A High Performance MEMS Miniature Tunable Bandpass Filter

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***Abstract*—A miniature tunable 3-pole filter is fabricated using coplanar waveguide (CPW) transmission-lines on glass substrate ($\epsilon_r = 4.6$, $\tan\delta = 0.006$) and an array of RF-MEMS varactors. The filter is tuned using a bias voltage of 0-80 Volts. The filter is ~3.6 mm long and gives a near ideal frequency response. A tuning range of 14% from 18.6 to 21.4 GHz was achieved, with a constant fractional bandwidth of 7.4±0.1% and a mid-band insertion loss of 3.85-4.15 dB.**

***Index Terms*—Microelectromechanical devices, Miniature Filters, Tunable Filters, MEMS Filters, MEMS varactors.**

I. Introduction

Low-loss bandpass filters are the basic components of transceivers, either as band-select or image-reject units. An ideal solution in highly integrated systems is using a miniature filter that occupies a small wafer area and can be tuned for different receive bands. This paper investigates the application of RF-MEMS varactors as the integrated tuning elements of a miniature bandpass filters at K-band. MEMS varactors are high-Q elements (> 300 at 21 GHz) and when used for loading the resonators of a CPW filter, they result in a low additional loss.

A number of researchers have successfully used MEMS capacitors to implement low-loss tunable filters [1][2][3][4]. The MEMS varactors, however, have a small capacitance ratio and in simple configurations they fail to provide a wide tuning range [3][4]. In the present work, we use 6 MEMS bridges to periodically load portions of an inductively-coupled CPW filter [5], in order to increase the tunability. The MEMS varactors are tuned by applying a DC bias voltage of 0 to 80 Volts, resulting in a voltage controlled loading and a tunable pass-band.

II. Slow-Wave MEMS resonators

MEMS capacitive bridges may be used to periodically load transmission lines and form a slow-wave structure with a high effective dielectric constant and a low characteristic impedance. Fig. 1a presents a MEMS slow-wave section consisting of 6 bridges in the middle of a short-ended half-wave CPW resonator. The circuit model is presented in Fig. 1b. Z_1 and $\epsilon_{r-eff(1)}$ are the characteristic impedance and effective dielectric constant of the unloaded CPW line. If n is the number of bridges ($n = 6$ in this case), C is the bridge capacitance, and p is the effective period of the loading

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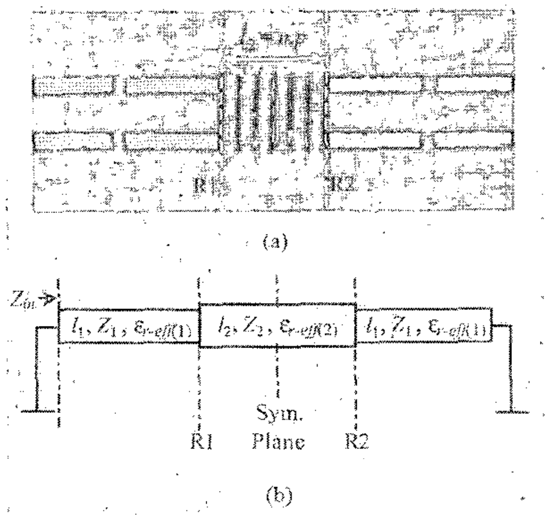

Fig. 1. MEMS slow-wave resonator; (a) short-ended half-wave resonator with $n = 6$ bridges, (b) circuit model.

structure, then Z_2 and $\epsilon_{r-eff(2)}$ of the loaded section are given by [6]:

$$\begin{aligned} &Z_2 = Z_1/\sqrt{K}, \\ &\epsilon_{r-eff(2)} = \epsilon_{r-eff(1)}K; \\ &K = 1 + \frac{cZ_1C}{p\sqrt{\epsilon_{r-eff(1)}}}, \quad c = 3\times10^8 \text{ m/sec.} \end{aligned} \tag{1}$$

In a practical design K can be quite large (~10-50).

