A Reconfigurable Double-Stub Tuner Using MEMS Devices

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Abstract **This paper presents for the first time a planar reconfigurable double stub tuner, that utilizes electrostatically activated MEMS switches. The tuner consists of a "4bitx4bit" digital capacitor bank and can match loads with real parts ranging from 5 to 108 Ω and imaginary parts from -60 to 48 Ω at 20 GHz. Simulated and measured results are presented.**

I. INTRODUCTION

Microwave and mm-wave technology that offers high-performance, low cost, small size and wide tunability is essential for today's cost driven commercial and military industries. In order to meet the above requirements, the research community during the last ten years has been focusing on entire system-on-a-chip solutions, where different components (e.g. passive, active) are integrated on the same substrate. To enhance the performance of these planar microwave circuits and address associated problems, researchers have been using bulk micromachining techniques and Micro-Electro-Mechanical-System (MEMS) devices [1].

One of the first MEMS devices developed for microwave applications was the switch. An air-bridge type electrostatically activated switch that uses a very high capacitance variation and has very small loss, but a high actuation voltage, has been demonstrated [2-3]. Switches with serpentine and cantilever springs that exhibit low pull-in voltages, small loss and good isolation [4], as well as thermally actuated switches have also been demonstrated [5].

This paper presents a novel planar, reconfigurable double stub tuner that utilizes electrostatically activated MEMS switches. The goal is to achieve a planar tuner that can match a wide variety of loads for frequencies ranging from 10 to 20 GHz. Such a component is an essential part for reconfigurable, low-cost wireless and satellite communication networks and radars, tunable navigation and positioning systems, and seekers for smart weapons.

II. RECONFIGURABLE TUNER DESIGN

The reconfigurable double-stub tuner presented in this paper was designed according to the procedure outlined in [6]. This procedure was used to determine the susceptances of each stub and the lengths between them to match the desired range of loads, arbitrarily chosen for this paper to be 20 to 80 Ω for the real part and −150 to +150 Ω for the imaginary. The desired match was assumed to be 50 Ω. The first step in the design process was to determine the distance of the first stub to the load. For simplicity the latter was assumed to be zero. The second step was to choose the distance between the two stubs. This distance is important since it limits the range of loads that can be matched. A large distance will decrease the range of loads that can be matched, while a small distance may be impractical to fabricate. Given a stub spacing, d, the range of G_L (the real part of the load admittance) that can be matched is given by [6] as:

$$0 \le G_L \le \frac{Y_o}{\sin^2 \beta d} \qquad (1)$$

If d is chosen to be 0.1 λ, then $0 \le G_L \le 0.058$ or the real part of the load impedance ($R_L = 1/G_L$) must be greater than 17.3 Ω to be able to be matched to 50 ohms. In this case, since the real part of the load to be matched is 20 to 80 Ω, a distance of 0.1 λ is sufficient.

Once the distance between the stubs was chosen, the susceptances of each stub that would match the range of loads to 50 Ω were determined. The equations for the susceptance of the two stubs are [6]:

$$B_1 = -B_L \pm \frac{Y_o + \sqrt{(1+t^2)G_L Y_o - G_L^2 t^2}}{t} \qquad (2)$$

and

$$B_2 = \frac{\pm Y_o \sqrt{Y_o G_L (1+t^2) - G_L^2 t^2} + G_L Y_o}{G_L t} \quad (3)$$

where G_L and B_L are the real and imaginary parts of the load admittance, respectively. The equivalent capacitances can be calculated from

$$C = \frac{B}{2\pi f} \quad (4)$$

where f=20 GHz is the design frequency.

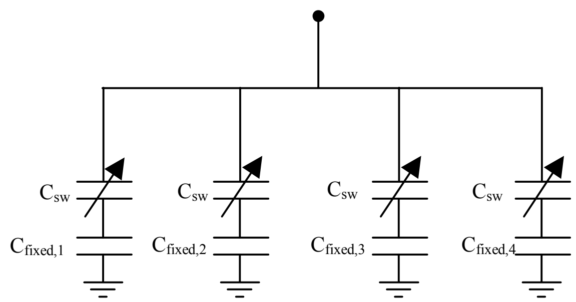


Fig. 1 Schematic of the "4-bit" reconfigurable stub.

