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<b>1. REPORT DATE (DD-MM-YYYY)</b> 23-10-2003		<b>2. REPORT TYPE</b> Final Technical Report		<b>3. DATES COVERED (From - To)</b> 04/15/02 - 08/31/03	
<b>4. TITLE AND SUBTITLE</b> RF-MEMS Based Tunable Matching Network				<b>5a. CONTRACT NUMBER</b> N/A	
				<b>5b. GRANT NUMBER</b> N00014-02-1-0561	
				<b>5c. PROGRAM ELEMENT NUMBER</b> N/A	
<b>6. AUTHOR(S)</b> Scott N. Barker				<b>5d. PROJECT NUMBER</b> N/A	
				<b>5e. TASK NUMBER</b> N/A	
				<b>5f. WORK UNIT NUMBER</b> N/A	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Rector and Visitors University of Virginia Office of Sponsored Programs 1001 N Emmet St. Charlottesville, VA 22901				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> GGL0424	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Office of Naval Research Ballston Centre Tower One 800 North Quincy St. Arlington, VA 22217-5660				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ONR	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> N/A	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b> Approved for public release, distribution unlimited					
20031106 121					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> This project investigates a tunable matching network using the double-slug tunable based on a distributed RF-MEMS transmission line (DMTL). The proposed design has a maximum voltage standing wave ratio (VSWR) of 16:1 with the number of match points ranging from 529 at 5 GHz to 1597 at 20 GHz. Simulation results are performed to demonstrate the capabilities of this design.					
<b>15. SUBJECT TERMS</b> tunable matching network, FJ-MEMS transmission line					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			N. S. Barker
Unclassified	Unclassified	Unclassified	UL	6	<b>19b. TELEPHONE NUMBER (include area code)</b> 434-924-6783

RF-MEMS Based Tunable Matching Network  
 ONR Grant Number N00014-02-1-0561 (UVA: GG10424)

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**Abstract**

This project investigates a tunable matching network using the double-slug tuner based on a distributed RF-MEMS transmission line (DMTL). The proposed design has a maximum voltage standing wave ratio (VSWR) of 16:1 with the number of match points ranging from 529 at 5 GHz to 1597 at 20 GHz. Simulation results are performed to demonstrate the capabilities of this design.

## 1 Introduction

Real-time adaptable RF front-ends are becoming an attractive method for dealing with the numerous communication architectures and frequency bands in use today. An important component in realizing such adaptable system is a tunable matching network that is able to maintain low loss and high linearity. Such a device could be used for tuning microwave amplifiers to operate in various modes or in different frequency bands. RF-MEMS have the capability of implementing these tunable matching networks with minimal degradation to the overall amplifier performance.

Recently, several researchers have applied RF-MEMS to the development of tunable matching networks. Papapolymerou et al.[1] have developed a double stub tunable matching network that can real impedances between  $1.5 \Omega$  and  $109 \Omega$  and imaginary impedances between  $-j107 \Omega$  and  $j48 \Omega$  at 20 GHz; and real loads between  $3 \Omega$  and  $94 \Omega$  and imaginary impedances between  $-260 \Omega$  and  $91 \Omega$  at 10 GHz to a  $50 \Omega$  system impedance. Jung et al.[2] developed an analog tunable matching network. A resonant cell is used with the RF-MEMS switch providing a shunt capacitance to ground, increasing the impedance tuning range. This design has been demonstrated to match impedances in the second and third quadrants of the Smith Chart while operating from 23.5 to 25 GHz. This paper presents the implementation of a double-slug tuner [3] using a distributed MEMS transmission line (DMTL) [4].

## 2 Double-slug tuner structure

The basic idea of an analog double-slug tuner is shown in Fig. 1. The two  $90^\circ$  sections determine the center frequency

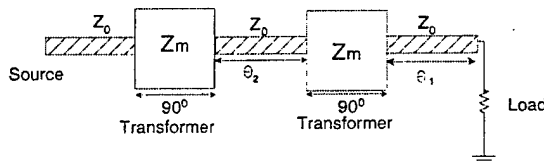


Figure 1: Schematic of a double-slug tuner.

and the lengths  $\theta_1$  and  $\theta_2$  define the impedance point being matched. The tuner operates by sliding the two slugs along the transmission line to match the load impedance to the source. A maximum VSWR is achieved when the two slugs are separated by  $90^\circ$  ( $\theta_2=90^\circ$ ). This maximum VSWR is determined by the impedance of the  $90^\circ$  sections and is given by:

$$VSWR_{max} = \left( \frac{Z_0}{Z_m} \right)^4 \quad (1)$$

For example, with  $Z_m=25 \Omega$  and  $Z_0=50 \Omega$ , the maximum VSWR is 16:1. By decreasing the value of  $Z_m$ , the VSWR value will be increased; however as this impedance is decreased, the insertion loss of the tuner will increase.

