Monolithic integrated MEMS phased array antenna scanning in two dimensions

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Abstract: A two-dimension scanning of phased array antenna has been presented. Aperture coupled microstrip patch antenna (ACMPA) elements are used to form a $2 \times 2$ array operating at 20 GHz. The array is monolithically fabricated with RF MEMS switches by using surface micromachining and anodic bonding process. The main beam can steer in two dimensions when the phase shifters are on the different state. The measurement results show that the array can complete a beam steering angle of approximate $\pm 30^\circ$ in both E-plane and H-plane, and the highest gain is 9.5 dB.

Keywords: monolithic integrated, MEMS phase shifters, MEMS switches, microstrip antenna, phased array antennas, reconfigurable antennas

Classification: Micro- or nano-electromechanical systems

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1 Introduction

Phased array antennas (PAAs) consist of multiple stationary antenna elements, which are fed coherently, and they use variable phase or time-delay control at each element to scan the radiated beam in space. PAAs employ switches/phase shifters to alter the phase of individual radiating element across an antenna aperture and thus they can enable the radiated beam to steer without any mechanical motion of the antenna system. PAAs offer many advantages over the conventional mechanically scanned gimbaled arrays. The advantages include faster scanning rate, the capability to track multiple targets, lower probability of interception, the ability to function as a radio/jammer, simultaneous air and ground modes, and synthetic aperture radar. PAAs have broad applicability for both commercial and military applications. Currently, PAAs are utilized in advanced military radars, cellular base stations, some satellite communication applications, and other communication systems. However, because of the complexity, large volume and high cost, the further application in some special area has been limited, such as in space and in ammunition [1, 2].

RF MEMS phase shifters and switches, as the critical elements in PAAs, which have exhibited excellent characteristics including small volume, low insertion loss and low dc power consumption compared to the GaAs based MMIC counterparts, have been demonstrated in [3, 4, 5]. With the advent of RF MEMS phase shifters and switches, there should be considerable business interests in the development of MEMS-based phase array antenna. The integration of the RF MEMS phase shifters with the antenna array is particularly important for the PAA systems to obtain reduced size and maintain high performance.
Some PAAs which are integrated with RF MEMS devices have been reported. In the [6, 7, 8], antenna array monolithic integrated MEMS phase shifters were presented. However, the specific method of the integration was not mentioned, only the simulation results were provided. In the [9, 10], the phase shifter and antenna were connected by means of wire bonding. Although the method was simple and easy, the loss of the lead wire still increased due to its increase in the transmission line, and the port impedance matching was also affected. In the [11, 12, 13, 14], it was the main way to complete the integration by fabricating the MEMS phase shifter and antenna array together, but these phased arrays can only complete one-dimensional scan. The function of phased array has been limited.

In this paper, we take a step forward in the development of MEMS-based monolithic integrated PAA which can perform two-dimensional scanning. Two-dimensional scanning can make PAA achieve a much wider scan range, while monolithic integration can make PAA maintain a small volume. The PAA in this study is composed of aperture coupled microstrip patch antenna (ACMPA) elements, and beam steering is obtained with RF MEMS phase shifters placed on open-ended transmission lines between the ACMPA elements. Section 2 presents details of the antenna and array design. Section 3 explains the design of the RF MEMS phase shifters and switches structure. Section 4 describes the fabrication steps of a $2 \times 2$ array antenna monolithically produced with the RF MEMS phase shifters and switches. Finally, Section 5 gives the simulation and measurement results.

2 Design of aperture coupled antenna and antenna array

The structure of the ACMPA is shown in Fig. 1(a). Antenna elements are similar to the sandwich structure. ACMPA consists of two substrates, which are antenna patch substrate and transmission line substrate respectively. The antenna patch is located on the patch substrate with a thickness of $h_p$. The length and width of the antenna are $L_p$ and $W_p$ respectively. The ground plane is placed between the two substrates, in the meantime the aperture is etching on the ground with the length of $L_a$ and width of $W_a$. The transmission line is lied on the substrate with the thickness of $h_f$. Beneath the antenna, the length of $L_s$ is beyond the center of the aperture, which is used to adjust the impedance of the antenna.

