MEMS Tunable Planar Inductors Using DC-Contact Switches

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***Abstract* — This paper presents a tunable MEMS inductor that is designed to operate from 5-30GHz on a 500μm thick quartz substrate. Series cantilever beams that are DC-contact type switches are used to achieve a tuning ratio of 1.7. Experimental results for a 600μm long inductor show tuning from 0.56nH to 0.34nH at 25GHz. The devices are intended for use as tuning elements at high microwave or mm-waver frequencies in circuits such as true time delay phase shifters.**

I. INTRODUCTION

Inductors are integral components in RF front end architectures that include filters, matching networks and tunable circuits such as phase shifters. The most common inductor topologies include planar spirals, air-core, and embedded solenoid designs [2]. In comparison to capacitors, however, relatively few tunable inductor configurations have been published, and among those presented many are hybrid approaches that employ (MEMS) switches to activate different static inductive sections. Furthermore, less attention has been paid to designs that enable control in the sub-nH range as is potentially desirable for matching purposes in applications that use distributed loading of small capacitances, e.g. in loaded-line phase shifters [3].

In this work, a distributed tunable inductor is designed to operate from 5-30GHz using DC-contact MEMS switches on a 500μm thick quartz substrate. A high inductance value is realized using a small length of high impedance line, while a low inductance is realized by reconfiguring the same circuit to yield a low impedance line using DC-contact switches. The first experimental results for the inductor show an inductance ratio of 1.7 with L_{high} of 0.56nH at 25GHz. The design and fabrication of the MEMS inductor is presented in Section II, followed by a comparison between measurement results and full-wave electromagnetic (EM) simulation in Section III. The conclusions are presented in Section IV.

II. DESIGN AND FABRICATION

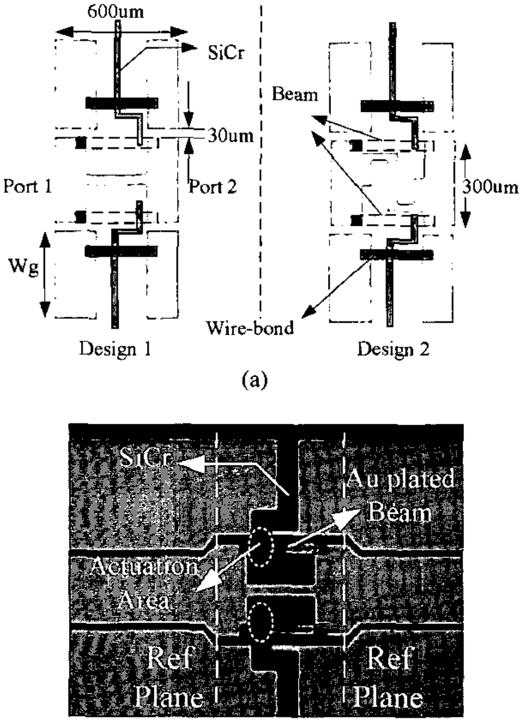
The variable inductor presented herein (Figure 1) is designed to operate from 5-30GHz. The design uses cantilever beams as series type DC-contact switches, suspended on 1.5μm thick posts that are located on the center conductor. When the beams are in the non-actuated state, the signal is carried only on the thin center conductor of the CPW line and a high value of characteristic impedance is obtained. Since the length of this section is electrically small (0.075λ at 25GHz) the topology effectively emulates an inductor with high inductance value (L_{high}). Similarly, when the beams make contact the effective width of the center conductor increases and the characteristic impedance (Z_l) with respect to the high impedance state is less; correspondingly, this represents a low inductance state (L_{low}). For $\beta l < \pi/4$, the reactance offered by the high impedance section (Z_h) is given by equation (1). The inductance ratio is directly related to the change in the impedance states (Z_h/Z_l).

$$X_{high} = Z_h \beta l \qquad (1)$$

In this work, two different topologies as shown in Figure 1 were studied. In design 1 (Figure 1a), the width of the beam and the center conductor is uniform. In the second design, the inductance ratio is increased by using a meandered center conductor (design 2). The overall length of the inductive section for both designs is approximately 600μm and the width of the cantilever beams is 50μm. A resistive SiCr line is used to provide DC-bias which enters through the ground plane. A cut in the ground plane is provided to minimize signal leakage (via SiCr) when the beams are in the actuated state. The split ground sections are connected using a thin wire-bond.

