

Tunable dual-frequency RF MEMS rectangular slot ring antenna

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ABSTRACT

This paper presents the design, fabrication, and measurement of a novel, tunable, dual frequency rectangular slot antenna using RF MEMS technology. The antenna tuning is achieved by electrostatically actuated RF MEMS variable capacitors on a stub. Two different capacitor structures are implemented on the antenna: cantilever type and fixed-fixed beam type. The latter one is not sensitive to the stress on the structural layer and its measurement results agree well with the simulation results. Each antenna is fabricated monolithically using an in-house surface micromachining RF MEMS process on a 500- μm thick glass substrate and occupies an area of about 21 mm \times 18 mm. The measurement results show that the antenna resonant frequency can be tuned in a 1 GHz range in the X-band.

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1. Introduction

With the development of advanced commercial and military microwave systems and applications, there is a growing need for a single antenna that can operate at different frequencies. For instance, an antenna whose resonant frequency is tuned continuously in a frequency range can be used in radar applications for frequency hopping. A tunable antenna can also be used in telecommunications to maintain different system frequencies with a single antenna unit in order to reduce the system size and cost. Various reconfigurable antennas using semiconductor components such as pin diodes and varactors are reported in the literature [1]. However, the losses of pin diodes and varactors increase significantly for high frequency applications. For such frequency applications, Microelectromechanical systems (MEMS) switches and variable capacitors seem to be better candidates and provide very good performances. MEMS technology and its application to RF systems enable production of tunable components such as switches, capacitors and matching networks with low power consumption, low insertion loss, and high linearity [2]. RF MEMS tunable circuit elements make the realization of reconfigurable antenna structures more efficient in terms of lower insertion loss and lower volumes. It has been shown in the literature that MEMS switches and MEMS variable capacitors are used in reconfigurable antennas to control the resonant frequency, bandwidth, polarization, and radiation pattern [4–11].

In many high frequency applications, instead of hybrid integration, monolithic implementation of microwave components with antennas is required to reduce the system size, losses due to connectors, and system complexity. In hybrid integration case, RF MEMS components having good performance can be placed on the antenna, and one can easily change the MEMS component on the antenna that is not working properly, which is impossible in monolithic integration. Furthermore, for relatively low frequency applications, such as X-band or lower frequencies, the antennas cover a large portion of the wafer. Thus the cost of an antenna, especially array antenna, monolithically integrated with RF MEMS components may be higher compared to the antenna produced on a regular substrate. On the other hand, hybrid integration of tunable components with antennas may require additional DC bias lines and wire-bonds, which increase the system design effort and implementation complexity. Moreover, these additional bias lines and wire-bonds may adversely affect the radiation characteristics. In this study, monolithic integration is preferred to obtain a compact antenna; otherwise more complicated design is needed to include bias lines and wire-bonds which may also reduce radiation performance of the antenna.

This paper presents a tunable, dual-frequency antenna monolithically integrated with RF MEMS variable capacitors to tune the operating frequencies, which were presented in Refs. [10,11]. The previous works include only the simulations and some preliminary measurement results. In this paper, more details on the fabrication process and antenna designs are discussed and complete measurement results including the radiation patterns and the details about the measurements are presented. The presented structures consist of rectangular slot ring antennas loaded with a stub on which MEMS variable capacitors are placed periodically. MEMS variable

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capacitors are electrostatically actuated and controlled via DC bias voltages. In the frame of this study, two different MEMS capacitor types are investigated as the loading element of the antenna: cantilever and fixed–fixed beam type. All MEMS capacitors on the antenna are actuated simultaneously by applying DC voltage between the RF signal line and the ground planes so that there is no need for additional bias lines which can increase the area of the antenna and can affect the radiation characteristics. The structures are designed by using Ansoft HFSS v9.2 and are fabricated with an in-house surface micromachining process presented in Section 2. Input return loss and radiation pattern measurements of the antennas are given and compared with the simulation results in Section 3.

2. Fabrication

The slot antennas presented in this work are fabricated using the surface micromachining process developed at Middle East Technical University (METU) for implementation of various RF MEMS components on 500- μm thick Pyrex 7740 glass substrates ($\epsilon_r = 4.6$). The process briefly given in Ref. [3] is optimized to reduce the stress of the structural layer and to increase the flatness of the suspended layer by properly controlling its deposition rate and thickness uniformity.

Fig. 1 shows the fabrication process flow used to fabricate the antennas with cantilever and fixed–fixed beam type capacitors. The process starts with sputtering of a 100/3000- \AA thick Ti/Au layer, which is required as the seed layer for electroplating of the base metallization. The base metallization layer is formed using a 2- μm thick gold layer, which is electroplated inside the regions defined by the mold SPR 220-3 photoresist. The remaining Ti/Au seed layer is etched using wet etching with selective titanium and gold etchants. A 3000- \AA thick Si_3N_4 layer is coated as the DC isolation layer using plasma enhanced chemical vapor deposition technique (PECVD) and patterned using the reactive ion etching (RIE) technique. The next step is the spin-coating of a photodefinable polyimide, PI 2737, as the 2- μm thick sacrificial layer. The sacrificial polyimide is cured partially in order to be able to remove it using organic strippers at the end of the process. The structural layer of the MEMS structures is a 1.2- μm thick gold layer which is sputter-deposited using the optimized recipes to increase to bridge flatness. The deposition rate for the sputtered gold is 10 $\text{\AA}/\text{s}$ at a pressure of 10×10^{-3} mbar. After the patterning of the gold structural layer, the sacrificial layer is wet etched in the SVC-175 photoresist stripper, rinsed in IPA, and dried in a supercritical point dryer. The process related effects on the performance of these two different structures are discussed in the following section. Fig. 2 shows the SEM photographs of the MEMS cantilevers on the loading section of the slot antenna.