The antenna array is consisted with $2 \times 2$ ACMPA elements, which are linearly spaced as parameter $d$ (center distance) in both X and Y directions at 20 GHz, as shown in Fig. 1(b). $d$ equals half a free space wavelength, $\lambda_0/2$. Phase shifters are placed on open-ended transmission lines between the ACMPA elements. The array’s feed network uses parallel feed transmission lines. T-junction power divider and a quarter wave transmission line are employed at the connection to match the impedance. The impedance of the line and the transformer part are $50 \Omega$ and $35.3 \Omega$, and they are nominated as $W_m$ and $W_z$ respectively in Fig. 1(b).

The ACMPA array has many advantages. One of the main advantages is that it is facilitated to integrate with the feeding network and phase shifters. In addition, this structure can adjust a lot of value independently including the material and the substrate thickness, the patch size, the length and the width of the slot, to improve
the characteristics of the antenna. Besides, the spurious radiation due to the transmission line, RF MEMS switch, and bias lines is backwards and does not disturb the radiation pattern.

Glass has been chosen as the antenna substrate due to its low relative dielectric permittivity \(\varepsilon_{rp} = 5.5\), and the silicon with high resistivity \(\varepsilon_{rf} = 11.9\) is used as the transmission line and phase shifter substrate. The advantages of using these two materials are that they can not only increase the antenna’s bandwidth compared with using two layers of silicon, but also can be integrated by the way of anodic bonding which is easy to implement through MEMS fabrication.

We can get the single antenna element’s size and performance through the calculation and simulation. The width of the antenna patch is estimated by the following equation:

\[
W_p = \frac{c}{2f} \left( \frac{\varepsilon' + 1}{2} \right)^{-1/2}
\]  

Fig. 1. (a) cross-sectional and (b) backside views of the aperture coupled microstrip patch antenna
\[ e'_r = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{1}{\varepsilon_{ri}}} \]  

(2)

Where \( c \) is the light speed in free space and \( e'_r \) is the effective dielectric constant of multilayer substrate. \( h_i \) and \( \varepsilon_{ri} \) represent the height and dielectric constant of each substrate. Performances of the single antenna element are simulated and optimized in the Ansoft High Frequency Structure Simulator (HFSS) as shown in Fig. 2. The return loss of the single element is \(-26.2\) dB at 20 GHz, and the gain is 4.8 dB.

![Fig. 2](image)

(a) return loss and (b) radiation plot of the single antenna element

The parameters of the array have been optimized in HFSS. All parameters mentioned above are optimized and listed in Table I.

| Parameter | Value (mm) |
|-----------|------------|
| \( W_p \)  | 2.6        |
| \( L_p \)  | 2.6        |
| \( W_a \)  | 0.4        |
| \( L_a \)  | 1.5        |
| \( L_s \)  | 0.8        |
| \( W_m \)  | 0.2        |
| \( W_z \)  | 0.4        |
| \( d \)    | 7.5        |
| \( h_p \)  | 0.5        |
| \( h_f \)  | 0.25       |

3 RF MEMS phase shifter and switch

According to the phased array theory, PAAs are a particular case when the array elements are fed with equal amplitude but different phases, in order to electronically steer the main beam towards certain directions in space.
The simplest scenario of analysis is a linear array of \(n\) isotropic elements separated by equal distance \(d\) as shown in Fig. 3. The total phase difference \((\psi)\) of the radiated electric fields from each element towards a point \((P)\) in the far-field is caused by the length difference of the element distance \((d)\), and by phase difference \((\Delta \varphi)\) from the excitation network. \(\psi\) is expressed by:

\[
\psi = \frac{2\pi}{\lambda_0} d \sin(\theta) + \Delta \varphi
\]  

(3)

Since the total field strength at \(P\) is the superposition of the radiation field strengths of each element in the line array, \(\psi\) equals zero in order to form constructive interference to achieve the maximum radiation. If a phase of \(0\), \(\Delta \varphi\), \(2\Delta \varphi\), to \((n-1)\Delta \varphi\) is introduced in the first, second, third and \(n^{th}\) element respectively, considering the origin as the reference for phase, then the beam is steered by the angle of \(\theta\) from broadside.

