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W-Band RF MEMS Double and Triple-Stub Impedance Tuners

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***Abstract* — Reconfigurable integrated impedance tuners have been developed for W-Band on-wafer noise parameter and load-pull measurement applications. The impedance tuners are based on double and triple-stub topologies and employ 11 switched MEMS capacitors producing 2048 (2^{11}) different impedances. Measured $|\Gamma_{MAX}|$ for the double-stub tuner is 0.92 and 0.82 at 75 and 100 GHz from 110 measurements out of 2048 possible impedances, and 0.92 and 0.83 for the triple-stub tuner. To our knowledge, this represents the first W-band integrated impedance tuner to date.**

***Index Terms* — RF MEMS, impedance tuner, matching network, noise parameter, load-pull, on-wafer.**

I. INTRODUCTION

Impedance tuners based on waveguides are used at frequencies above 50 GHz in noise parameter and load-pull measurements of active devices. In practice, these are large in size and expensive. The maximum achievable reflection coefficient, $|\Gamma_{MAX}|$, which can be generated using waveguide tuners is very high (about 0.97) but this is referred to the waveguide flange. For on-wafer measurements, the loss of the connecting waveguide sections and W-band-to-CPW probe can limit $|\Gamma_{MAX}|$ to about 0.7-0.8 at 50-110 GHz [1,2]. If a tuner can be integrated inside an RF probe, the loss between the tuner and the DUT can be minimized. Also, measurement automation can be increased with electrically controllable tuners.

In this work, we present the first integrated impedance tuners operating at W-Band (75-110 GHz). The impedance tuners are based on double- and triple-stub topologies and switched MEMS capacitors. The MEMS switches are used since they provide excellent performance compared to mm-wave transistors or varactor diodes [3].

II. IMPEDANCE TUNER DESIGN

The impedance and electrical length of the stubs and connecting t-line are controlled at discrete positions by digital-type RF MEMS capacitors (Fig. 1) as done previously in [4-6]. This method results in more wideband tuning and better impedance coverage compared to standard reconfigurable impedance tuners [7,8]. In the switched capacitor-based tuner, the number of the switched capacitors (N) and their capacitance values (C_U, C_D) have the most important effect on the tuning range and bandwidth. In general, a larger N yields more wideband operation and better impedance coverage but results in an increased component size and loss. Other parameters that need to be optimized are the spacing of the switched capacitors and the lengths of the stubs. There are many variables and several acceptable solutions. The tuners were optimized to have 11 switched capacitors producing 2048 (2^{11}) different impedances, and Agilent ADS.[1] was used to for the optimization procedure. The fabricated impedance tuners are shown in Fig. 2, and the process is similar to [4-6] having the same materials and layer thicknesses.

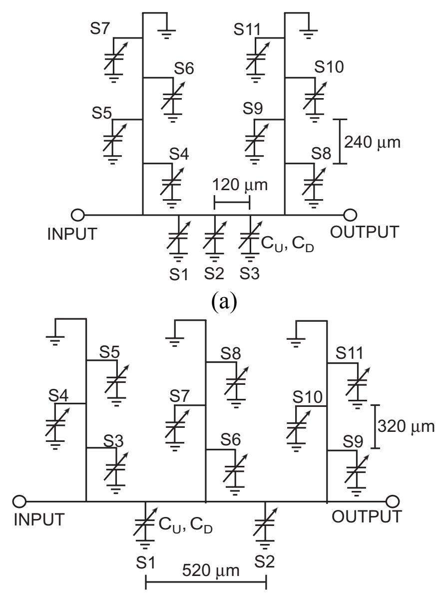

Fig. 1. a) Schematic a of the reconfigurable W-Band double-stub and b) triple-stub impedance tuners.