3. Tunable dual frequency slot antenna loaded with MEMS variable capacitors

This section presents the design, simulation, and measurement results of the tunable dual frequency slot antenna with MEMS variable capacitors. Due to their ease of implementation and low profiles, slot antennas with different geometries have been investigated by several researchers [12–16]. In this study, the coplanar waveguide (CPW) fed rectangular slot ring antenna with a stub shown in Fig. 3(a) is preferred. The implementation and actuation of MEMS variable capacitors on this structure are simple, since the ground and signal planes of the antenna are at the same side of the substrate. Furthermore, the overall antenna is compact in contrast to the microstrip patch antenna loaded by MEMS capacitors [9]. It has been reported in Ref. [16] that a rectangular slot antenna performs dual frequency operation. In our design, the stub is inserted

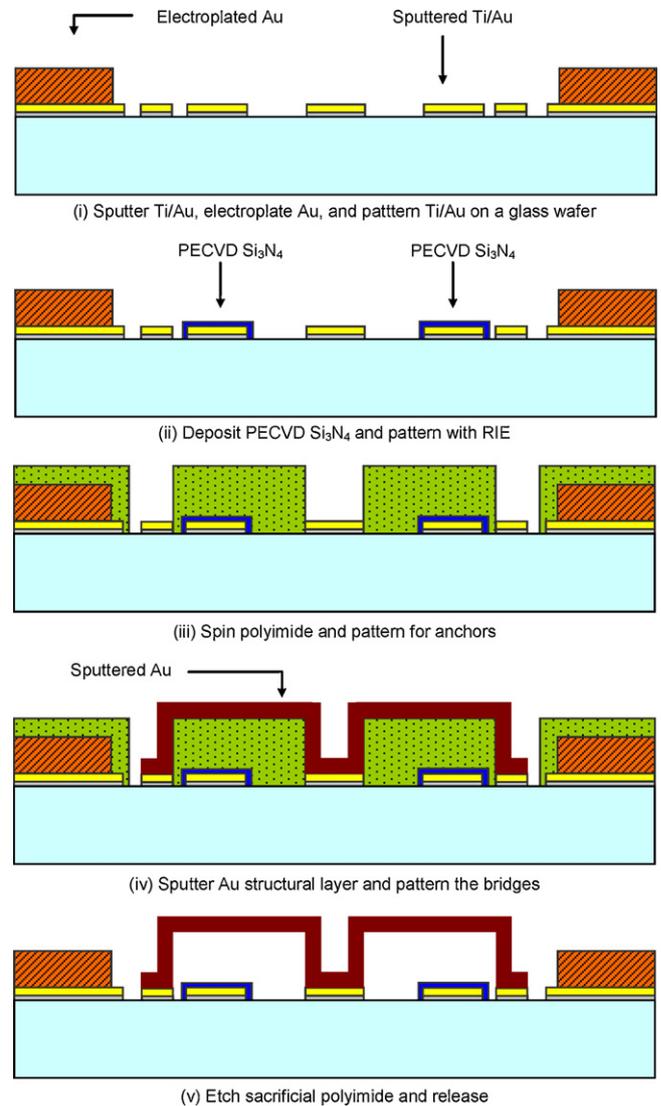


Fig. 1. The process flow used in the fabrication of the frequency tunable slot antenna structures.

for two purposes: to reduce the cross-polar component [16] and for the implementation of MEMS variable capacitors to change the frequency of the antenna. The length of the stub is selected to be nearly quarter-guided wavelength [16]. The dimensions of the stub, i.e., the characteristic impedance and the electrical length of the stub, affect the resonant frequencies and the separation between the frequencies. The input impedance of the antenna, hence the resonant frequencies of the antenna, varies with the change of the electrical properties of the stub, i.e., the characteristic impedance and the electrical length. In order to change the characteristic impedance and the electrical length of the stub, i.e., to load the antenna dynamically, 6 MEMS cantilevers or fixed–fixed beam type capacitors are distributed periodically onto the stub. The number of capacitors and the distance between the capacitors is optimized with EM simulations to obtain input matching at low and high frequencies, simultaneously. Fig. 3(a) shows the general view of the rectangular slot antenna loaded with 6 MEMS cantilevers.