1-bit MEMS phase shifter has been designed to generate the required delay on each antenna elements. The switch-line type of phase shifter has been implemented with the aim of monolithically integrating the RF-MEMS switches in the gaps of the phase shifter as shown in Fig. 4. The phase shifter consists of two transmission lines with different electrical lengths \((l_1\) and \(l_2)\) and four MEMS switches \((1, 2, 3, 4)\) in the Fig. 4). When switches 1, 2 are at on state of one phase shifter, and switches 3, 4 at on state of another, the signal transmits through \(l_1\) and \(l_2\) respectively of two phase shifters, so that time delays to get the phase shift due to the different length of transmission line. Then the relationship between phase shift \((\Delta \varphi)\) and length of paths is given by Eq. (4).
\[ \Delta \phi = \frac{360^\circ}{\lambda_g} (l_2 - l_1) \] (4)

where \( \lambda_g \) is the wavelength in the medium. The relationship between steered angle \( \theta \) and the length of phase shifter transmission lines can be calculated from Eq. (3) and Eq. (4). In this paper, the main beam is intended to be steered by \( \theta = 30^\circ \) in both E-plane and H-plane, so the difference of two transmission lines is expressed by:

\[ (l_2 - l_1) = \frac{\lambda_g}{4} \] (5)

At this time, the phase shift caused by shifter is \( \Delta \phi = \pi/2 = 90^\circ \).

Because phase shifters are located between the antenna elements, the loss of phase shifters will affect the performance and efficiency of the whole system. Generally, the loss of phase shifters mainly includes the transmission loss of the line and the loss of the MEMS switch etc. Hence, superior performance of the MEMS switch is very necessary.

The structure and parameters of RF MEMS switch are shown in Fig. 5. When a DC voltage is applied between the cantilever and the pull-down electrode, the cantilever pulls down until the end of the cantilever beam touches the transmission line and the switch closes. In order to reduce the air damping during the pull-down of the switch, and decrease the time of switch closing, holes are etched at the cantilever beam. Meanwhile, a pair of contact arm is introduced in our study. The advantages of the contact arms are that they not only reduce the contact resistance, but also reduce the coupling capacitance between the cantilever beam and the transmission line, and improve the isolation of the switch when it is at the on state.

Values of switch parameters is optimized through the simulation, and the performance results are provided in Fig. 6. When the switch is on the down state,
the return loss is less than $-20$ dB for the good of impedance matching, and the insertion loss is less than $-0.2$ dB in the range of DC-30 GHz. And when the switch is on the on state, the improvement of isolation with contact arms is also proved from the results.

The model and the performances of the phase shifter with RF MEMS switches is provided in Fig. 7. The phase shifter is $0.78 \times 2.2$ mm in area, and has a good impedance matching. In the frequency band of 17–23 GHz, the phase shift characteristics of the phase shifter exhibit good linearity and the phase shift error is less than $\pm 5^\circ$. And the phase shift error is less than $\pm 2^\circ$ in the frequency band of 18 to 21 GHz.

Fig. 6. (a) down state S-parameter of the RF MEMS switch (b) isolation with different arms of the on state

Fig. 7. (a) phase shifter with switches (b) S parameter of when the phase shifter is on the different path and (c) phase character
4 Fabrication of the PAAs