Partial loading of the CPW resonator around the voltage maximum proves to be very effective in reducing the resonance length. There are two different effects involved in miniaturization; 1)the slow phase velocity over the loaded region, and 2)the step impedance configuration.

A MEMS slow-wave tunable resonator was designed based on a 1,400 μm long short-ended CPW transmission line, with the cross sectional dimensions 80/160/80 μm (G/W/G). These dimensions are chosen to minimize the conductor losses [7]. The resonator was fabricated using 3 μm thick electroplated gold on a 500 μm-thick glass wafer with $\epsilon_r = 4.6$ and $\tan\delta = 0.006$. The measured CPW line parameters are $Z_1 = 76\ \Omega$, $\epsilon_{r-eff(1)} = 2.723$, and the attenuation constant is $\alpha_1 = 0.7$ dB/cm at 21 GHz. The MEMS varactors are fabricated using gold membranes at an average height of

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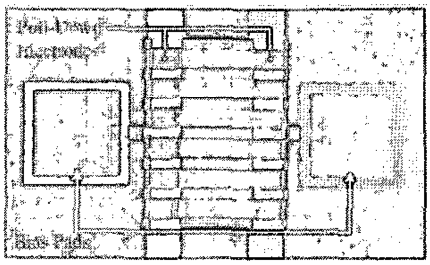
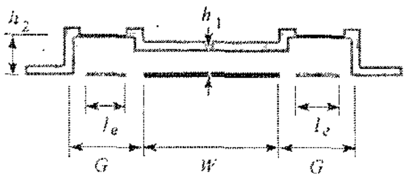
0.9 μm above the center conductor of the CPW line. Fig. 2a shows the 6 MEMS varactors in the loaded section of the CPW resonator. The pull-down electrodes are 60 μm long and are located in the CPW gaps near the bridge anchors. To increase the capacitance ratio of the varactors, a step profile is used [8], which is higher at the pull-down areas and lower in the middle section (Fig. 2b). To reduce the ohmic losses, the bridge is electroplated with 2 μm gold except above the pull-down electrodes. This ensures a flexible membrane with a reasonable spring constant.


(a)



(b)

Fig. 2. Tunable load section with 6 varactors; (a) photograph, (b) bridge profile.

The resonator described above is tuned by using a bias voltage of 0-80 V (Fig. 3). Table I provides the measured and fitted data for different values of the bias voltage. The measured unloaded Q's and the normalized resonance lengths (wrt. the wavelength of the unloaded CPW line at the resonance frequency) are also given in this table. The slow-wave resonators are more than 3-4 times shorter than a standard resonator ($l = 0.5\lambda_g$) and show considerable miniaturization. This situation generally entails a smaller quality factor. However, the MEMS capacitors used in this case are high-Q elements with an estimated Q of 350-500 at 21 GHz (for the bridge equivalent series resistance of 0.25±0.05 Ω) and do not cause a significant degradation in the resonator Q. The MEMS capacitor value has been extracted from the resonator model of Fig. 1b and Eq. (1), and shows a capacitance ratio of 2.84:1. This is the highest reported capacitance change by an analog MEMS varactor to date.

III. MINIATURE TUNABLE FILTER

A bandpass filter may be designed by coupling of the slow-wave MEMS resonators through inductive impedance inverters. An inductive impedance inverter is the T combination of a shunt inductor and two series negative transmission-line

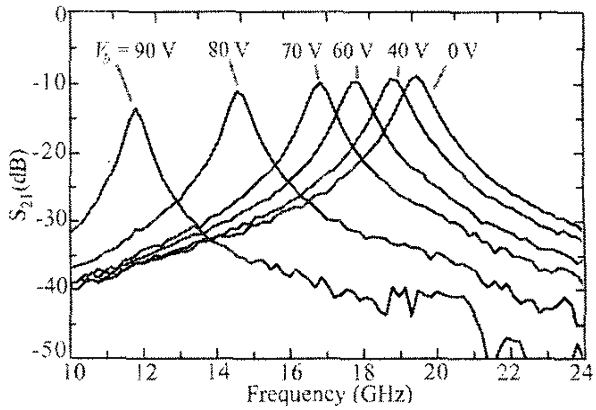


Fig. 3. The measured $|S_{21}|$ of the tunable resonator for different values of the bias voltage.