3.1. Cantilever type capacitors

Fig. 3(b) gives the cross-sectional view of the cantilever type capacitors. Cantilever type capacitors need only one anchor so that their design and implementation are simpler. These cantilevers

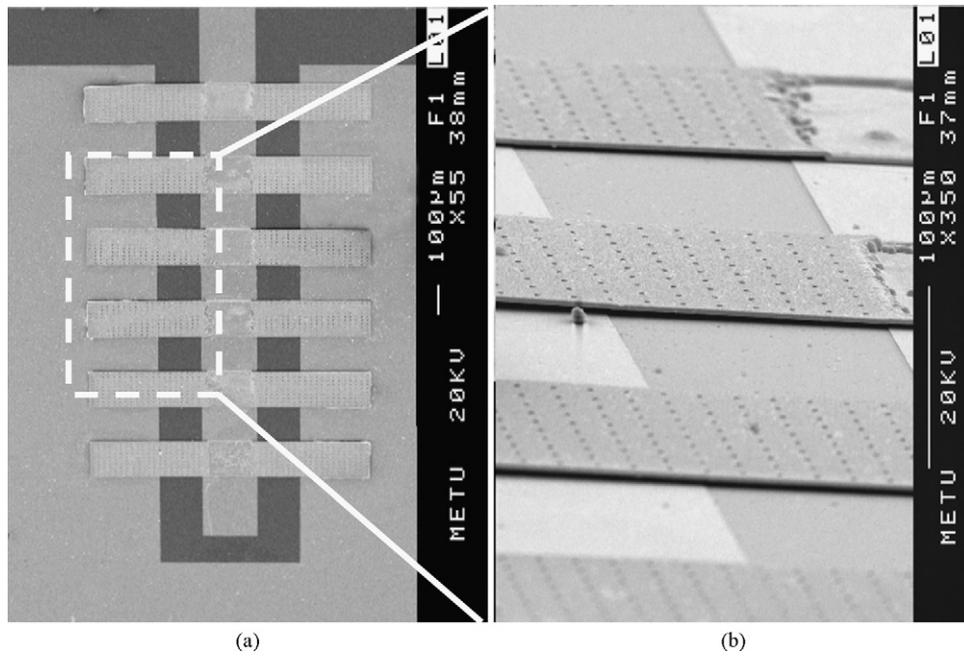


Fig. 2. SEM photographs of the loading section of rectangular slot antenna with cantilever type MEMS capacitors: (a) top view and (b) the detailed view of the cantilevers.

resemble a “T-wing” structure [17] which can be actuated electrostatically by applying a DC voltage to the CPW feeding line as shown in Fig. 3(a). The cantilevers are designed at $2\ \mu\text{m}$ height when they are not actuated, and they are lowered down to $1.4\ \mu\text{m}$ by actuation. The maximum amount of deflection of the bridge height, which is

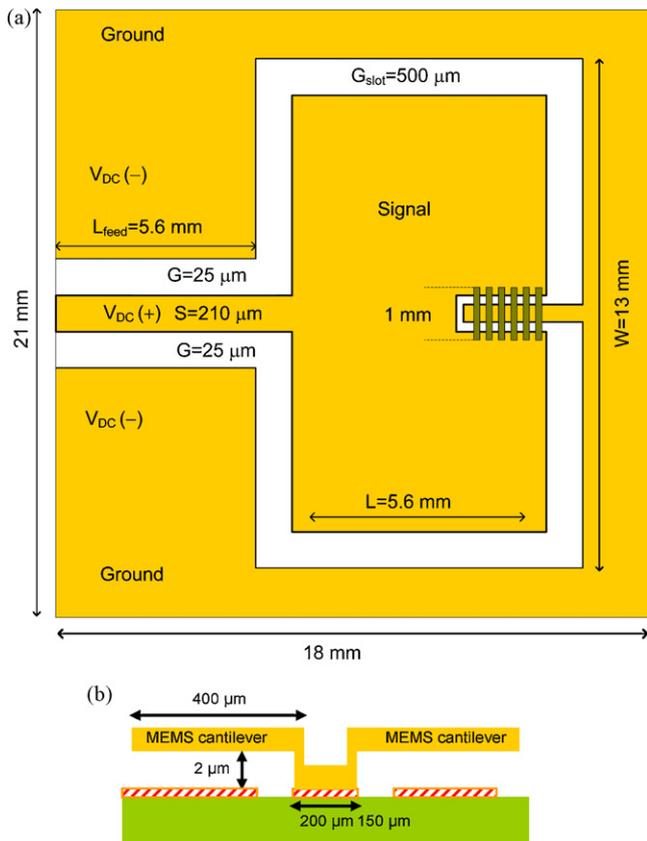


Fig. 3. (a) The general view of the rectangular slot antenna loaded with MEMS cantilever type of capacitors. (b) The cross-sectional view of the cantilever type capacitor loading the antenna.

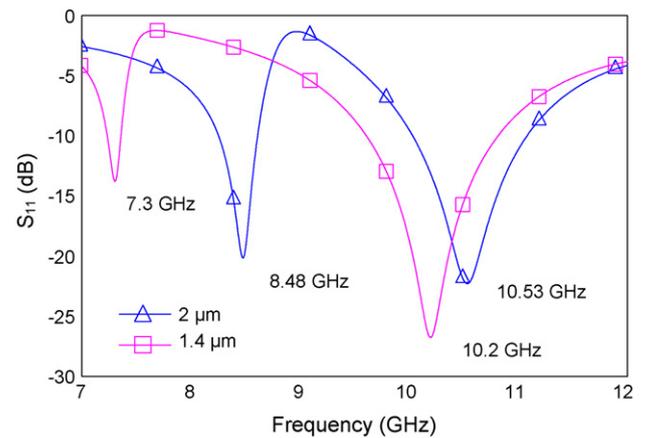


Fig. 4. The simulation results for the reflection coefficient characteristics for the rectangular slot antenna loaded with 6 MEMS cantilever type capacitors when the height of the cantilevers are varied from $2\ \mu\text{m}$ to $1.4\ \mu\text{m}$.

