

PUBLICATION P8

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In: 2004 IEEE MTT-S International Microwave Symposium  
Digest, Forth Worth, TX, USA, 2004. Pp. 717–721.  
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# A 20-50 GHz Reconfigurable Matching Network for Power Amplifier Applications

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**Abstract** — A reconfigurable matching network has been developed and it is based on loaded line techniques. It consists of 8 switched MEMS capacitors producing 256 ( $2^8$ ) different impedances and is only 1x2.5 mm in size on a glass substrate. The network is ideally suited to match power amplifiers with 10-20  $\Omega$  output impedance to 50-60  $\Omega$  systems at 20-50 GHz. The estimated loss of the network is only 1-1.5 dB at 40 GHz while matching a 10-20  $\Omega$  load to a 50  $\Omega$  load. The reconfigurable network can also be used as an impedance tuner in noise parameter and load-pull measurements of active devices at 30-65 GHz.

**Index Terms** — RF MEMS, impedance tuner, noise parameters, load-pull, matching network, phased array.

## I. INTRODUCTION

The output impedance of power amplifiers (PA) with 1-2 W output power and a 5 V power supply is typically between 10 and 20  $\Omega$ , and are mismatched in 50  $\Omega$  systems. Optimum power transfer from the PA to an antenna can be ensured with a wideband low-loss impedance matching network (Fig. 1). Both the output impedance of the PA ( $Z_{PA}$ ) and the input impedance of the antenna ( $Z_A$ ) can vary and the matching network should be flexible to maintain optimum power transfer in the both cases.  $Z_{PA}$  can change as a function of frequency and with different bias conditions.

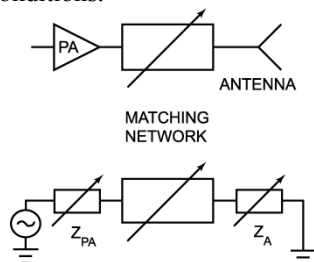


Fig. 1. A reconfigurable matching network used between a power amplifier and a radiating antenna.

In addition to matching applications, reconfigurable matching networks can be used as impedance tuners in noise parameter and load-pull measurements of active devices. Commercial impedance tuners are usually either coaxial or waveguide structures requiring large space [1].

Reconfigurable impedance matching networks/ tuners are typically based on the double-stub [2,3] or triple-stub topologies [4] and can be made using MMIC or RF MEMS technologies. A problem related to MMIC varactor or transistor based matching networks is limited tuning range because of the resistance of active devices. Also, MMIC matching networks have electrical noise and intermodulation products which affects the system performance.

In this work, a novel reconfigurable RF MEMS matching network, based on a transmission line (t-line) loaded with 8 identical switched MEMS capacitors is presented. The network is capable of very wideband PA matching with low loss at 20-50 GHz.

## II. DESIGN

The phase velocity and impedance of a t-line can be changed by loading it capacitively. This idea has been used successfully in distributed transmission-line (DMTL) MEMS phase-shifters [5]. The loaded line technique can be applied to reconfigurable matching networks by loading a t-line with  $N$  digitally controlled switched MEMS capacitors each having capacitances  $C_U$  (up-state position) and  $C_D$  (down-state position). The line impedance is chosen to be approximately 50  $\Omega$  when the MEMS capacitors are in the up-state position. When a MEMS capacitor is actuated to the down-state position, the loading on the t-line increases thus resulting in a localized low impedance and a high effective dielectric constant (around the region of the MEMS capacitor). Since the loading is increasingly capacitive with more MEMS switches being actuated, the network will transform a 50-60  $\Omega$  load into a low input impedance (or vice versa due to reciprocity), and the higher the capacitive loading, the lower the input impedance. A 4 to 8-element design results in 16 to 256 ( $2^N$ ) different impedance points on the Smith Chart, and the distributed nature of the design ensures wideband frequency coverage. Also, at high frequencies and due to the varying electrical length of the loaded t-line, when the switched capacitors are actuated, the

impedance coverage covers the entire Smith chart and not only the low impedance region.

