Reconfigurable Integrated Patch Antenna for G-Band Applications

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***Abstract*—This paper presents a novel low actuation voltage MEMS switch integrated with elevated patch antenna on a high dielectric substrate GaAs for G-band applications. The proposed antenna is composed of MEMS switch is used for change a T-stub length, CPW feed line, air-bridge, and a radiating patch. The antenna topology effectively creates a low-substrate dielectric constant and undesired substrate effects can be eliminated, since the antenna substrate is essentially air which the lowest possible dielectric constant. This will increase the radiation efficiency, gain, and the radiation bandwidth. The antenna is also used a cantilever beam MEMS switch to reduce the actuation voltage. The simulation and measurement data have shown high performance reconfigurable antenna with low actuation voltage of 12.5volt and approximately 10GHz tunability.**

***Index Terms*—integrated antenna, mm-wave, surface wave, CPW, planar transmission line, MEMS switch, cantilever beam MEMS switch, reconfigurable antennas**

I. INTRODUCTION

Millimetre-wave antennas have been experiencing a resurgence in popularity recently as many application have been allocated, or are proposing to use, frequencies within this operating band. Probably the most significant factor impacting on current applications is the natural absorption of these frequencies by the atmosphere [1]-[3]. Signal attenuation at different rates in the atmosphere for different frequencies results from absorption by water vapour and molecular oxygen [4]. The characteristics of atmosphere absorption pose both problems and solutions for G-band antenna applications. For example, at 183GHz, the atmosphere will interact with electromagnetic radiation and absorb the energy. This means 183GHz is not a good frequency for use in long range communications, because of high signal attenuation. On the other hand, since the 183GHz signal does not travel far without significant attenuation, this frequency is useful for secure short range communications. Another use could be for communications between satellites in high earth orbit, since there is almost no water vapour and the oxygen at this height above the earth [3]. Printed antennas are largely adopted for these wireless communication systems, since the shorter wavelength of mm-wave frequencies results in boarder bandwidth and smaller antennas size, avoiding the need for bulky horn antennas and its associated losses resulting from routing signals off-chip to transition from the active MMIC to the horn [5].

There are two significant trends which are appearing in the new generation of wireless communication systems. One is integrate RF, analog and digital subsystems on single substrate and operating at frequencies beyond 100GHz. The other is to integrate multi-tasks in one system using antennas whose operating frequency can be reconfigured for different frequency bands. These trends are a very challenging the antenna design due to different substrate property requirements and different operation bands needed [6]-[8].

For example, the signals in subsystems are often carried through high dielectric substrates. However, the antenna performance is greatly reduced on high dielectric substrates due to the effective of the surface wave, which leads to reduce the bandwidth, degrade the radiation pattern, lower efficiency and undesired coupling between the various antenna elements in array configurations [9]-[13]. Further, tuning of antenna by using solid state switches (PIN diodes, transistors) at mm-wave frequencies lead to limited antenna efficiency, due to high insertion loss [14]-[16].

To improve the antennas performance, various techniques have been discussed. In order to reduce the effective of the antenna substrate, several methods have been reported such as stacking substrates and coupling through aperture [1], using bulk micromachining to make a cavity underneath and around antenna patch [11], Electronic Bandgap (EBG) structure [9], or suspending the patch antenna over an air cavity using a membrane or using supporting posts [6]-[8]. The elevated antenna approach can be considered as an alternative to a conventional printed antenna approach, with concomitant advantages of low loss, broad bandwidth, and reduced dependence on substrate effects.

Still other techniques have been reported which allow multi-bandwidth antennas by using RF-MEMS switches,

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since they offer high isolation, very low insertion loss, good linearity, and the MEMS actuator does not require any special epitaxial layers as in the case of diodes, even though MEMS switches have been shown to give very good performance, current implementations still suffer from a high actuation voltage - restricting their potential for integration with MMICs. In order to lower the actuation voltage of the MEMS switch, three different routes can be followed. These are: increasing the area of actuation; diminishing the gap between the cantilever and bottom electrode; add designing a structure with a low spring constant [15].