To obtain a large range of capacitances, the circuit depicted in Fig. 1 was designed. The circuit consists of 4 sets of capacitors in parallel. Each set consists of the series combination of an RF membrane MEMS switch and a fixed 'stub' capacitor. The MEMS switch used is as described in [7]. In effect, the MEMS switch toggles the fixed capacitor 'on' or 'off'. When the MEMS switch is in the 'up' or 'off' position, it has a capacitance value of approximately 35 fF. When it is in the 'down' or 'on' position, it has a capacitance value of approximately 3 pF [2]. The equivalent capacitance of the series combination of the MEMS switch and the fixed capacitor is then:

$$C_{eq} = \frac{C_f * C_s}{C_f + C_s} \quad (5)$$

where C_f is the value of the fixed capacitor and C_s is the capacitance of the MEMS switch. Thus, when the switch is in the 'off' position, $C_s << C_f$ and $C_{eq} \approx C_s$. When the switch is in the 'on' position, $C_f << C_s$ and thus $C_{eq} \approx C_f$.

The desired range of capacitances is achieved by using several sets of these series combinations of switches and fixed capacitors in parallel, or, a 'digital' bank of capacitors. Each combination of switch and fixed capacitor represents one 'bit' of equivalent capacitance. The more 'bits' used, the larger the number of capacitance steps available, and thus the larger the range of loads that can be matched. For this paper, four bits were chosen for each 'stub' of the double-stub tuner. The fixed capacitor values were chosen in accordance with the results based on (4). Four capacitor values were chosen that cover the range of capacitances needed to match the desired range of loads. The capacitances calculated from (4) are the equivalent capacitances, C_{eq}. The fixed capacitances were then calculated using (5) and solving for C_f. This resulted in fixed capacitor values ranging from 45 fF to 1155 fF. The fixed capacitors were realized with open-circuited stubs. Agilent's *HP-ADS* circuit simulator was used to determine the transmission line length and width that would result in the correct capacitance.

The overall performance of the circuit was simulated with *HP-ADS*. Each switch was modeled as a capacitor with two possible values, 35 fF and 3 pF, representing the 'off' and 'on' states, respectively. Since each 'stub' consists of four 'bits', there are a total of 256 different configurations of the double-stub tuner. Each of these 256 configurations was simulated to see what load would be matched to 50 Ω. The results are shown in Fig. 2.

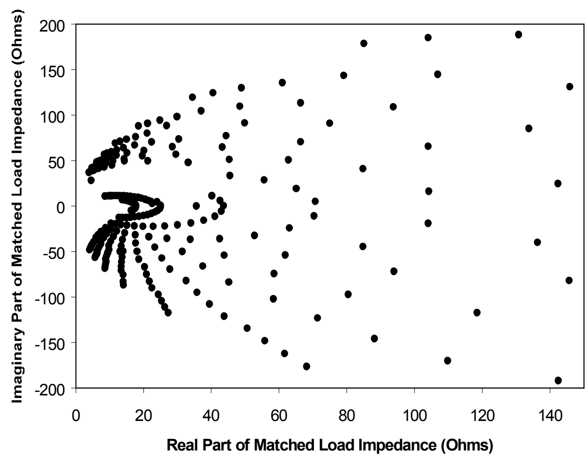


Fig. 2 Simulation results of possible load impedance values that can be matched to 50 ohms.

