Quasi-Optical E-Band MEMS Switching Arrays

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Abstract — **This paper presents modeling, design, fabrication, and testing of an E-band MEMS based quasi-optical switching array. The quasi-optical MEMS switching array has been demonstrated with an isolation of better than 10 dB from 70~85GHz. The maximum demonstrated ON /OFF ratio is over 15 dB at 76GHz.**

I. INTRODUCTION

RF microelectromechanical systems (MEMS) switches with high performance have recently been demonstrated up to 110 GHz [1]. Integrated with quasi-optical grid array technology, RF MEMS switches have the potential to form low cost, high performance, wide bandwidth, monolithic quasi-optical control elements [2]-[4].

In this approach, a quasi-optical (QO) grid array is loaded with a two dimensional array of MEMS switches. The significant performance improvements possible with MEMS switching arrays, as compared to typical semiconductor switching arrays, have important implications in system designs for both military and commercial telecommunications at microwave and millimeter-wave frequencies.

II. MODELING OF RF MEMS SWITCHING ARRAY

A schematic drawing of the current quasi-optical switching array configuration is shown in Fig. 1. Here, the microwave beam impinges from the left side, passes through the MEMS grid array, and then continues to the right.

The QO MEMS switching array can be modeled as a shunt CLR lumped element resonant circuit and two transmission lines with characteristic impedances of the substrate and air, respectively, as shown in Fig. 2. For this simple equivalent model, the MEMS device can be treated as a variable capacitor in series with a very small resistor, and the metal strip (antenna leads) of the quasi-optical array can be modeled as a fixed inductor.

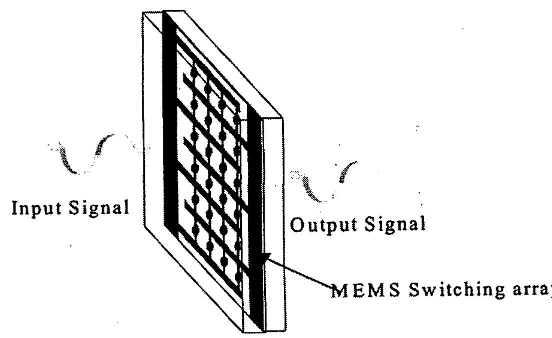

Fig. 1. MEMS based Quasi-optical switching array.

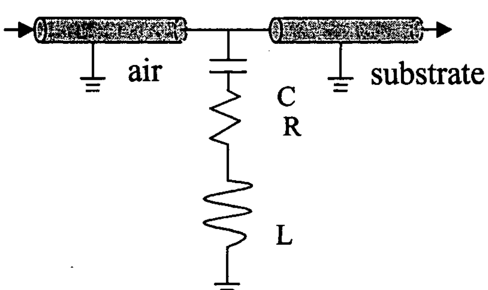

Fig. 2. Equivalent circuit of MEMS switching array.

The lumped impedance of the quasi-optical switching array can be written as:

$$Z = R + j\omega L + \frac{1}{j\omega C} = R + j\omega L\left(1 - \frac{1}{\omega^2 LC}\right) \quad (1)$$

where R is the series resistance of the MEMS device. The resonant frequency, ω_0, is given by

$$\omega = \frac{1}{\sqrt{LC}} \quad (2)$$

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An air bridge structure RF MEMS switch, as illustrated in Fig. 3, is employed in the array realization. The MEMS switches are devices in which the active element is a thin metallic movable membrane suspended across a distance (≈4 μm) above the substrate surface. A SiO_2 dielectric layer, approximately 0.1 μm thick, covers the fixed bottom metal surface.

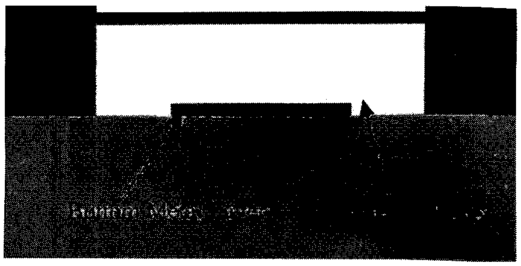

Fig. 3. Cross section of air bridge structure MEMS switch.

Shown in Fig. 4 is a photograph of one of the MEMS switches, fabricated in the UC Davis micro-fabrication lab using surface micro-machining techniques [6]. There are 20x20 MEMS single switches on the 630 μm thickness quartz substrate. The QO unit cell is 800 μm x 800 μm.

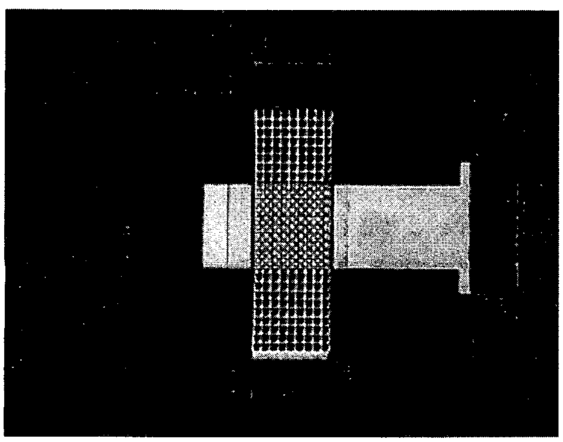

Fig. 4. Single air bridge structure MEMS switch.