In the first case, the area can only be increased by so much before compactness becomes a prevailing issue. In the second case, the isolation (parasitic parallel plate capacitance) associated with the RF signal restricts the value of the gap. The third route is the one with the most flexibility, since the design of the springs does not considerably impact the size, weight, and performance of the antenna. A cantilever beam switch structure can be considered to provide very low values of spring constant in a compact area as well as providing high cross-axis sensitivity between vertical and lateral dimensions. However, with low pull-down voltage switches, stiction (adhesion) problem in cantilever beam MEMS switch with metal-to-metal can be a serious problem. Therefore, before the integration of MEMS switches with the antennas, the adhesion problem associated with the contacts needs to be resolved. Therefore, in this paper, we propose a simple integrated way to prevent the stiction problem without significant effect on pull-down voltage. This solution should be effective no matter what the actual cause of stiction is [14], [17].

Although, there is much work to be found in literature on printed antennas and multi-band antenna at microwave frequencies, a very little information can be found in the literature at G-band (140GHz to 220GHz). The design of printed antenna on high dielectric substrate working at G-band and possessing high performance, fully combatable with MMICs, and can be tuning for different band using low actuation voltage RF-MEMS switch still remain a challenging tasks. This paper will provide characterization of such antennas.

II. Antenna Design

To reduce the dielectric substrate loss, the rectangular patch is elevated above a CPW ground plane by 13μm height of gold posts. By elevating the patch, antenna topology effectively will create a low dielectric substrate since the antenna substrate is essentially air, which is the lowest possible dielectric constant. This will help increase the radiation efficiency, gain, and the bandwidth. In order to decide appropriate dimension of the antenna and optimum design, investigation was performed by simulation software HFSS. For this design the rectangular patch dimensions are $L \times W = 746\mu m \times 806\mu m$ with 13μm height and 2μm thickness. The patch is fed by a gold feeding post which connected to a CPW feed line on Gallium Arsenide (GaAs) substrate. The feeding post is placed in the middle of the width of the patch to avoid the excitation of the orthogonal TM01 mode. To tuning the elevated patch antenna at desired frequency, the feeding post must be located at that point on the patch where the input impedance is equal to 50Ω at the resonant frequency. Hence, a trial and error method is used in this design to locate the feed point using HFSS simulation software. The antenna ground plane has to be large enough to reduce diffraction of the edges for reducing ripples in the main pattern and backward radiation, and to shield the antenna from the underlying elements and vice versa. Hence, for this design, the ground plane dimensions were chosen as $Ws \times Ls = 1.5mm \times 2.03mm$ with 1.2μm thickness of gold to reduce the antenna ohmic losses. To tuning the antenna at different frequency bands, the CPW feed line loaded with reconfigurable T-stub. The antenna resonant frequency can be controlled by the change of the length of the T-stub using MEMS switch which has been reported in [17].

The cantilever beam MEMS switch structure has a movable top cantilever beam which consists of a contact pad and two non-meandered suspensions connected with two supporting posts from one side at the input signal line. The other side is elevated above the bottom output signal line. The contact pad connects RF signal lines and enables actuation when a DC voltage is applied. The area of contact pad is a more limited variable than others because the lager contact pad, the lower the insertion loss, but also the poorer the Off-state electrical isolation because of the increased capacitive coupling between the contacts pads. This capacitance can be reduced by increasing the air gap, but this increase in the gap also increases the pull-down voltage because the same gap distance also determines the actuation capacitance. Also, the increase in the pad area increases the overall mass of the cantilever beam and thus the switching time of the MEMS switch. When there is no DC voltage applied, the cantilever beam will be in the up position where the contact pad does not allow the RF signal to directly pass through the switch.

The cantilever beam can be pulled down to the bottom contact by applying a DC voltage - creating a short circuit that allows the RF signal to pass through the switch. If the DC voltage is then reduced, the cantilever beam releases back up (typically at a lower voltage than the actuation voltage).

The geometry of cantilever beam in this design was chosen to produce the lowest possible pull-down voltage. However, reduction of the spring constant might cause more stiction problems during operation. Therefore, in this design, we propose a simple integrated way to prevent the stiction problem using two tiny posts located on the substrate at the free end of the cantilever beam. These tiny posts will limit the downward motion of the contact pad and maximize the mechanical restoring force without significant effect on pull-down voltage.

The cantilever beam MEMS switch is designed at 3.5μm height when they are not actuated, which provides a good isolation for RF signal. When the cantilever in the ‘up’ position the contact pad does not allow the RF-signal to pass through the switch. By applying a DC voltage between signal lines the cantilever beam can be pulled down creating a short circuit that allows the RF-signal to pass through the switch. If the DC voltage is then reduced, the cantilever beam releases back up (typically at a lower voltage than the actuation voltage). The lowest actuation voltage measured on the fabricated switches was 12.5volt without stiction problem.