Bias Voltage (V)	0	60	80	90
Resonance Frequency (GHz)	19.52	17.90	14.64	11.83
Normalized Length (to λ_g)	0.150	0.138	0.113	0.091
Resonator Q	40	35	34	30
Bridge Capacitance (fF)*	88	106	160	250
Loading Factor K	25.3	30.3	45	70

* Extracted value using model.

TABLE I
MEASURED PARAMETERS OF THE MEMS SLOW-WAVE RESONATOR FOR DIFFERENT BIAS VOLTAGES.

lengths (Fig 4a). In the CPW design, the shunt inductors are realized using narrow inductive lines between the center conductor and the ground plane [5]. For larger values of inductance, the lines are extended inside the ground conductors (see Fig. 4b), forming short-circuited high-impedance CPW stubs. To avoid anomalies in the asymmetric inductive stubs at the input and output, the ground path is closed using air-bridges that are formed in the same process along with the MEMS capacitors.

The complete circuit model of the miniature tunable filter is shown in Fig. 4a. This model has been used to design a 3-pole Chebychev filter with 8% equi-ripple bandwidth centered at 21 GHz and 0.05 dB pass-band ripple. The filter is based on the slow-wave MEMS resonators with 6 bridges as described in the previous section except that the bridges are made at the height of 1.2 μm to reduce self biasing and other nonlinear effects. Based on a bridge capacitance of $C = 70$ fF and an effective loading period of $p = 50$ μm, the designed model parameters are given in Table II. A photograph of the fabricated filter is seen in Fig. 4b.

The filter is tuned by applying a bias voltage of 0 to 80 volts (the bridges collapse at higher voltages). Fig. 5 shows the measured and simulated S-parameters of the miniature tunable filter for V_b = 0, 50, 70 and 80 Volts. The exact value of the bridge height and capacitance vs. the bias voltage cannot be calculated using simple formulas due to the

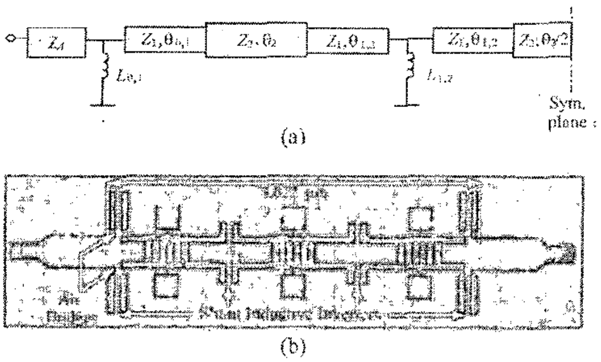


Fig. 4. The 3-pole miniature tunable filter: (a) the circuit model(only one half of the circuit is shown), (b) photograph.

$Z_A(\Omega)$	50	$\theta_{0,1}$ (deg.)	10.9
$Z_1(\Omega)$	76	$\theta_{1,2}$ (deg.)	18.9
$Z_2(\Omega)$	17.1	θ_2 (deg.)	55.5
$L_{0,1}$ (pH)	140		
$L_{1,2}$ (pH)	39		

TABLE II

MODEL PARAMETERS FOR THE 21 GHZ FILTER 8% SLOW-WAVE FILTER.

complex mechanical structure of the stepped-profiled bridge. The simulated S-parameters are based on the circuit in Fig. 4b with model parameters given in Table II, electrical lengths at 21 GHz replaced by the physical length, and $C = 69$ and 93 fF for $V_b = 0$ and 80 Volts, respectively. The measured pass-band center frequency shifts from 21.44 GHz at 0 V to 18.60 GHz at 80 V, while the fractional bandwidth remains constant at 7.5$\pm$0.1%. The tuning range of this filter is $\pm$7% around the mid-range frequency of 20.0 GHz. The mid-band insertion loss varies from 3.85 dB in the upper band to 4.15 dB in the lower band.