The switched capacitor is a series combination of a MEMS switch and metal-air-metal (MAM) capacitors (Fig. 3). The size of the MEMS switch is 200 µm x 40 µm x 0.9 µm and the area of the fixed MAM capacitor is 280 μm^2, respectively. The MAM capacitors are realized as a part of the anchor area of the MEMS switch. These are electroplated to 3 µm, and being very stiff, they are not actuated with the bias voltage. The CPW dimensions are 50/50/50 µm (G/W/G) and under the MEMS switches 45/90/45 µm in both designs. The center

[1] Advanced Design System 2002, Agilent Technologies, Santa Clara, CA, USA, 2002.

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conductor was widened under the MEMS switches for a lower pull-down voltage. Measured pull-down voltage was 28 V, and a 36 V bipolar actuation was used for getting a firm down-state contact and avoiding charging in the dielectric layer.

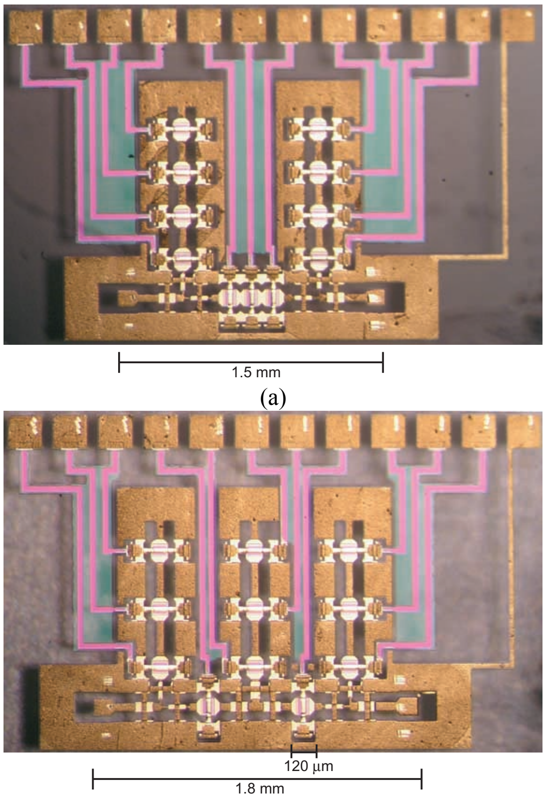


Fig. 2. a) Photograph of the fabricated W-Band double-stub and b) triple-stub impedance tuners.

TABLE I

FITTED VALUES FOR THE SWITCHED MEMS CAPACITOR.

C_{MEMS} Up-State (fF)	24
C_{MEMS} Down-State (fF)	410
C_{MAM} (fF)	52
R_{BIAS} (kΩ)	> 3
L_{MEMS} (pH)	6
R_{MEMS}+ R_{MAM} (Ω)	0.7

The switched MEMS capacitor total up and down-state capacitances are C_U = 23 fF and C_D = 46 fF (X_U=-j78 Ω and X_D=-j39 Ω at 90 GHz), which results in total capacitance ratio of 2.0. Previous lower frequency designs employed a capacitance ratio of 3.5-4.5 for the entire coverage of the Smith Chart [4-6]. The quality factor of the switched MEMS capacitor is calculated using $Q = (2\pi f C(R_{MEMS} + R_{MAM}))^{-1}$ and results in Q_U = 111 and Q_D = 54 at 90 GHz. This means that the switched capacitors do not contribute a lot to the loss of the tuner circuit. Measured and simulated S-parameters for the tuners are shown in Fig. 4. The T-junctions were simulated with Sonnet[2], and the S-parameters for the tuners with Agilent ADS using the equivalent circuits of the switched capacitors (Figs. 3 and 4, and Table I).