Fig. 1 shows reconfigurable antennas integrated with MEMS switch which connected with CPW feed to tune the operating frequency. By contacting the switch, reactance of feed line impedance will be change as result the antenna resonant frequency can be tuning for different bands. The antenna was designed and simulated using the Ansoft HFSS simulator, which is based on the finite element technique. A waveport at the antenna input terminal was used for the simulation with meshing at λ/4 to obtain higher simulation resolution.

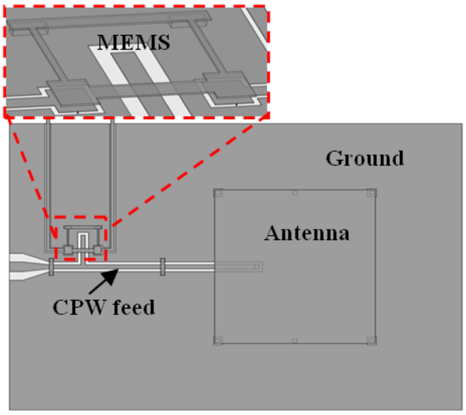


Figure 1. The configuration of rectangular elevated patch antenna design

III. Fabrication

The antenna fabrication was based on a standard III-V MMIC airbridge technology. The antenna has three levels of height, the first level consists of the ground plane and dc switch pads, then cantilever beam of MEMS switch was elevated by 3.5µm gold posts, and finally the patch was elevated by 13µm gold posts. The antenna was fabricated on a 630µm thickness SI GaAsbandwidth when we cannot change the substrate thickness for the sake of the rest of the module circuits.

Three steps were required to realize the antenna structures. First the ground plane and dc switch pads were defined by e-beam exposure and development of a 1.5 µm thick layer of PMMA followed by electron beam evaporation and lift-off of a 50nm/1.2µm thickness nichrome/gold layer. The second and third steps employ photolithography and electroplating techniques to form the suspended airbridge structures at two other levels. Fig. 2 shows an SEM image of the completed antenna substrate with a dielectric constant of 12.9. The height of the MEMS switch and patch above the substrate can be varied as required for optimum antenna performance by changing the thickness of the photoresist layers, which is used in the airbridge process. This can be used to further enhance the patch.

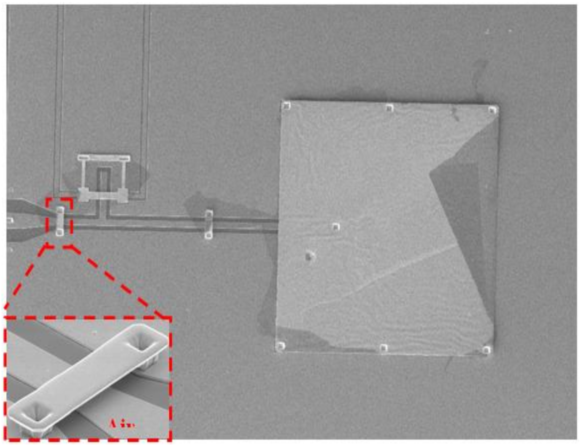


Figure 2. SIM photo of fabricated reconfigurable antenna

IV. Results

The proposed antenna is designed using an Ansoft HFSS simulator, and the fabricated antennas were characterized using an Agilent PNA Vector Network Analyzer and 140GHz to 220GHz OML heads and in wafer dc prop station. The resonant frequency of the antenna when the MEMS switch is in the up-state occurs at 173GHz with good matching of 22dB and bandwidth of 5GHz from 171GHz to 176GHz.