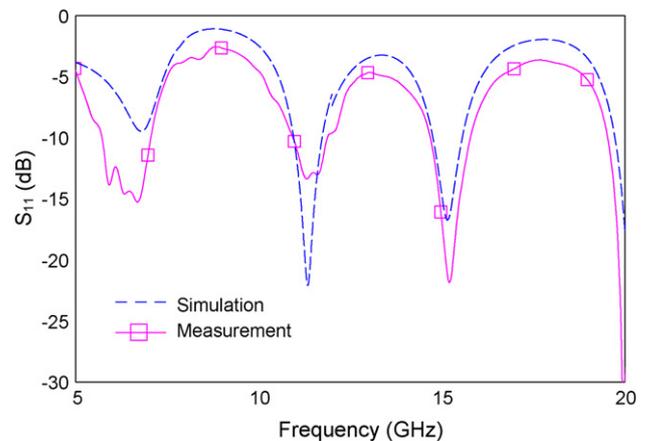


Fig. 5. The comparison between the simulation and measurement results of the unloaded antenna structure.

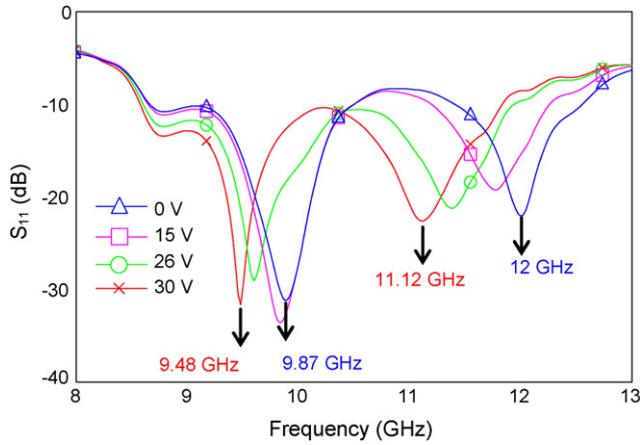


Fig. 6. The reflection coefficient characteristics of the antenna loaded with MEMS cantilevers for different actuation voltages.

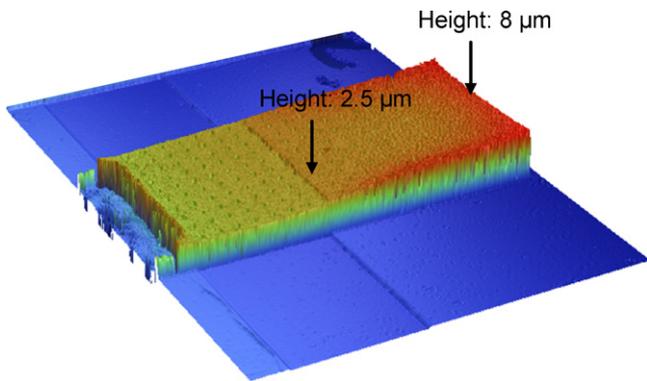


Fig. 7. The surface profiler view of the cantilever on the loading section of the antenna structure. The height of the cantilever is about 8 μm at the tip.

designed to vary between 2 μm and 1.4 μm, is limited due to the pull-in phenomenon in electrostatic actuators [2]. The tuning range of the antenna can be increased by employing electrothermally actuated MEMS capacitors [18]. However, the switching time of electrothermally actuated capacitors (100 ms) is higher compared to the electrostatically actuated ones (10 μs), which limits their use in many radar systems requiring high switching speeds [19]. For the capacitors used in this work, the loading capacitance on

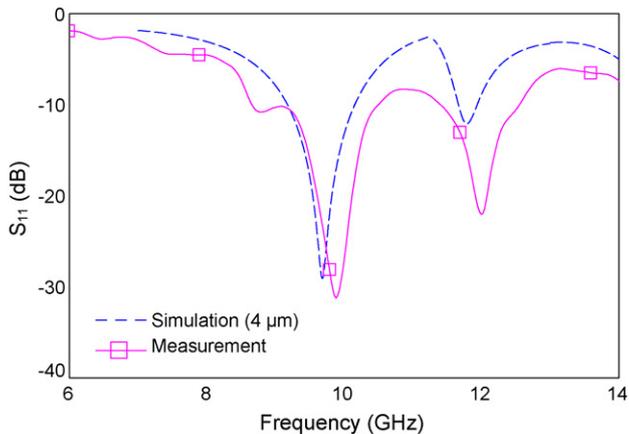


Fig. 8. The comparison between the simulation and measurement results for the loaded antenna structure. The cantilever height for the simulated structure is 4 μm.

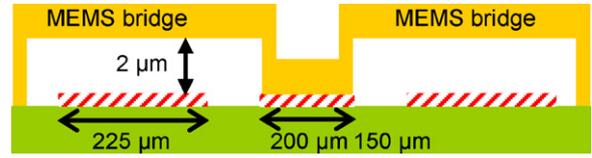


Fig. 9. The cross-sectional view of the fixed-fixed beam type capacitor loading the antenna.