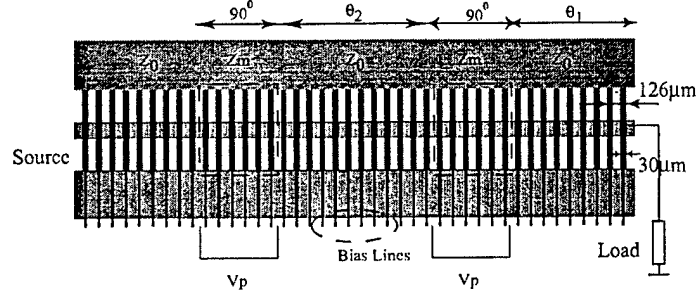


Figure 2: The topology of a double-slug tuner implemented with a DMTL.

On the basis of this double-slug tuner, a distributed MEMS transmission line is used to implement a tunable matching network as shown in Fig. 2. The DMTL is designed on a high-impedance CPW line and each RF-MEMS switch has an individual bias line. With the switch in the up-state, the CPW line is capacitively loaded down to  $50 \Omega$ . When the switch is actuated, the capacitive load increases such that the transmission line impedance is lowered to be the desired value (eg.  $25 \Omega$ ). This matching network can be adjusted for different load impedances by varying the spacing between the slugs and for different center frequencies by varying the physical length of the  $90^\circ$  slugs.

### 3 Design and Simulation Results

The DMTL double-slug tuner is designed on a quartz substrate ( $\epsilon_r=3.78$ ) using a finite ground CPW line [5] with  $G/W/G=100\mu\text{m}/100\mu\text{m}/100\mu\text{m}$ , where  $G$  and  $W$  are respectively the gap and width of the center conductor of the CPW line. The unloaded CPW line has an impedance of  $96 \Omega$  ( $Z_{ul}$ ).

#### 3.1 Design equations

For the  $90^\circ$  sections, the phase change is defined as [6]:

$$\beta = n_{90} * \omega \sqrt{sL_t(sC_t + C_b)} \quad (2)$$

where  $n_{90}$  is the number of switches for the  $90^\circ$  section,  $\omega$  is the frequency, and  $C_b$  is the switch down-state capacitance.  $L_t$  and  $C_t$  are the unloaded transmission line inductance and capacitance per unit length, and  $s$  is the switch spacing. By choosing the desired slug impedance,  $Z_m$ , the required down-state bridge capacitance is found to be:

$$C_b = \frac{sL_t}{Z_m^2} - sC_t \quad (3)$$

where

$$C_t = \frac{\sqrt{\epsilon_{eff}}}{Z_{ul}} \quad (4)$$

The spacing is determined by choosing the desired number of switches needed for the  $90^\circ$  slug ( $n_{90}$ ) at the operating frequency:

$$s = \frac{1}{n_{90}} \left[ \frac{1}{4} \left( \frac{\lambda_0}{\sqrt{\epsilon_{eff}}} \frac{Z_m}{Z_{ul}} \right) \right], \quad (5)$$

where  $\left[ \frac{1}{4} \left( \frac{\lambda_0}{\sqrt{\epsilon_{eff}}} \frac{Z_m}{Z_{ul}} \right) \right]$  represents the quarter wavelength of the  $90^\circ$  section. The total number of the RF-MEMS beams is calculated as:

$$N = n_{90} \left( 3 \frac{Z_0}{Z_m} + 2 \right) \quad (6)$$

where  $Z_0$  is the impedance for the up-state of the switch and  $Z_m$  is the down-state impedance. Therefore the total length of the DMTL will be:

$$l = s \cdot N \quad (7)$$

The capacitance ratio is calculated as:

$$C_r = \left(\frac{Z_0}{Z_m}\right)^2 \frac{(Z_{ul})^2 - (Z_m)^2}{(Z_{ul})^2 - (Z_0)^2} \quad (8)$$

and for  $Z_{ul}=96 \Omega$ ,  $Z_0=50 \Omega$ , and  $Z_m=25 \Omega$ , the capacitance ratio is found to be 5.1.

### 3.2 RF-MEMS Contactless Switch

Capacitive RF-MEMS switches, as used in this research, typically have a capacitance ratio of at least 20 and as high as 100 when the beam is pulled down onto the dielectric [7]. Although such a high capacitance ratio is necessary for RF switches, it becomes a problem when the RF-MEMS devices are used as loading capacitors in a distributed MEMS transmission line where the capacitance ratio must be limited to 2-5. Additionally, the intimate contact that occurs between the RF-MEMS beam and the dielectric leads to problems with switch reliability [8]. One method that has been used by several researchers to control the capacitance ratio is to place a metal-air-metal capacitor in series with the RF-MEMS capacitor [9][10]. Although this allows very accurate up- and down-state impedances to be realized, it does not address the reliability problems due to contact with the dielectric.