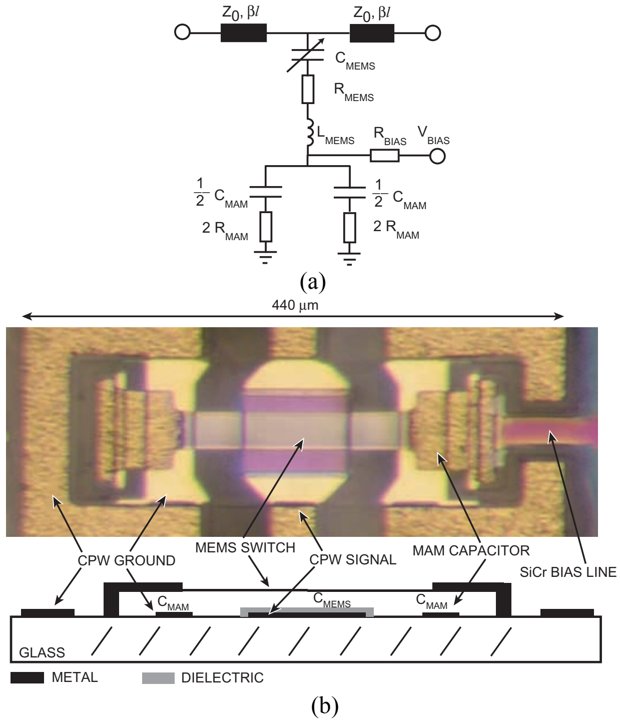


Fig. 3. a) Circuit model and b) photograph with schematic side-view of the W-Band switched capacitors.

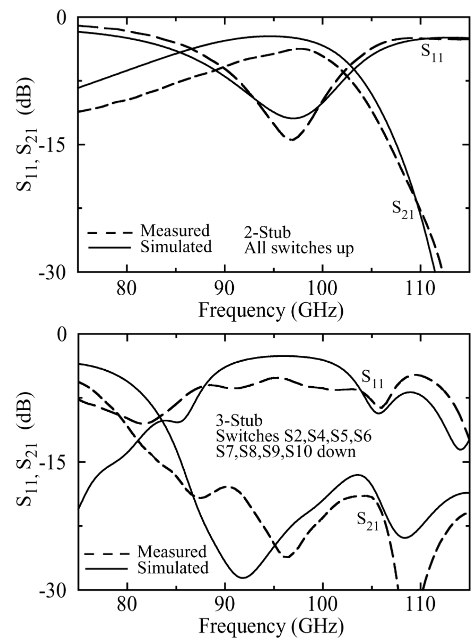
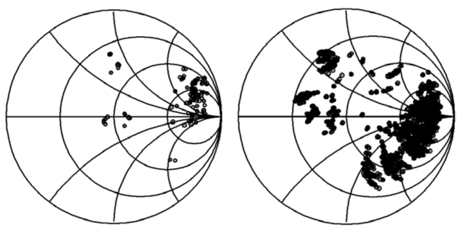


Fig. 4. Measured and simulated S-parameters for the double-stub tuner when all of the switches are in the up-state position and for the triple-stub tuner when switches S2, S4, S5, S6, S7, S8, S9, S10 are in the down-state position.

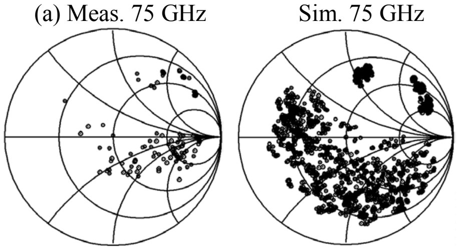
[2] Sonnet, ver. 8.52, Sonner Software Inc., Syracuse, NY, 1986-2001.

III. IMPEDANCE COVERAGE

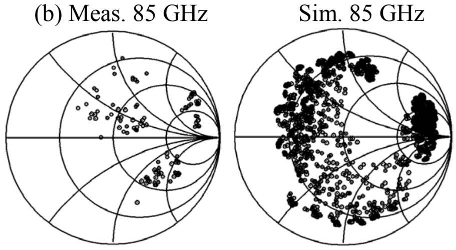
The tuners can produce 2048 (2^{11}) different impedances. Measured (110 points for the 2-stub tuner, and 90 for the 3-stub) and simulated (all 2048 points) impedance coverage for the tuners are shown in Figs. 5 and 6. Measured $|\Gamma_{MAX}|$ was 0.93, 0.87 and 0.87 at 75, 90, and 105 GHz for the double-stub tuner from 110 measurements and 0.92, 0.87, and 0.83 for the triple-stub tuner from 90 measurements. The tuners have reasonably good impedance coverage with high reflection coefficients at W-Band frequencies, and demonstrate that stub tuners can be employed at 110 GHz and above.