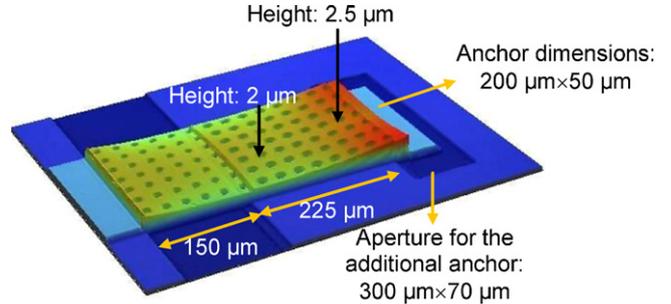


Fig. 10. The surface profiler view of the fixed-fixed beam on the loading section of the antenna structure. The height of the beam over the entire surface is about 2 μm.

the stub increases as the cantilevers are bended by applying a DC voltage, resulting in a change in the characteristic impedance and the electrical length of the stub that provides a shift in the resonant frequencies. Fig. 4 shows the Ansoft HFSS simulation results for 7–12 GHz band. When the cantilevers are at 2 μm height, the resonant frequencies occur at 8.48 GHz (10 dB BW: 4.2%) and 10.53 GHz (10 dB BW: 10%). As the height of the cantilevers moves down to 1.4 μm, the resonant frequencies shift down to 7.3 GHz (10 dB BW: 1.6%) and 10.2 GHz (10 dB BW: 11.7%), respectively. The antenna radiates broadside with a similar pattern for all of the frequencies in the tuning range.

RF measurements of the rectangular antenna structure are performed using an HP 8720D 0.05–20 GHz vector network analyzer and Cascade Microtech Summit 9000 manual probe station using Picoprobe 40-A-GSG-150P CPW probes. A 7-mm thick air foam is placed underneath the antenna in order to minimize the impact of the chuck on the antenna input impedance. A Picosecond 5542-230 bias tee is used to actuate the MEMS cantilevers during RF measurements. Fig. 5 gives the comparison between the simulation results and the measurement results of the antenna structure without MEMS cantilevers. The deviations of the simulation and the measurement at the maxima of the reflection coefficient are due

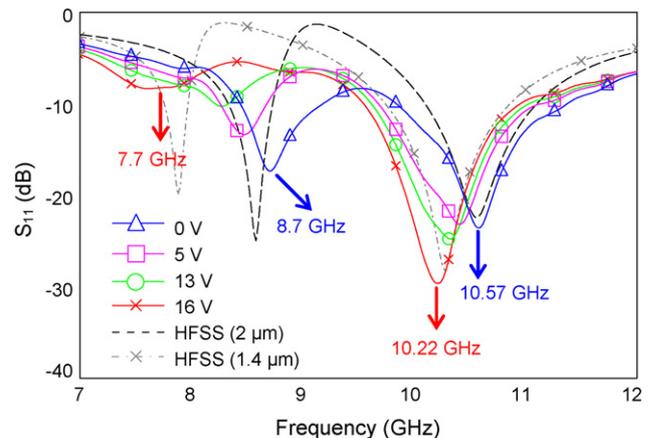


Fig. 11. The reflection coefficient characteristics of the antenna loaded with MEMS fixed-fixed beams for different actuation voltages.

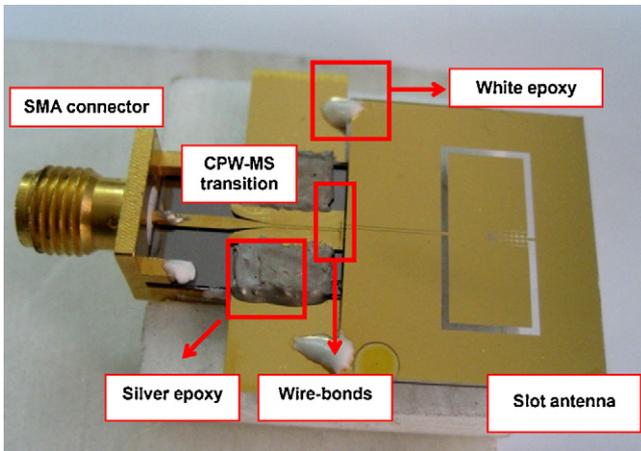


Fig. 12. The setup used to integrate the SMA connector to the CPW fed slot antenna for radiation pattern measurements.

to the finite conductivity of the gold layer used in the fabrication, which is assumed to be infinite to reduce the number of meshes and the computational efforts during the simulation. Furthermore, the dielectric loss of the glass substrate is not modeled accurately in simulations, since the glass dielectric loss varies from wafer to wafer [20]. This fact is also observed by the authors with two port CPW line measurements. It is deduced from the measurements that the dielectric loss of glass wafers may vary between 0.01 and 0.02. Fig. 6 gives the reflection coefficient characteristics of the structure with cantilever type capacitors for different actuation voltages up to the pull-in voltage. The pull-in voltage for the cantilevers is about 32 V. The resonant frequencies are shifted towards lower frequencies continuously with the increase of the applied DC voltage on the cantilevers. The lower and higher resonant frequencies can be tuned from 9.87 GHz to 9.48 GHz and from 12 GHz to 11.12 GHz, respectively. These results prove that MEMS cantilever type capacitors can be used as loading elements on a slot antenna in order to tune its resonant frequency. However, the results obtained from the actuation of the cantilevers show a discrepancy compared to the simulation results. The resonances occur at higher frequencies