The equivalent circuit and picture of a switched MEMS capacitor are shown in Figs. 2-3. The switched capacitor is a combination of a capacitive MEMS switch attached fixed metal-air-metal (MAM) capacitors. Typically, the capacitance ratio of a capacitive MEMS switch is 30:1, and this can be lowered using fixed capacitors in series with a capacitive MEMS switch. The fabricated switched capacitor is based on a coplanar waveguide (CPW) with dimensions 100/100/100  $\mu\text{m}$  (G/W/G) on a 500  $\mu\text{m}$  glass substrate ( $\epsilon_r = 4.6$ ). Dimensions of the MEMS switch are 250  $\mu\text{m}$  x 80  $\mu\text{m}$  x 0.8  $\mu\text{m}$ . Fabrication of the switched MEMS capacitor is based on standard surface MEMS techniques and is identical as used in [4]. Fitted (based on measurements) values for the equivalent circuit of switched MEMS capacitor and t-line properties are presented in Table 1. The measured capacitance ratio of the RF MEMS switch is 8:1 due to its low height and the thick silicon-nitride layer. The total up-state and down-state capacitances of the switched capacitor ( $C_{\text{MEMS}}$  in series with  $C_{\text{MAM}}$ ) are  $C_U = 45.1$  fF and  $C_D = 129$  fF, respectively, resulting in a capacitance ratio of 2.9:1. The quality factor of the switched MEMS capacitor is calculated using  $Q = (2\pi f C (R_{\text{MEMS}} + R_{\text{MAM}}))^{-1}$  and at 30 GHz results in up and down states values of  $Q_U = 168$  ( $C_U = 45.1$  fF,  $X = -j118 \Omega$ ) and  $Q_D = 59$  ( $C_D = 129$  fF,  $X = -j41.3 \Omega$ ).

There are many different parameters that can be optimized in the loaded-line network. The highest frequency of operation is limited by the Bragg frequency (see below) of the loaded-line, and the lowest impedance, which can be matched to 50  $\Omega$  is dependent on the loading capacitance. A closed-form design technique has not been found since the location, electrical length, and loaded-line impedance change with the actuation of the MEMS switched capacitors, and therefore, Agilent ADS [6] is used extensively for choosing  $C_U$ ,  $C_D$ ,  $s$ , and the number of capacitors. The design was optimized to have 8 switched capacitors and is presented in Fig. 4.

In this design, the loaded line characteristics are  $Z_U = 47 \Omega$  and  $\epsilon_{\text{reff}_U} = 9.1$ , and  $Z_D = 31 \Omega$  and  $\epsilon_{\text{reff}_D} = 21$ , when the MEMS switches are in the up-state and down-state positions, respectively. The impedance in the up-state was designed to be 50  $\Omega$  but it is lower since the MEMS bridges are curved down resulting in a larger loading capacitance. The Bragg frequency is calculated using [5]:

$$f_B = \frac{cZ_L}{\pi s Z_0 \sqrt{\epsilon_{\text{reff}}}} \quad (1)$$

and is 105 GHz and 69.5 GHz when all the bridges are in the up-state and down-state positions, respectively. In general, it is desirable to have a relatively high Bragg frequency to obtain good operation over a wide frequency range.

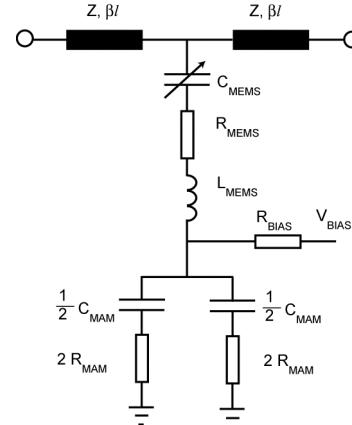


Fig. 2. Equivalent circuit a switched MEMS capacitor.