A. Capacitance

Through the application of a DC electrostatic field, the MEMS membrane contacts the dielectric layer directly and is therefore capacitively coupled to the upper metal contact. The distance or space between the two metal surfaces of the MEMS switch is a nonlinear function of the DC bias applied to the switch. Electrically, the MEMS switch functions as a variable capacitance or varactor device. In the up of "OFF" state, the capacitance of the MEMS switch is

$$C_{up} = C_{dielectric} // C_{g0} \approx C_{g0} \qquad (3)$$

In the down or "ON" state, the switch capacitance is :

$$C_{down} = C_{dielectric} \qquad (4)$$

These MEMS single switches have been characterized using an HP 4280A C-V Plotter, with the results plotted in Fig. 5. the measured "OFF" state capacitance is ~58fF. The measured "ON" state capacitance of ≈2.6 pF compares well with a simple parallel-plate capacitance calculation of 3.2 pF, which assumes an active area of 9000 $(\mu m)^2$ arising from the overlap of the membrane and the bottom metal surface. The primary cause of this discrepancy arises from the surface roughness of the membrane and the SiO_2 dielectric layer.

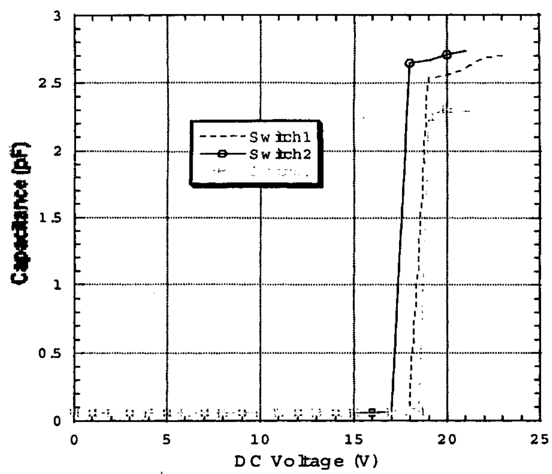

Fig. 5. C-V characteristics of MEMS switches.

B. Inductance

In the quasi-optical MEMS array, the metal strip parallel to the E-field of the microwave beam is treated as a dipole antenna, which couples the EM wave to the active devices on the quasi-optical grid array. In steady state, current flows along the strip, and magnetic energy is stored around the strip.

Two methods have been employed to estimate the quasi-optical inductance. The first is a calculation using a quasi-static model [4], where the strip inductance is approximately given by

$$L = \frac{\mu_0}{2\pi} \ln\left[\csc\left(\frac{\pi W}{2a}\right)\right] \qquad (5)$$

The second method employed was to conduct HFSS and ADS simulations of the quasi-optical inductor structures. Figure 6 shows a typical magnetic field distribution around the strip computed from an HP HFSS simulation. Parallel metal strips can be best modeled as inductors in the one-dimensional simulation model. The HP ADS software package has been utilized to derive accurate equivalent circuit models by finding the best fit to the S parameter output data provided by the HFSS simulation. A comparison between the HFSS/ADS simulation results and the quasi-static analytical solution is given in Fig. 7. The 350μm strip widths yield an approximate inductance of 75pH. The resonance frequency of the array, determined by this inductance and "OFF" state capacitance, is 76GHz.

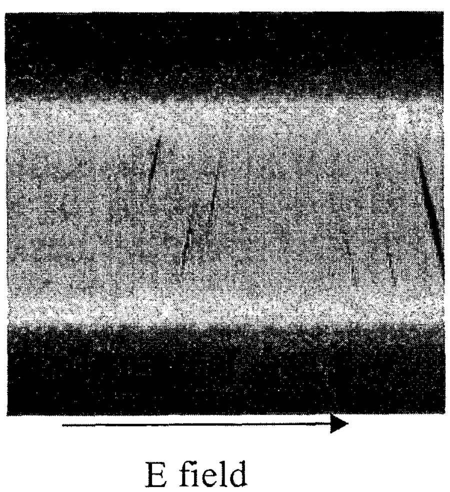

Fig. 6. The current distribution of the QO metal strip.

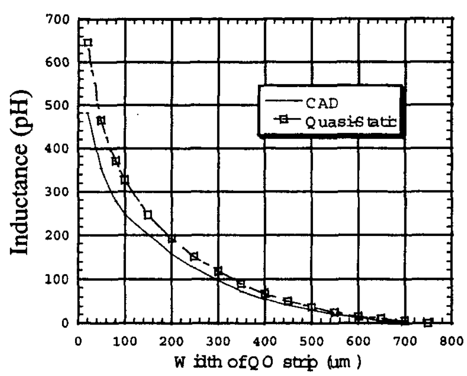

Fig. 7. Comparison between simulated and theoretical inductance values for the QO metal strip.