The measured performance data is summarized in Table III along with the extracted values of the bridge capacitance for the different bias voltages. An average resonator Q of 40 can be estimated using the formulas in [9], predominantly limited by the losses in the CPW line. Simulation shows that up to 1 dB improvement in the insertion loss can be obtained by using a quartz substrate ($\epsilon = 3.8$, $\tan\delta = 0.0001$).

Bias Voltage (V)	0	50	70	80
Center Frequency (GHz)	21.44	20.74	19.72	18.60
Bandwidth 1-dB (%)	7.37	7.52	7.35	7.58
Insertion Loss (dB)	3.85	3.90	3.94	4.15
Bridge Capacitance (fF)*	69	74	83	93

* Fitted values based on measurements

TABLE III

MEASURED PARAMETERS OF THE MINIATURE TUNABLE FILTER FOR DIFFERENT VALUES OF BIAS VOLTAGE.

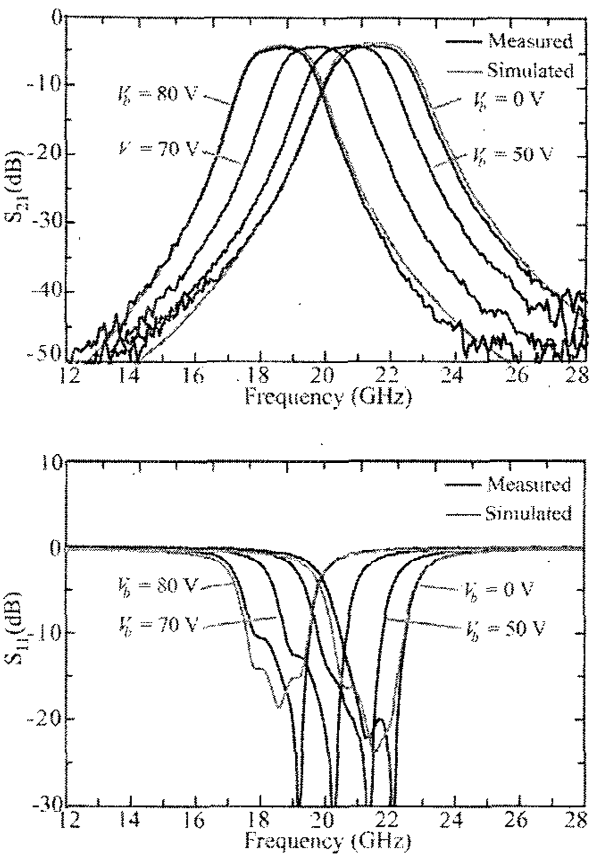


Fig. 5. Measured and simulated S-parameters of the miniature tunable filter for $V_b = 0$ and 80 Volts.

IV. CONCLUSION

MEMS capacitors and varactors have been used to develop a miniature tunable filter at K-band frequencies (18-22 GHz). The miniature tunable filter is obtained by inductive coupling of CPW MEMS slow-wave resonators. The pass-band center frequency tunes from 18.60-21.44 GHz with the combined pass-band covering 17.90-22.23 GHz. The fractional bandwidth is nearly 7.5% over the whole tuning range. Mid-band insertion loss was measured at 3.85-4.15 dB. With high-Q MEMS bridges, the mid-band insertion loss of the miniature and tunable filters are dominated by the ohmic and dielectric losses in the CPW structure, resulting in a performance comparable to the standard bandpass filters on CPW line.

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