The inductors were fabricated on a 500μm thick quartz substrate (ε_r=3.78, tanδ=0.0004) according to the following steps:

- SiCr bias lines are deposited using E-beam evaporation to a thickness of 0.08μm and defined using liftoff technique. The line resistivity is approximately 2.1kΩ/sq.
- Lift-off processing is used to define the CPW metal lines to a thickness of 0.9μm (Cr/Au).
- PMMA sacrificial layer is patterned to a thickness of 1.5μm.
- The cantilever beams are deposited by evaporating a seed layer, followed by electroplating.
- The beams are defined and the sacrificial layer is removed using photoresist remover.
- The sacrificial PMMA is removed and critical point drying is used to release the MEMS structures.



(a)

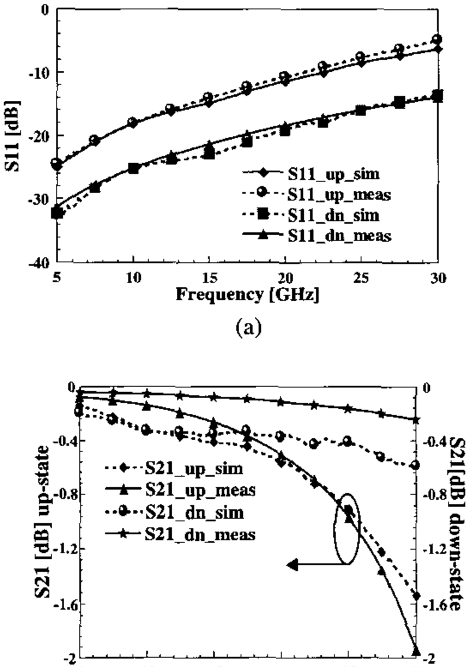
(b)

Figure 1: (a) Schematic of tunable MEMS inductor: Design 1 uses a uniform high impedance line; Design 2 uses a meandered center conductor; (b) Microphotograph of the fabricated structure (Design 1).

III. MEASUREMENT RESULTS

The inductors were measured from 5-30GHz using an Anritsu Lightning 37369C vector network analyzer and 150μm pitch GGB microwave probes. A Thru-Reflect-Line (TRL) calibration was performed using calibration standards fabricated on the wafer. A high voltage bias tee was used to supply voltage through the RF probe to avoid damaging the VNA test ports. Typical actuation voltage for the DC contact cantilever beams is approximately 25-35V. The measured results are compared with full wave EM simulation performed using Agilent ADS Momentum™.

Figure 2 (a) and (b) show a comparison of S_{11} and S_{21} between measured data and the simulation results for design 1. The agreement in S_{11} for both the states is good from 5-30GHz. The measured S_{21} is 0.3dB lower at 30GHz when the beam is in the actuated state; this difference may be due to the contact resistance of the beam and the excess inductance due to the wire-bond connecting the ground plane sections. The insertion loss in both the states can be improved by plating the CPW transmission lines (except the area underneath the cantilever).



(a)

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Figure 2: (a) Comparison of S_{11} between measurement and simulation results in up and down-state; (b) Comparison of S_{21} between measurement and simulation results for both the states.

Figure 3 shows a comparison of phase between the measured and EM simulation. It is seen from this figure that the discrepancy between measured and simulated phase is less than 7% (less than 5° at 30GHz) in both states. This difference seen in the phase response may be due to the wire-bond and the location of the wire-bond with respect to the ground plane edge.