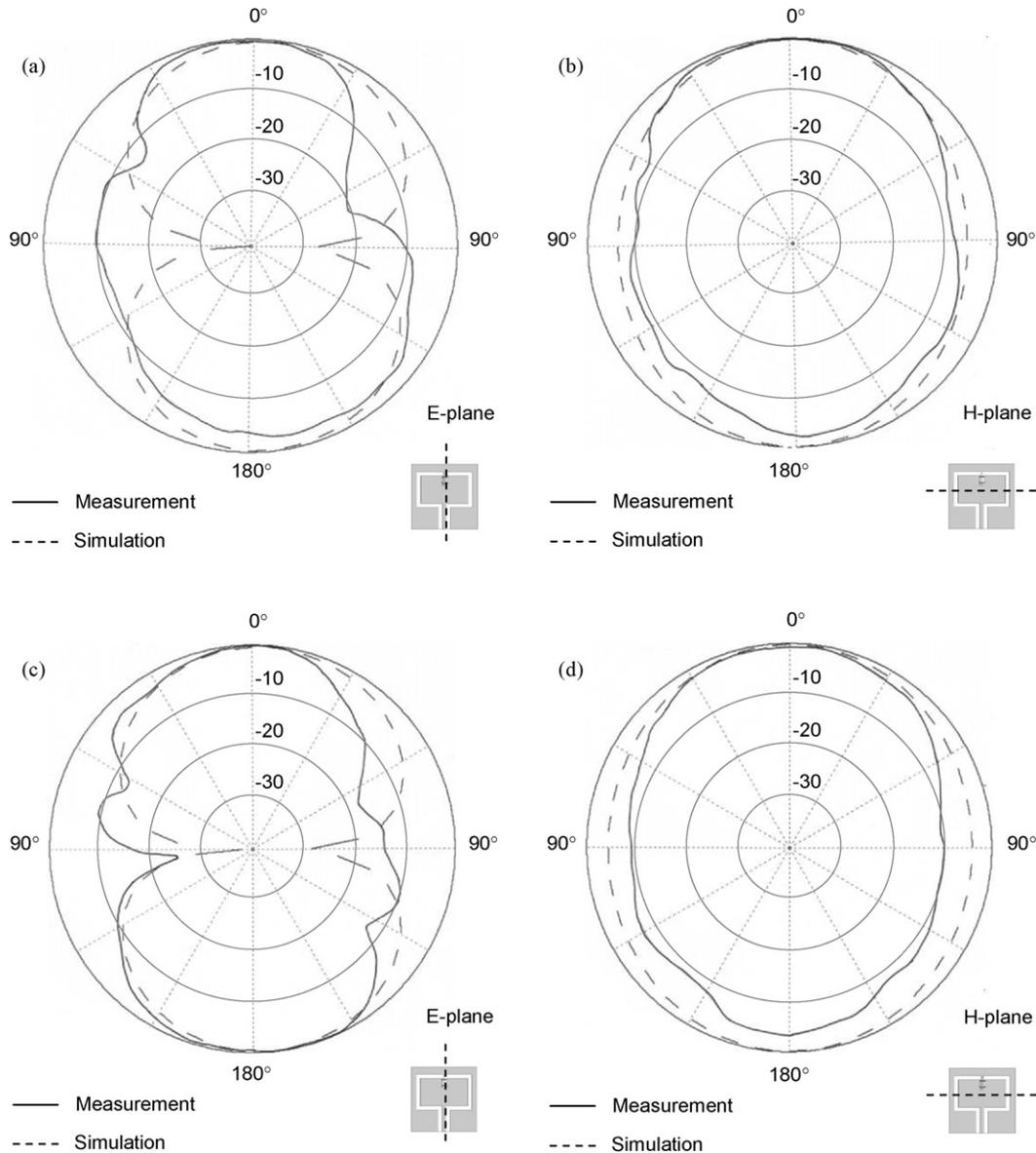


Fig. 13. Measured and simulated radiation pattern without any DC bias voltage: (a) E-plane at the upper band. (b) H-plane at the upper band. (c) E-plane at the lower band. (d) H-plane at the lower band.