III. DESIGN LAYOUT

The final circuit is shown in Fig. 3. The series combinations of switches and fixed capacitors were fabricated on 500 µm silicon using the capacitive MEMS switch design reported in [7]. The remainder of the circuit was fabricated on 10 mil Alumina substrate. The silicon circuits were bonded to the Alumina circuit with ribbon bonds. The lines connecting the switch-capacitor sets were made 0.5 wavelengths long, or a multiple thereof, so that the capacitance value seen at the input of the switch-capacitor set would be the same at the point where the four sets 'add'. Likewise, the line connecting the four sets of switch-capacitors to the main transmission line was made a multiple of a half-wavelength. The distance between the two 'stubs' of the double-stub tuner was made 0.1 wavelengths long as previously discussed. Via-less CPW-to-microstrip transitions were used to facilitate on-wafer probe measurements.

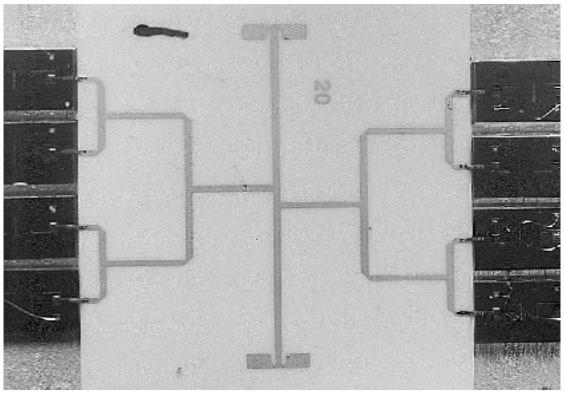


Fig. 3. Fabricated "4-bit x4-bit", double-stub reconfigurable tuner.

IV. MEASUREMENTS

Two sets of measurements were taken with an Anritsu-Wiltron vector network analyzer that was calibrated with the TRL technique. The first set included only the switch-stub circuits. There were seven such sets, each of progressively higher susceptance value. This was the part of the circuitry fabricated on the 500 μm silicon substrate. Fig. 4 shows a close-up picture of the stub-switch combination.

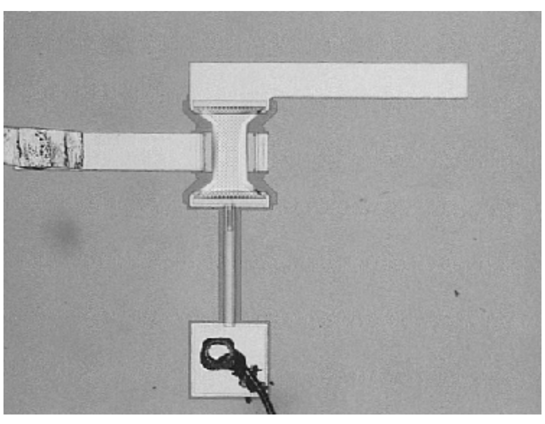
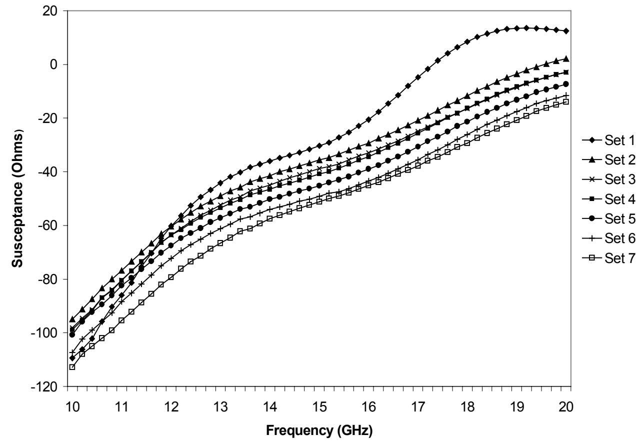
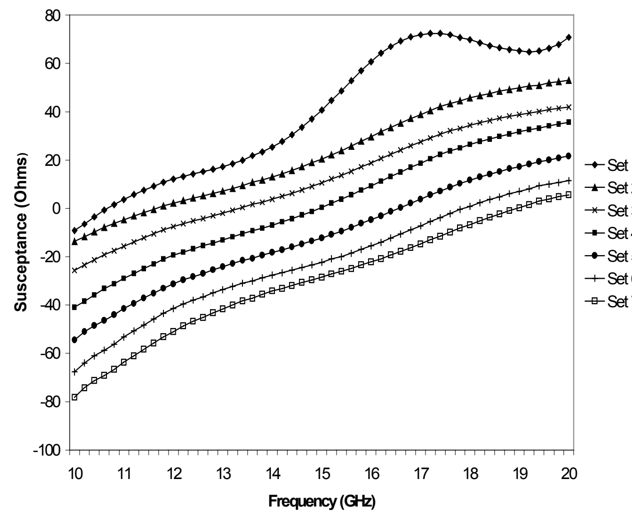