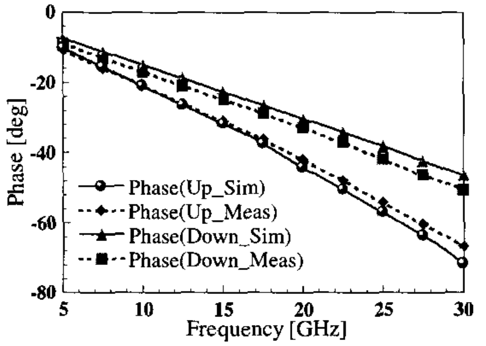
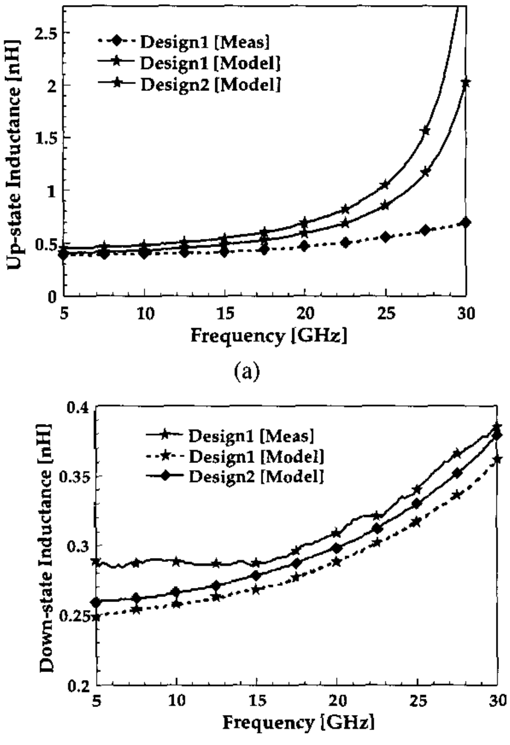


Figure 3: Measured and simulated phase for the inductors in L_{high} state and L_{low} state.

The effective inductance (L_{eff}) of the circuit is extracted by numerically shorting port 2 of the inductor and is related to the input impedance (Z_{in}) by equation 2. Figure 4 shows a comparison of L_{eff} extracted from the measured data (design 1 only) and the simulated data for designs 1 and 2.

$$L_{eff} = \frac{\mathrm{Im}\{Z_{in}\}}{2\pi f} \qquad (2)$$

The extracted L_{eff} when the beams are in the up-state agrees well with EM simulation results for frequencies less than 20GHz. The discrepancy beyond 20GHz can be attributed to the location of the wire-bond in the fabricated device, which altered the resonant frequency of the device. The agreement in L_{eff} in the down-state is good through 30GHz. Table 1 lists the extracted L_{eff} for the measured and simulation data at 25GHz. The measured L_{ratio} (1.7 at 25GHz) for design 1 is limited by the inductance due to the wire-bond, which can be reduced in future iterations by using an air-bridge. Furthermore, it is seen via simulations that the inductance ratio increases for the design with the meandered center conductor.



(a)

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Figure 4: (a) Effective inductance in the non-actuated; (b) Effective inductance in the actuated state. The solid line in both graphs represents EM simulation data for design 1 and design 2 and the dashed line represents extracted data from measurement results.

Table 1: Extracted L_{eff} from measurement results (design 1) and EM simulated data for design 1 and design 2.

Freq = 25GHz	**L_{eff} (Non-actuated state)**	**L_{eff} (Actuated State)**	**L_{ratio} = L_{high}/L_{low}**
Design 1 [Meas]	0.56	0.34	1.64
Design 1 [Model]	0.85	0.32	2.69
Design 2 [Model]	1.05	0.33	3.18

IV. CONCLUSION

In this paper, a planar MEMS variable inductor designed to operate up through 30GHz that utilizes

DC-contact cantilever beams is presented. The measured return loss for both the states is in good agreement with EM simulation results; however, there is a difference of 0.3dB in the insertion loss for the actuated state. Experimental results for a 600µm long device show a tuning from 0.56nH to 0.34nH at 25GHz (inductance ratio of 1.7). The L_{ratio} can be increased by using an air-bridge instead of a wire-bond and/or using a meandered center conductor.

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