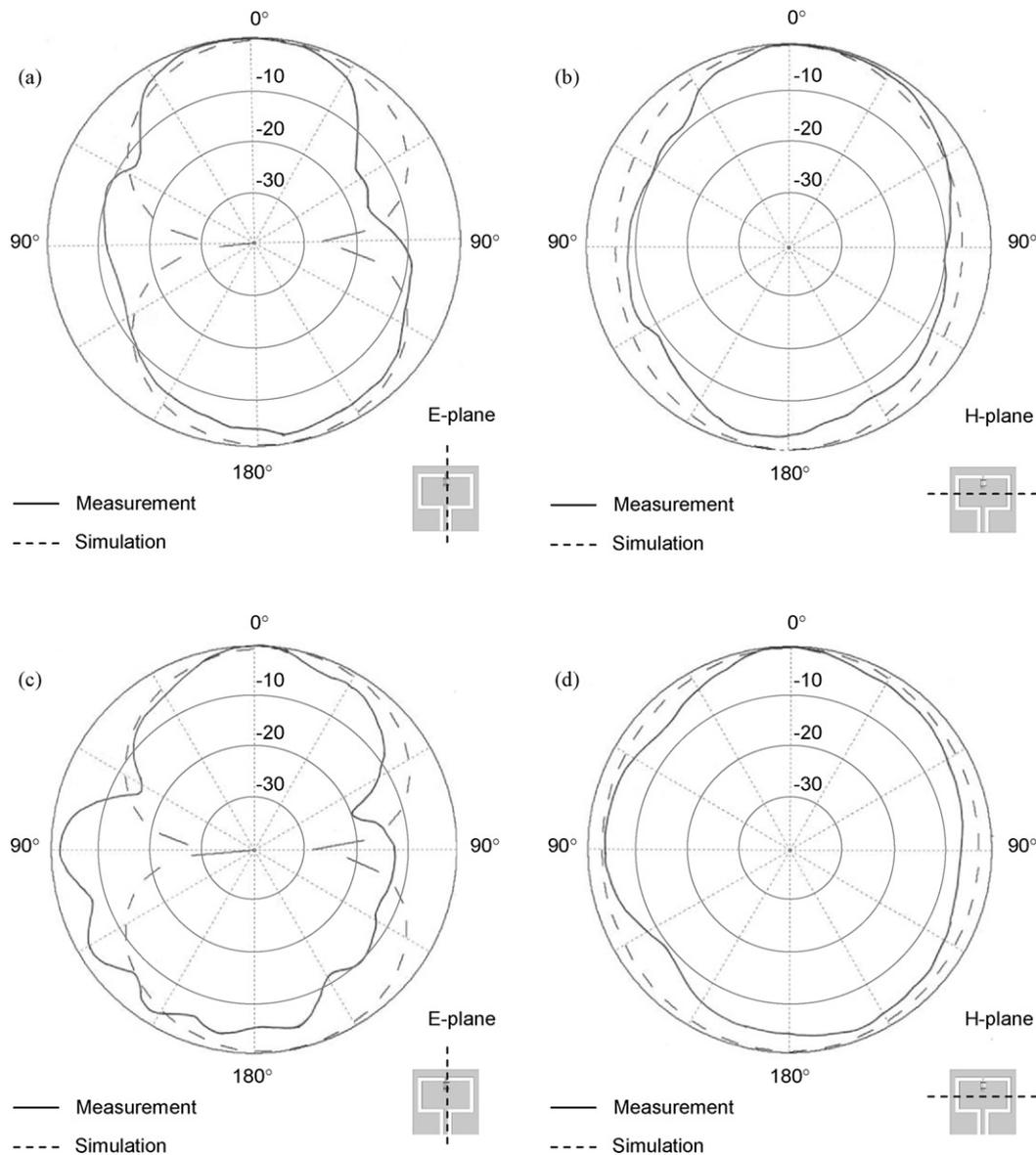


Fig. 14. Measured and simulated radiation pattern under 16V actuation voltage: (a) E-plane at the upper band. (b) H-plane at the upper band. (c) E-plane at the lower band. (d) H-plane at the lower band.

for the measured antenna since the capacitive loading for the measured antenna is lower with respect to the simulated antenna. The loading of the cantilevers is reduced since the cantilevers are curled up to $8\ \mu\text{m}$ at the tip due to the stress gradient occurred in the structural layer as it is difficult to obtain a stress-free cantilever having a length of $400\ \mu\text{m}$. Fig. 7 shows the bend observed from the surface profiler measurements obtained using Wyko NT 1100 Profiler. The height of the cantilevers is approximately $4\ \mu\text{m}$ on average, although $2\text{-}\mu\text{m}$ height has been aimed. Fig. 8 shows that the measurement result for the loaded antenna structure agrees well with the simulation result when the initial cantilever height is taken as $4\ \mu\text{m}$. These results verify that the cantilevers have internal stress causing a change in the expected operation range. It is possible to design an antenna with cantilever type capacitor at the required frequency band either by taking into account the bending of the cantilever due to stress or increasing the number of loading capacitors with shorter cantilever lengths. As an alternative solution, we propose to use fixed-fixed beam capacitor, which is discussed in the following section.

3.2. Fixed-fixed beam type capacitors

This section presents the design, simulation, and measurement of the tunable dual frequency slot antenna with fixed-fixed beam type capacitors. Fig. 9 shows the cross-sectional view of the fixed-fixed beam capacitors. The additional anchors of the beam are located inside the apertures opened in the signal conductor. Fig. 10 shows the 3D surface profiler data of the fabricated fixed-fixed beam. The aperture opened on the antenna plane to locate the additional anchors occupies an area of $300\ \mu\text{m} \times 70\ \mu\text{m}$. It is verified with the simulations that these apertures do not have any impact on the radiation characteristics at the frequency of interest. It is observed that the fabricated capacitor height is quite close to $2\ \mu\text{m}$ on average, verifying the advantage of fixed-fixed beam structures when there is a stress gradient on the structural layer. Fig. 11 shows the measurement results of the fabricated antenna for different actuation voltages up to 17V pull-in voltage, where a good agreement with the simulation results is achieved. It should be noticed that the fixed-fixed beam type MEMS capaci-

tors in this work, which are fabricated with the optimized process, have lower actuation voltages compared to the actuation voltages reported in Ref. [11]. These results show that the lower and higher resonant frequencies can be tuned from 10.57 GHz to 10.22 GHz and from 8.7 GHz to 7.7 GHz, respectively. It should be noted again here that the deviations of the simulation and the measurement at the maxima of the reflection coefficient characteristics stem from both conductor and dielectric losses. The agreement can be increased by using a substrate with a lower dielectric loss such as quartz [20].

