shows operating frequency shift of the antenna versus air gap height. The power consumption of thermal actuator in down-state position is 3.23mW which is marked in the Fig. 7. Fig. 9 shows thermal distribution over thermal actuator structure in down-state position.

From micromechanical behavior point of view, the antenna system should have tolerable mechanical noise frequency ranges to operate efficiently in different mobile communication system applications. Table III shows results of the finite-element analyses of the mechanical noise frequencies of the structure with 8, 6 and 4 number of the connected thermal actuators. As the results show, in the presented antenna system, increasing number of the thermal actuators raises mechanical noise frequency range of the structure. Reason for this effect is increase in robustness.

On the other hand, power consumption standpoint declares that minimum number of thermal actuators must be used. So a trade-off between mechanical noise frequencies ranges of structure and overall power consumption of the actuators determines number of the thermal actuators. Fig. 10 shows the contour plot of displacement at first resonant mode for 8 numbers of the connected thermal actuators. Other methods in expanding mechanical noise frequency range are increasing the springs thickness and decreasing number of discretized part of the patch from 8 to 4 but that is expected this methods cause to decrease in downward deflection of the patch.

### Table III. Mechanical Noise Natural Frequencies for Different Number of Connected Thermal Actuators

<table>
<thead>
<tr>
<th>Number of connected thermal actuators</th>
<th>Mechanical noise natural frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>290</td>
</tr>
<tr>
<td>6</td>
<td>267</td>
</tr>
<tr>
<td>4</td>
<td>239.6</td>
</tr>
</tbody>
</table>

III. FABRICATION PROCESS

The fabrication process flow is shown in Fig. 11. The process begins with a chemical-physical polishing of the silicon substrate to the height of 108µm. A 1µm silicon-oxide layer is grown by thermal oxidation and structured as sacrificial layer (a). PECVD process is used to recap and structure a 200-nm-thick layer of silicon-nitride as an electrical insulator (b).
To form the hot-arms and the shuttle a 2.5-μm-thick polysilicon layer is deposited and formed by RIE process (c). The hot-arms are released by etching the sacrificial layer in a gas phase HF (d). A 150-nm gold layer is deposited through lift-off process and followed by a bulk etching on the back side of the silicon substrate by KOH solution to form a 4-μm-thick silicon membrane (e). Finally, by the aid of a very thick photoresist layer, the RIE is performed to form the cold arms, meandered springs and suspended epitaxial silicon membrane (f) [7].

IV. RESULTS AND DISCUSSION

Fig. 12 illustrates return loss of proposed antenna system in different downward deflections of the discretized patch. As the figure shows, by increasing the applied dc voltage from 0V to 2V, operating frequency of the antenna shifts continuously from 17.387GHz in up-state position (104μm air gap height) to 16.812GHz in down-state position (85 μm air gap height). The achieved tuning range is 575MHz. Bandwidth of antenna in up and down-state positions is 680MHz and 645MHz respectively. By increasing the applied dc voltage, the tuning range can be expanded but penalties are growth in the power consumption and distributed temperature of the structure. Fig. 13 shows the radiation pattern of the antenna in E and H-plane in sample states, which is investigated by finite-element analysis. It is obvious in figure that radiation pattern of the antenna system is approximately invariant in the tuning range.

(a) Growth and structuring of silicon oxide

(b) Deposition and structuring of silicon nitride

(c) Deposition of polysilicon and structure by RIE

(d) Release of hot-arms using HF solution

(e) Performing lift-off process and bulk etching

(f) Performing RIE process to form cold arms, springs and membrane

Figure 11. Fabrication process

Figure 12. Return loss of the antenna system for various applied voltages
V. CONCLUSION

In this work, a micromachined microstrip patch antenna capable of frequency reconfiguration has been proposed. The idea of frequency tuning in the presented work was control of the variable air gap height by the aid of employed driving mechanism namely thermal actuation. The thermal actuators enforced the discretized patch to have downward deflection. The patch was discretized due to increasing the downward deflection. The antenna operating frequency could be tuned from 17.387GHz in up-state position to 16.812GHz in down-state position by the CMOS compatible dc voltage in the range of 0-2V. The tuning range (575MHz) could be increased but simultaneously the power consumption and distributed temperature over structure grows. The bandwidth of antenna in up-state position was 680MHz, which diminishes to 645MHz in downstate position. This antenna system could be used in radar and satellite applications.

REFERENCES


Figure 13. Radiation pattern of the antenna in various applied voltages: (a) 0V (Up-state) (b) 0.8V (c) 1.2V (d) 2V (Down-state)