The monolithic integrated phased array antenna presented in the work is produced by using the MEMS process. Fig. 8 shows the simplified process flow. The process starts by photolithography and BOE etching on glass substrate to construct the aperture on the ground plane. Then the 200/1800 Å Cr/Au layer is evaporated as the ground (a). After that, the glass substrate and silicon substrate are combined together by using anodic bonding of 350°C and 200 N with 1000 V voltage applied (b). Next, microstrip antenna patches are processed by sputtering and patterning a 120/2000 Å thick Cr/Cu layer on the glass substrate side (c). Then a 2 µm thick photoresist is spun to protect the patches while other processes are proceed. The silicon substrate side is used to construct the transmission lines with RF MEMS phase shifter and switches integrated. The process at silicon side starts with a 100/1000 Å thick Cr/Cu seed layer deposition by sputtering (d). Then the transmission lines and electrode are patterned and electroplated at a height of 2 µm (e). After that, 5 µm thick photoresist is spin-coated to form the sacrificial layer and patterned to obtain hollows for the anchor regions on the transmission lines, which is about to construct the anchor of RF MEMS switches to integrate with the feed network (f). Next, a seed layer of 1000 Å thick Cu is sputtering, and after the pattern by photoetching, 2 µm Cu is electroplated to be the cantilever of the switch (g). Finally, the sacrificial layer and seed layers are removed from top to bottom and layer by layer slowly by using wet etching (h).

![Fig. 8. The process flow of the phased array antenna.](image-url)
The size of the 2 × 2 antenna array is about 16.5 mm × 16.5 mm. Fig. 9 shows the photographs of the fabricated array, in which the diameter of the coin is 25 mm. While Fig. 10 shows the optical photographs of the series RF MEMS phase shifter and switch monolithically integrated to the transmission line.

![Fig. 9](image1)  ![Fig. 10](image2)

5 Simulation and measurement results

The simulations of the ACMAA are carried out in HFSS to compare with the measurements. The phase shifter have three states (−90°, 0° and 90°) in both X and Y plane, which can steer the main beam in E-plane and H-plane respectively for ±30° from the analysis in section 3.

When the phase shifter is at 0° state, which means that there is no transmission line length difference between two phase shifter in X or Y plane, the main beam will not steer and $\theta = 0°$. The parameter $S_{11}$ is shown in Fig. 11 when there is no phase differences among antenna elements. The measurement is in good agreement with the simulation results. The return loss in the measurement is −17.2 dB at 20 GHz. The gain and the bandwidth is about 9.5 dB and 4% respectively.
When the switches are actuated to make the signal transmit through different paths of phase shifters, the phase between two antenna elements changes and the main beam of the array starts to be steering. When the phase shifters and switches which are located in Y direction are working as state \((0^\circ, \pm 90^\circ)\), the beam is steering in E-plane at the angle of \((0^\circ, \pm 30^\circ)\). Accordingly, when the phase shifters and switches are working as state \((\pm 90^\circ, 0^\circ)\) in X direction, the beam is steering in H-plane at the angle of \((\pm 30^\circ, 0^\circ)\). The results of two dimensional beam steering are given in Fig. 12.

The antenna in the E-plane of the actual steering angle is \(+29.16^\circ\) and \(-30.8^\circ\), with the gain of 8.7 dB and 7.7 dB respectively. While the steering angle in H-plane is \(+28.54^\circ\) and \(-31.52^\circ\), with the gain of 7.7 dB and 8 dB respectively. The deviation of the main beam direction may be caused by the fabrication error and the test error.

6 Conclusion

A two-dimension \(2 \times 2\) phased array antenna is achieved by integrating RF MEMS phase shifter and switches with ACMPA at 20 GHz. In both X and Y plane, the
progressive phase shift between the elements is adjusted by the on and off state positions of the DC series RF MEMS switches inserted in the transmission line of the antenna elements. The full array is produced monolithically, so that small volume is obtained by the dimension of $16.5 \times 16.5 \times 0.75 \text{ mm}$. Good agreement between the simulated and measured results is gained. Meanwhile, measured results demonstrate that the main beam of the array can be switched to achieve approximately $\pm 30^\circ$ in both E-plane and H-plane with the help of the RF MEMS switches. The gain of the array is 9.5 dB when no phase difference between antenna elements, while achieves about 8 dB during the beam steering. According to the authors’ knowledge, this monolithically integrated RF MEMS phased array antenna has great potential for the development of radar and wireless communication.

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