C. Resistance

The series resistance of the MEMS switches arises from the MEMS bridge and is significantly smaller than that of a corresponding semiconductor device. In the previously reported GaAs switching array [4], the series resistance of Schottky diode is ~15 Ohm and due to both metal and semiconductor losses. In contrast, for the E-band MEMS switching array, the single MEMS bridge resistance is approximately 0.10~0.12 Ohm and is predominantly conductor loss.

III. E-BAND QUASI-OPTICAL MEMS SWITCHING ARRAY

For a quasi-optical MEMS switching array, in the "OFF" state, the capacitance value is very small, the impedance of the shunt element is high and the circuit is open. In the "ON" state, the impedance of the inductance and capacitance cancel each other, and the entire system is a short circuit, and the incident microwave signal is completely reflected. Because the contrast ratio of MEMS switches between two state is extremely high, and the series resistance is low, MEMS switching array can provide a broadband and high isolation QO switching element.

A quasi-optical broadband switching array consists of hundreds to thousands of single MEMS bridge switches. Unlike GaAs varactor switches [4],[5], a MEMS switch capacitor is sensitive only to the DC bias amplitude, so that a single bias configuration can be employed. A schematic drawing of the bias lines is shown in Fig. 8, where the DC bias voltages emerge from both sides of the wafer, and interlaced bias lines are connected to the bias pads. This can also be observed in the photograph provided in Fig. 9, in which a portion of the MEMS switching array is displayed.

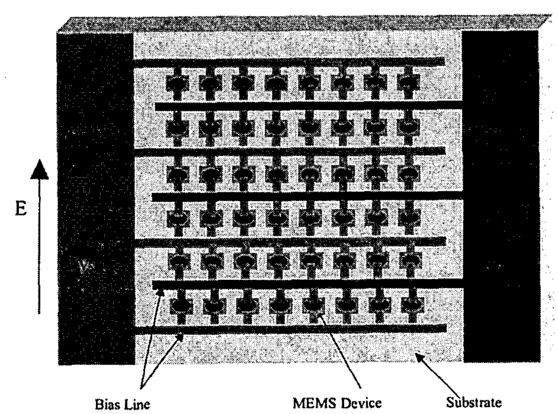

Fig. 8. Layout of Switching Array.

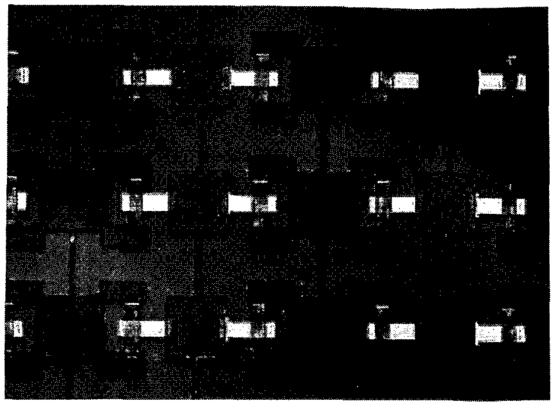

Fig. 9. Photograph of a portion of the E-band MEMS switching array.

The millimeter-wave performance of the E-band MEMS switching array was tested using the layout illustrated in Fig. 10, with a maximum ON/OFF contrast ratio of 15 dB observed at the center frequency of 76 GHz (see Fig. 11).

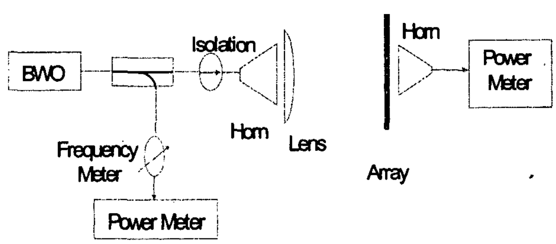

Fig. 10. Schematic layout of the E-band test setup.

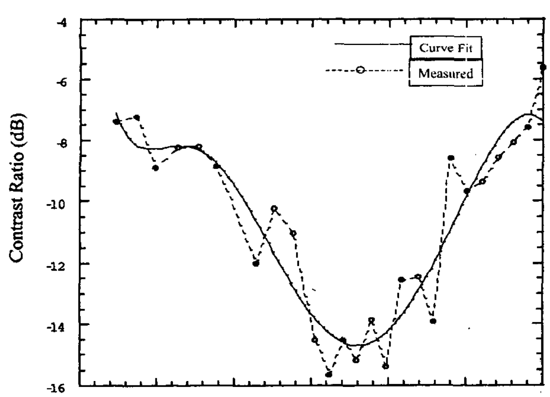

Fig. 11. The measured ON/OFF contrast ratio of the E-band MEMS switching array, plotted as a function of frequency overlaid with a ninth order polynomial curve fit.

IV. Conclusion

Novel RF MEMS structure based quasi-optical power switching arrays have been investigated. The results show that the RF MEMS switch grid arrays provide the possibility of a new class of quasi-optical systems.

Acknowledgement

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