In an attempt to address both the capacitance ratio and switch reliability, we have developed a contactless RF-MEMS switch as shown in Fig. 3.

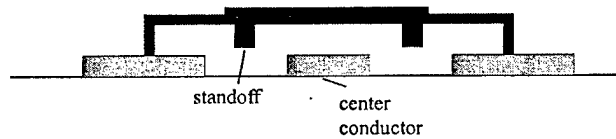


Figure 3: The contactless RF-MEMS switch.

By fabricating standoffs on the bottom side of the RF-MEMS beam its range of motion is limited. Therefore, by properly designing the standoff height and location, the capacitance ratio can be controlled and the beam is prevented from contacting the center conductor. As seen in Fig. 3 and Fig. 4, the center part of the beam is much thicker than

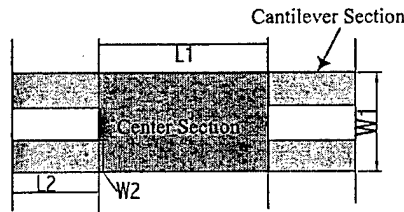


Figure 4: The top view of one bridge section.

the cantilever section. This design is used to prevent the center part of the beam from bending when the switch is actuated. The spring constant for this switch design is modelled as four cantilevers with guided ends and is 5.2 N/m for the design parameters given in Table 1 where  $t_1$ ,  $t_2$  are the thickness of the beam for the center part and the

Table 1: design parameters.

$n_{90}$	8	$W_1$	30 $\mu\text{m}$
$C_{b0}$	28 fF	$L_1$	128 $\mu\text{m}$
$C_b$	93 fF	$t_1$	3.5 $\mu\text{m}$
$s$	126 $\mu\text{m}$	$W_2$	10 $\mu\text{m}$
$C_r$	5.1	$L_2$	80 $\mu\text{m}$
$h_{up}$	2 $\mu\text{m}$	$t_2$	0.6 $\mu\text{m}$
$h_{down}$	0.4 $\mu\text{m}$		

cantilever part (see Fig. 4).

### 3.3 CPW ground plane design

The RF-MEMS switches of the proposed tunable matching network are connected with individual bias lines. In order to control the movement of each bridge independently, the bias lines should be isolated. MIM (metal insulator metal) capacitors are implemented in the CPW ground plane to separate the DC bias lines while maintaining the RF ground plane.

### 3.4 Simulation Results

To demonstrate the matching performance and frequency tunability, a calculation is carried out with 64 switches spaced  $158 \mu\text{m}$  apart (total length is 1 cm).  $Z_m$  is arbitrarily decided to be  $25 \Omega$ , and 8 switches are chosen for the  $90^\circ$  section at 10 GHz. Using *tl* [11] to simulate the DMTL for every possible position of the two 'slugs', the match points are determined with transmission line loss of 0.6 dB/cm and switch loss of  $0.1 \Omega$  included. For 10 GHz operation, there are 1177 possible matched points, shown in Fig. 6(a) and the Smith Chart is well covered with match points. To increase the center frequency of the tuner to 20 GHz, the number of switches in the  $90^\circ$  section is reduced to 4, which increases the possible match points to 1597 as shown in Fig. 6(b). When the center frequency is decreased below 10 GHz, the resolution in  $\theta_1$  and  $\theta_2$  increases, but the possible number of match points is dramatically decreased due to the decreased available number of bridges for  $\theta_1$  and  $\theta_2$  (seen in Fig. 6(c)). However, if we increase the length of the matching network without changing the switch spacing, we can effectively increase the operating bandwidth of the matching network.

In order to demonstrate the operation of the tuner over frequency, an impedance of  $10+j50 \Omega$  is matched at different frequencies and the frequency response is calculated in [12]. Seen from Fig. 5, as frequency changes, the bandwidth is larger, but the fractional bandwidths are relatively constant.

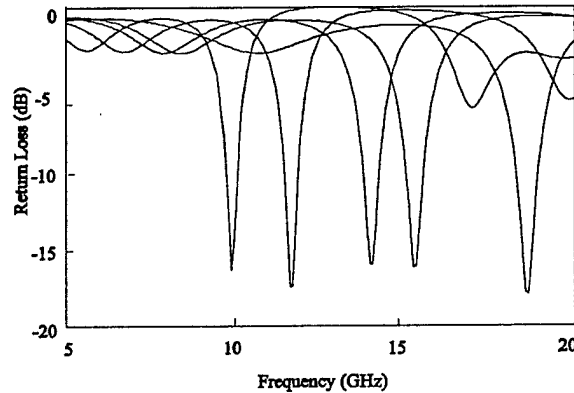


Figure 5: The frequency response of the DMTL based double-slug tuner for a load impedance of  $10+j50 \Omega$  matched at various frequencies.