In order to measure the radiation pattern of the antenna, the SMA connector is attached to the antenna using a CPW-microstrip transition manufactured on a 500- μm thick glass substrate using the same fabrication process. Fig. 12 shows the setup prepared for radiation pattern measurements. The transition is fixed to the antenna using white epoxy. Silver epoxy is used to provide the connection between the microstrip ground and the CPW ground of the transition. The electrical connections between the transition and feed of the slot antenna are achieved using wire-bonds. The radiation pattern measurements are performed at the in-house anechoic chamber. Figs. 13 and 14 show the measured and simulated radiation patterns for the resonant frequencies for no bias and 16 V actuation voltages, respectively. The measured patterns show a good agreement with the simulations, particularly for the H-plane. The discrepancy in the E-plane is acceptable as the effect of transition part to the radiation pattern is considered, which is not included in the simulations to reduce the computational efforts. The simulations indicate that both of the antennas have nearly the same gain values as expected. The peak gain values are found to be 1.5 dBi and 3.5 dBi for the lower and higher resonant frequencies, respectively. The back side radiation is measured to be lower than the front side radiation which may be due to the substrate losses and the CPW-microstrip transition extension supporting the antenna at the back side.

4. Conclusions

This paper presents the design, fabrication, and measurement results of a tunable, dual frequency rectangular slot antenna which is loaded by electrostatically actuated RF MEMS variable capacitors distributed periodically onto a stub. The stub is realized with the insertion of the ground plane into the conductor carrying the RF signal in order to implement a compact system. In the frame of this study, two different capacitor types are investigated: cantilever and fixed-fixed beam. Cantilever beam type capacitors are curled up easily even with a small stress gradient, as the required beam sizes are long to have the desired capacitances. The antenna with cantilever beam type capacitors is still operational, but the capacitor should be designed by taking into account the bending due to stress. It is observed that the fixed-fixed beam capacitor structure is more immune to the structural layer stress in the fabrication process. The produced antenna with fixed-fixed beam capacitors agrees well with the simulation results. The measurement results for this antenna indicate that both of the resonant frequencies can be tuned from 10.57 GHz to 10.22 GHz and from 8.7 GHz to 7.7 GHz by increasing the actuation voltage. These results show that the loading of slot antennas with RF MEMS variable capacitors provides a tunable dual frequency antenna that can operate in a frequency range continuously. This antenna structure can be an appropriate solution to reduce the volume of the systems requiring multi-frequency antennas.

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Biographies

Kagan Topalli was born in Eskisehir, Turkey, in 1979. He received B.S. and Ph.D. degrees in electrical and electronics engineering from Middle East Technical University (METU), Ankara, Turkey, in 2001 and 2007, respectively. Between 2001 and 2007, he has worked as a research assistant at METU in the Department of Electrical and Electronics Engineering. He is currently being employed as senior research scientist in the METU-MEMS Center. His major research interests include development, characterization, and integration of novel RF MEMS structures such as switches, phase shifters, and impedance tuners for RF front ends at microwave and millimeter-wave, reconfigurable antennas, phased arrays, microwave packaging, and microfabrication technologies. Dr. Topalli received the “METU Thesis of the Year Award” in 2007 for his Ph.D. dissertation, which was awarded by the Prof. Mustafa N. Parlar Education and Research Foundation.

Emre Erdil was born in Bursa, Turkey, in 1979. He received B.S. and M.S. degrees in electrical and electronics engineering from METU, Ankara, Turkey, in 2001 and 2005,

respectively. He is currently working toward the Ph.D. degree at METU in Department of Electrical and Electronics Engineering. He is currently being employed as senior engineer at Capital Markets Board of Turkey. His major research interests include development and characterization of novel MEMS integrated reconfigurable antennas such as microstrip, slot, and reflectarray antennas. He is also interested in computer networks and network security.

Ozlem Aydin Civi received B.S., M.S. and Ph.D. degrees in electrical and electronics engineering from METU, Ankara, Turkey, in 1990, 1992 and 1996 respectively. She was a research assistant in METU between 1990–1996. In 1997–1998 she was a visiting scientist at the ElectroScience Laboratory, Ohio State University. Since 1998, she has been with the Department of Electrical and Electronics Engineering, Middle East Technical University, where she is currently an associate professor. Her research interests include analytical, numerical and hybrid techniques in EMT problems especially fast asymptotic/hybrid techniques for the analysis of large finite periodic structures, multi-function antenna design, phased arrays and RF MEMS applications. Since 1997, she is a national expert of the European actions COST260, COST284, COST-IC0603 on antennas. She is one of work package leaders of AMI-COM, a European Network of Excellence on RF MEMS. Since 2004, she is a technical reviewer of the European Commission for scientific projects in the fields of antennas and communication. She has published over eighty journal and international conference papers. She was a recipient of 1994 Prof. Mustafa Parlar Foundation Research and Encouragement award with METU Radar Group and 1996 URSI Young Scientist award. She was chair of IEEE AP/MTT/ED/EMC Chapter between 2004–2006 and Turkey Section between 2006–2007. She is a member of the Administrative Committee of the Turkish National Committee of URSI.

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