Fig. 4 Photo of a fabricated "MEMS switch-stub" set.

These seven circuits were measured in both of the two states, the 'off' state of the switch and the 'on' state. Measurements were taken from 10 to 20 GHz and for the 'on' state a DC voltage of 35-55 V was applied. The results are shown in Fig. 5a for the 'off' state and Fig. 5b for the 'on' state. These results demonstrate that the goal of progressive steps of susceptance was achieved. Note that because of the presence of the bonding wires there are positive values of the susceptance, especially for the "on" case above 15-16 GHz.



(a)



(b)

Fig. 5. Measured susceptance values for the seven "switch-stub" sets in the (a) 'off' state and (b) 'on' state.

Using the measurements described above, another *HP-ADS* simulation of the entire 20 GHz, 4-bit x 4-bit circuit was performed. The Alumina circuitry was modeled with *HP-ADS* microstrip elements. The measured data was used for the switch-stub sets. An ideal 50-Ω resistor to ground was placed on one port and the input impedance was measured looking into the opposite port. The results of this simulation are shown in Fig. 6. One noteworthy outcome of this simulation was that it showed how sensitive the circuit is to variation in line lengths and widths. Changing some line widths by only a few microns would change the

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resulting matched load value by tens of ohms. These variations are bound to be present in the hand-placed ribbon bonds connecting the silicon circuits to the Alumina circuit. Thus, while these HPADS simulations predict that the matched load value will change with changing switch- stub settings, they are not expected to predict the precise value of the matched load and a more detailed analysis is required.

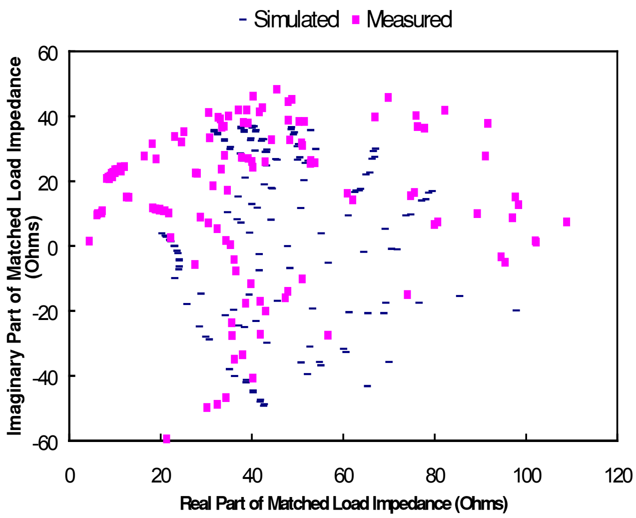

Fig. 6. Simulated results using measured data for the switch-stub sets and measured values of the complete circuit.

The second set of measurements taken was that of the whole circuit shown in Fig. 3, at 20 GHz. The results of these measurements are shown in Fig. 6. As can be seen, the double stub tuner can match loads with a real part ranging from 5 to 108 Ω and imaginary parts ranging from -60 to 48 Ω.

V. Conclusions

This paper has demonstrated a novel, planar microwave reconfigurable double stub tuner utilizing MEMS switches. Measured results have shown a matching load range from 5 to 108 Ω for the real part and -60 to 48 Ω for the imaginary part at 20 GHz. Measured values are hard to predict with simulations, due to the sensitivity the load impedances exhibit to bonding wire lengths. This tuner is a compact, low-cost, low-power solution for future reconfigurable microwave/mm-wave systems.

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