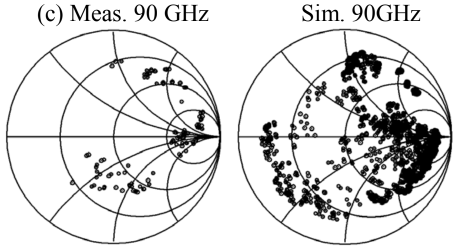
(a) Meas. 75 GHz   Sim. 75 GHz



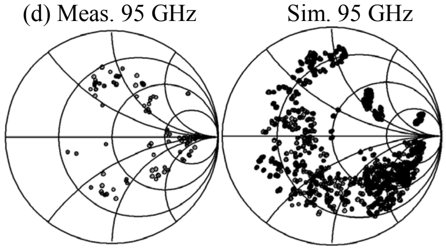
(b) Meas. 85 GHz   Sim. 85 GHz



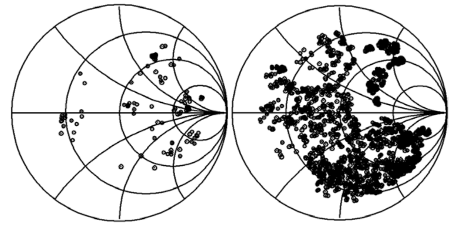
(c) Meas. 90 GHz   Sim. 90GHz



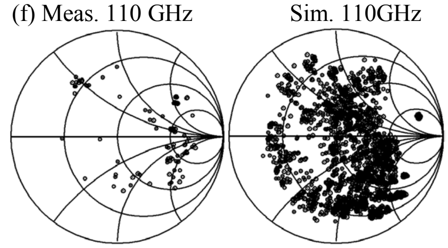
(d) Meas. 95 GHz   Sim. 95 GHz



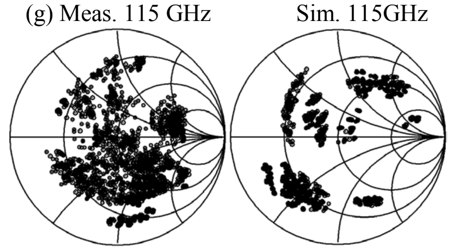
(e) Meas. 105 GHz   Sim. 105 GHz



(f) Meas. 110 GHz   Sim. 110GHz

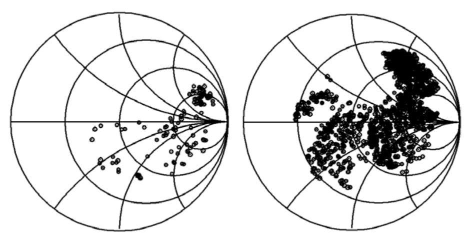


(g) Meas. 115 GHz   Sim. 115GHz

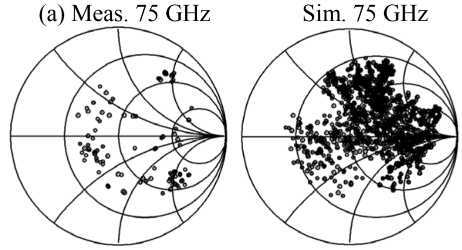


(h) Sim. 120 GHz   Sim. 130GHz

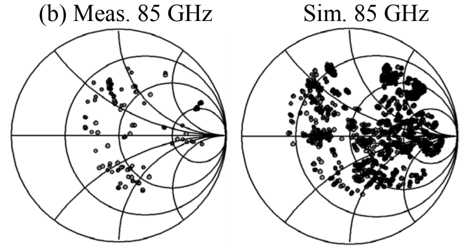
Fig. 5. (a)-(h) Measured (110 points) and simulated (2048 points) S_{11} impedance coverage of the reconfigurable W-Band double-stub impedance tuner. The tuner was terminated with 50 Ω at Port 2.