## 4 Fabrication Procedures

The DMTL RF-MEMS tuner is fabricated on a  $500 \mu\text{m}$  thick quartz wafer. First the SiCr bias lines are sputtered and defined using BOE wet etch. The SiCr thickness is  $1300 \text{ \AA}$  and results in a line resistivity of  $1000 \Omega/\text{sq}$ . The center conductor and the ground planes are then defined by a lift-off process of evaporated Ti/Au/Ti= $200/8000/200 \text{ \AA}$ . Then  $\text{Si}_3\text{N}_4$  is then deposited by reactive sputtering [13] and defined with Reactive Ion Etching (RIE), which will form the insulator layer for the MIM capacitors of the ground plane. The sacrificial layer is PMMA [14] and the height of the bridges is  $2 \mu\text{m}$ . The membrane layer is then deposited by sputtering a seed layer followed by plating the center part of the beams, the ground plane and part of the center conductor. Finally the bridge is defined and the sacrificial layer is removed by acetone. The bridges are released using a critical point dryer system. A photomicrograph is shown in Fig. 7.

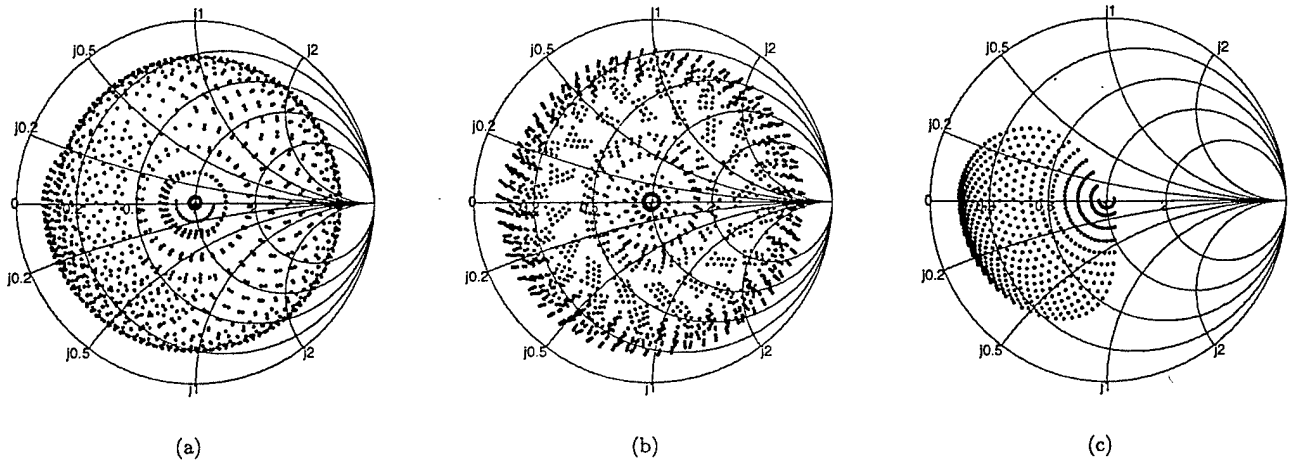


Figure 6: Simulation of DMTL double-slug tuner at (a)10GHz:8 switches for the 90° and 1177 matched points (b)20GHz:4 switches for the 90° section and 1597 matched points (c)5GHz:16 switches for 90° section and 529 matched points.

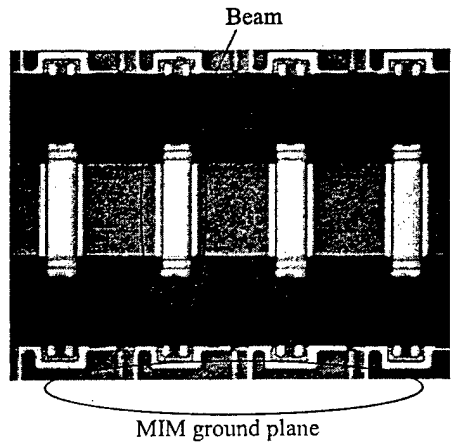


Figure 7: The photomicrograph of the fabricated device.

### 5 Conclusion and Discussion

In this project, an RF-MEMS based double-slug tuner is investigated. Simulations have been performed showing a very good tuning operation with good coverage of the Smith Chart. The proposed design has a maximum voltage standing wave ratio (VSWR) of 16:1 with the number of match points ranging from 529 at 5 GHz to 1597 at 20 GHz.

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