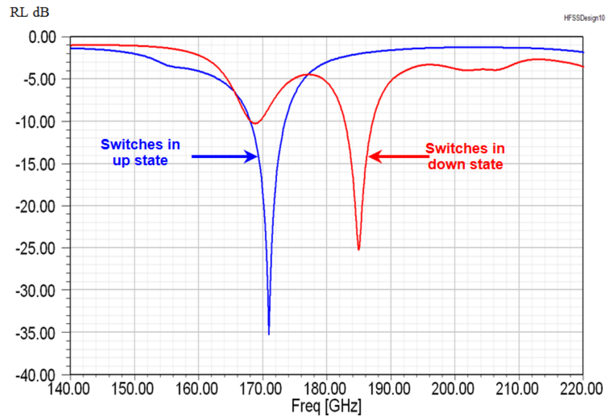


Figure 3. Simulated results of return loss antenna at different switch states

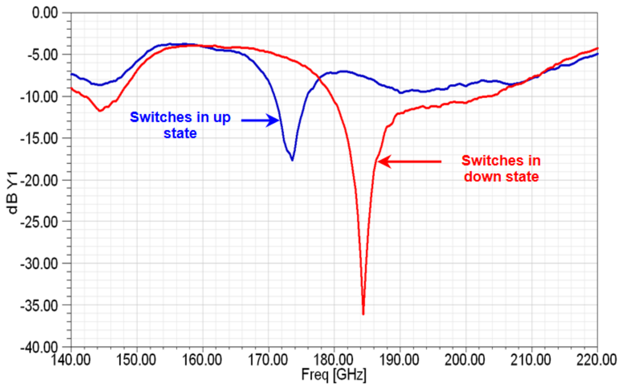
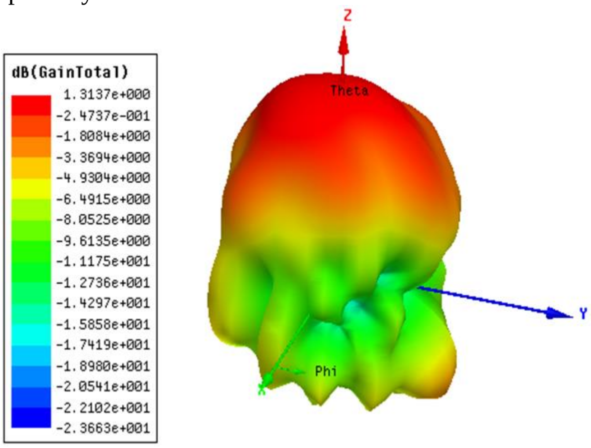


Figure 4. Measured results of return loss antenna

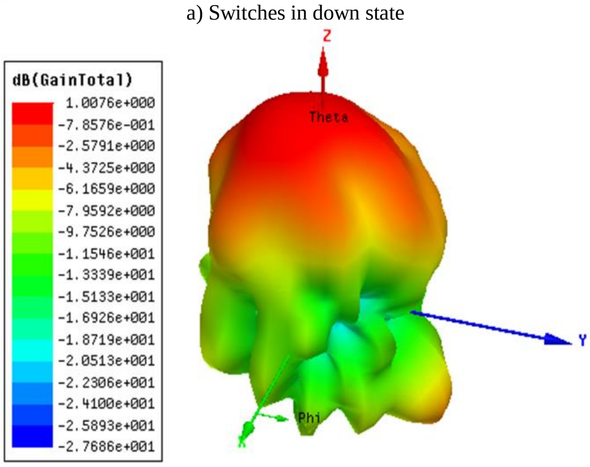
As the height of the cantilevers moves down to short the stub at 12.5volt pull-down voltage, the resonant frequency shifts to 184GHz with excellent matching of 36dB and with nearly the same bandwidth as in the off-state. Fig. 3 and Fig. 4 show the simulation and measurement return loss of the reconfigurable antenna at different switch states. The slight different between the simulation and measurement return losses can be attributed to the small geometrical disparity between the fabricated prototype and the simulated one. However, this can be easily overcome in an industry manufacturing process where all of the fabrication conditions are optimized for a specific process.

The antenna radiates broadside for the two resonances and changing the reactive input impedance does not cause any adverse effect on the radiation patterns as shown in Fig. 5.

Also, the dc biasing connection between the top and bottom plates of MEMS switch does not have a significant effect on the antenna performance since it is separately connected.



a) Switches in down state



b) Switches in up state

Figure 5. Simulated radiation pattern (gain dB)

V. CONCLUSION

The antenna scheme offers an easy method to integrate antenna with other MMICs, eliminate the most undesired substrate effects and maximize antenna performance on high dielectric substrates. Also, because there is no needing for additional transition, therefore a single chip wireless mm-wave system including the antenna can be achieved with a very compact size, low cost, and high performance. Further, because the CPW feed line is formed on the substrate and the radiating patch is lifted on the air, therefore the radiating patch and the feed line can be optimized separately like aperture coupled antenna.

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