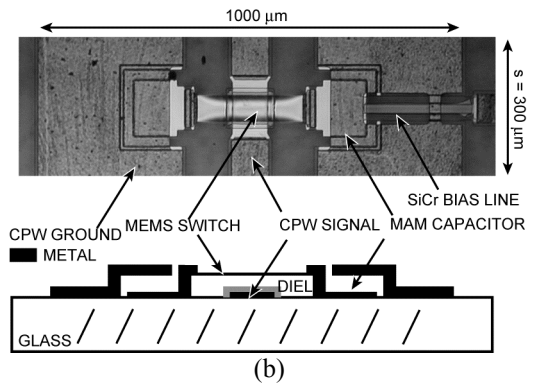


Fig. 3. Picture and cross-section of a switched MEMS capacitor.

TABLE 1  
MEASURED T-LINE PROPERTIES FROM THE TRL CALIBRATION, FITTED VALUES FOR THE SWITCHED MEMS CAPACITOR, AND LOADED LINE CHARACTERISTICS.

$\epsilon_r$	4.6
$Z_0 (\Omega)$	86.2
$\epsilon_{\text{reff}}$	2.72
$\alpha$ (dB/cm), 20/30/40 GHz	0.52/0.78/1.1
$C_{\text{MEMS}}$ Up State- $C_{\text{UP}}$ (fF)	61
$C_{\text{MEMS}}$ Down State- $C_{\text{DOWN}}$ (fF)	500
$R_{\text{BIAS}}$ (k $\Omega$ )	> 3
$L_{\text{MEMS}}$ (pH)	9.5
$R_{\text{MEMS}} + R_{\text{MAM}}$ ( $\Omega$ )	0.7
$C_{\text{MAM}}$ (fF)	167
$s$ ( $\mu\text{m}$ )	300
$Z_U (\Omega), \epsilon_{\text{reff}_U}$	47, 9.1
$Z_D (\Omega), \epsilon_{\text{reff}_D}$	31, 21

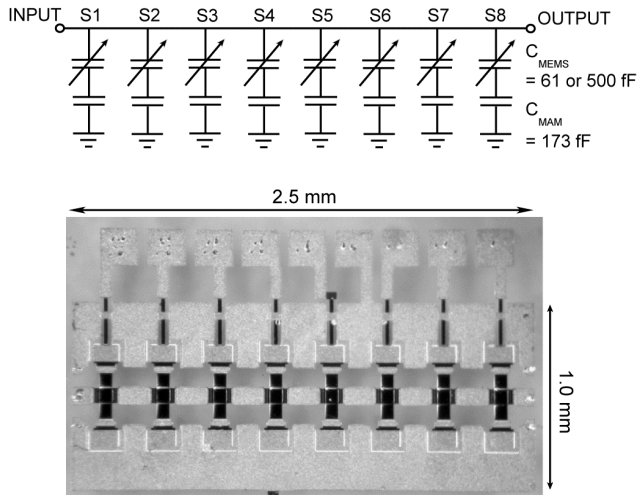


Fig. 4. Schematics and picture of the reconfigurable matching network with 8 switched MEMS capacitors (S1-S8).

The measured and simulated S-parameters for the 8-element matching network are shown in Fig. 5. Agilent ADS is used for fitting the values of the switched MEMS capacitor (Fig. 2 and Table 1).