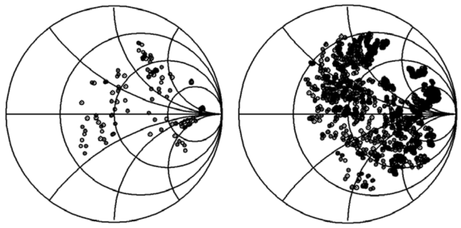
(a) Meas. 75 GHz   Sim. 75 GHz



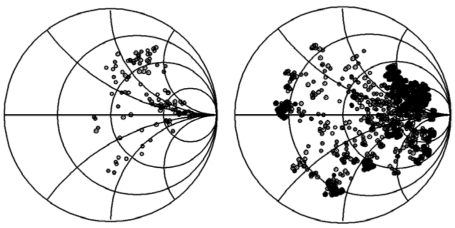
(b) Meas. 85 GHz   Sim. 85 GHz



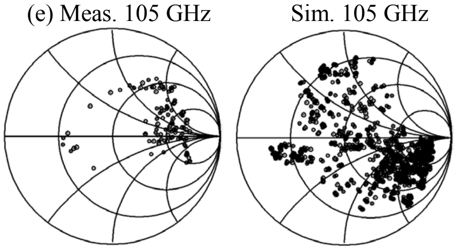
(c) Meas. 90 GHz   Sim. 90 GHz



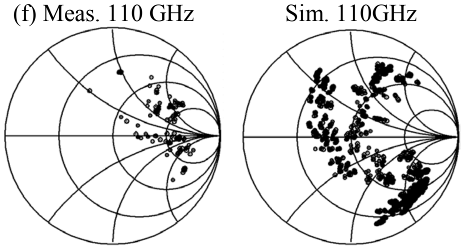
(d) Meas. 95 GHz Sim. 95 GHz



(e) Meas. 105 GHz Sim. 105 GHz

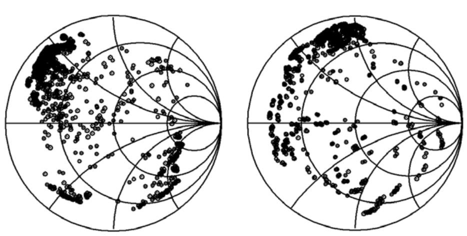


(f) Meas. 110 GHz Sim. 110GHz



(g) Meas. 115 GHz Sim. 115GHz

Fig. 6. (a)-(g) Measured (90 points) and simulated (2048 points) S_{11} impedance coverage of the reconfigurable W-Band triple-stub impedance tuner. The tuner was terminated with 50 Ω at Port 2.



Sim.85 GHz Sim. 110GHz

Fig. 7. Simulated impedance coverage for the re-designed triple-stub impedance tuner with C_U = 10 fF and C_D = 80 fF.

The impedance coverage of the tuners can be further improved by decreasing the up-state capacitance (C_U 10-15 fF), increasing the down-state capacitance of the switched capacitor (C_D 60-80 fF), and re-designing the T-junctions. The measured up-state capacitance was higher than intended because the MEMS switches were curved down a bit. The T-junctions can be improved by making them more compact and lowering the transmission line impedance. With these improvements, we feel that the double and triple stub tuners can cover the entire Smith chart over the W-band frequency range (see Fig. 7).

IV. CONCLUSIONS

Reconfigurable W-Band double- and triple-stub impedance tuners were presented. The tuners were developed for on-wafer noise parameter and load-pull measurement purposes. The electrical tuning of impedance is realized with 11 switched MEMS capacitors, and 2048 (2^{11}) different impedances can be generated with the tuners. The tuners are small enough to be integrated inside W-band RF probes.

ACKNOWLEDGEMENT

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