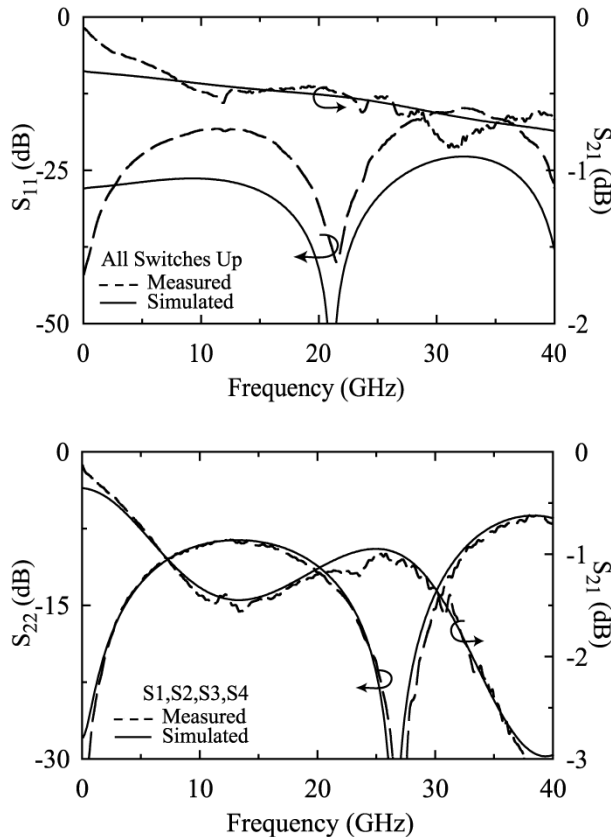
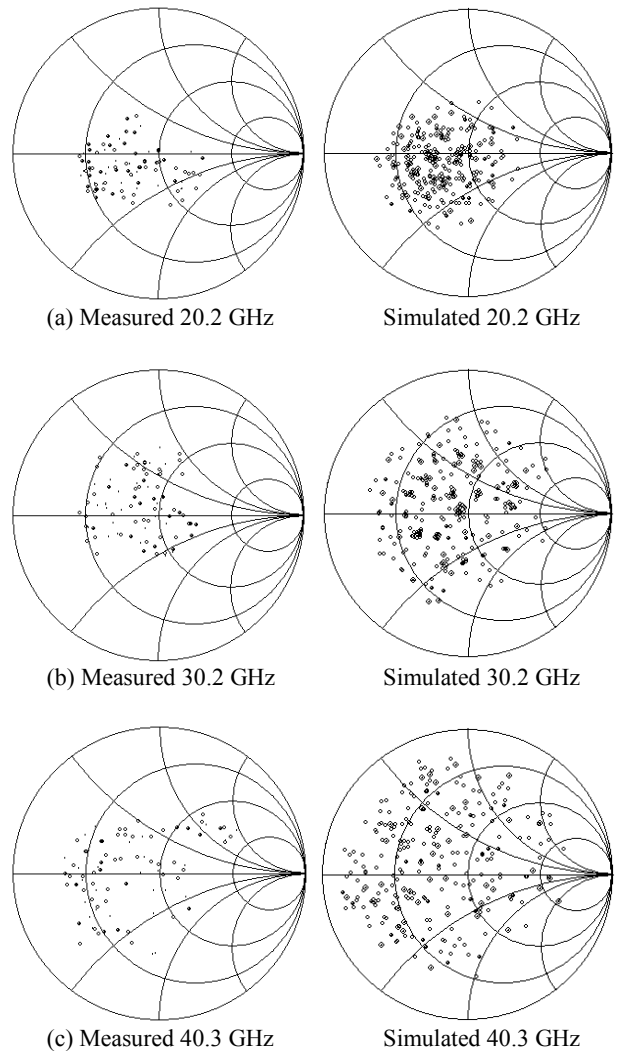


Fig. 5. Measured and simulated S-parameters for the reconfigurable matching network with two different switch combinations. The combinations are written in the figures.

### III. IMPEDANCE COVERAGE AND MATCHING

#### A. Impedance coverage

The measured (90 points) and simulated (256 points) impedance coverage of the reconfigurable distributed matching network is presented in Fig. 6 at 16-60 GHz. The measurements were done up to 40.3 GHz with 90 different switch settings out of 256 possible combinations, and only simulated results are presented above 40 GHz. Other data at 24, 28, 34, and 38 GHz are not shown, but they all agree well with simulations. Notice that the network is ideally suited for matching low impedance loads at all frequencies up to 60 GHz.



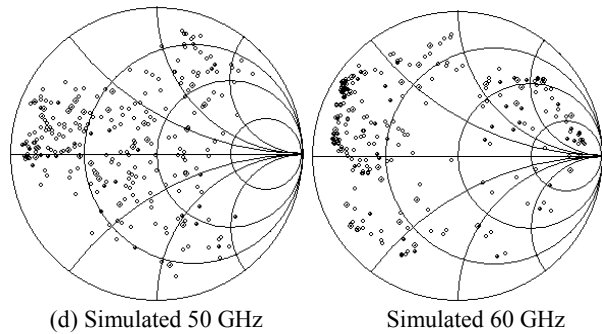


Fig. 6. (a)-(d) Measured (90 points) and simulated (256 points) impedance coverage of the reconfigurable distributed impedance matching network.

### B. Case study: Matching 10 and 20 $\Omega$ loads to 50 $\Omega$

The accurate circuit model can also be used to analyze different matching conditions. 10 and 20  $\Omega$  loads are matched to 50  $\Omega$  at different frequencies separately and the input reflection coefficient (seen from the 50  $\Omega$  source) and loss of the network are shown in Fig. 7. The loss in dB is defined as  $10\log(1-\text{loss})$  and a loss of 0.2 results in a 1 dB loss. For a 20  $\Omega$  load, the loss is 0.7-1.25 dB from 10 to 40 GHz, which is indeed very low. For a 10  $\Omega$  load, the loss is 1.2 dB up to 40 GHz and only 1.4-1.6 dB at 50-55 GHz. This is also very low for a 5:1 impedance match. The reason is that the network is electrically and physically very short and the loaded capacitors have a high Q. Also, no short circuits are induced in the MEMS components, and a capacitance change of 3:1 with  $X = -j120$  to  $X = -j40$  is present on the network. To our knowledge, this work represents state-of-the-art performance at 20-60 GHz.

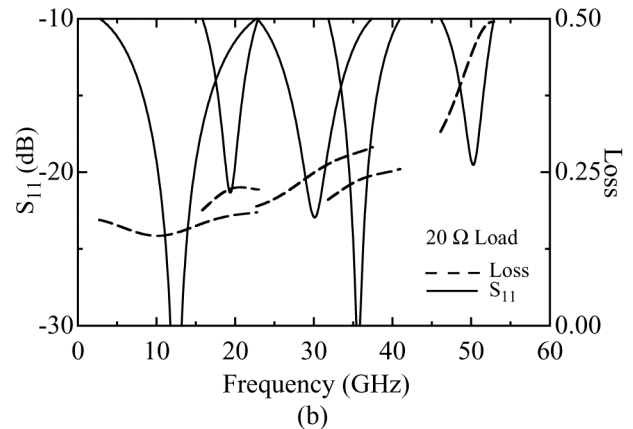
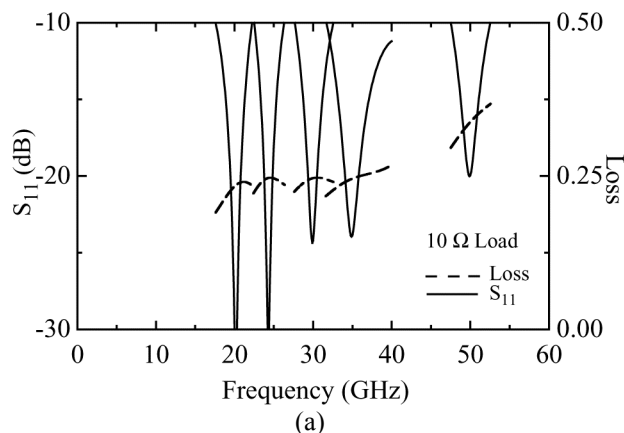


Fig. 7. Simulated input reflection coefficient and loss of the distributed matching network with a 10  $\Omega$  (a) or 20  $\Omega$  (b) load matched to 50  $\Omega$  separately at different frequencies with different switch combinations.

## CONCLUSIONS

This paper presented a novel reconfigurable matching network. It is based on loaded-line techniques and it was realized with 8 switched MEMS capacitors producing 256 ( $2^8$ ) different impedances. The loaded-line reconfigurable networks are much more efficient than double or triple stub networks (less space and elements) and are ideally suited for wideband low-impedance power amplifier matching.

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