High-Q Millimeter-Wave MEMS Varactors: Extended Tuning Range and Discrete-Position Designs

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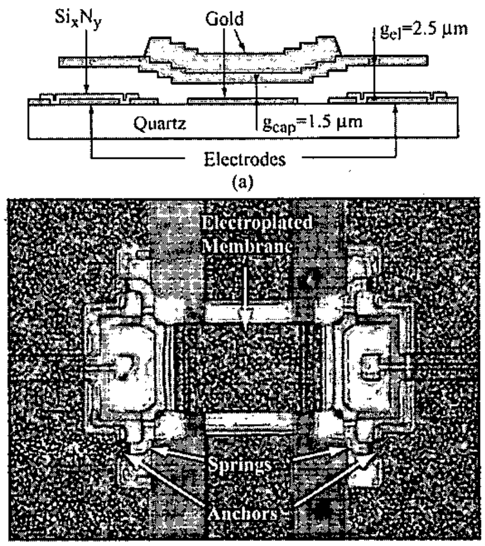
Abstract **— This paper presents the design, fabrication and measurement of two high-Q micro-electro-mechanical (MEMS) varactors suitable for 20–60 GHz applications. The varactors are composed of a movable bridge placed in a shunt configuration on a coplanar waveguide line. The first design is an extended tuning range varactor showing a capacitance ratio of 1.46. The second design demonstrates a discrete-position varactor with a capacitance ratio of 1.90. Both designs result in a tuning voltage of 18–25 V and an excellent quality factor of 95–100 at 34 GHz (C = 80 fF). The very high resonant frequency of the varactors makes them suitable for applications at microwave and millimeter-wave frequencies.**

I. INTRODUCTION

The need for high-Q variable capacitances in microwave and millimeter-wave applications has recently led to the development of numerous designs of MEMS varactors. The main configurations investigated so far are the movable parallel-plates (vertical design) [1-3], the interdigital design (horizontal design) [4] and the switched capacitors bank using MEMS switches [5]. MEMS varactors have several advantages over their solid-state counterparts: potential for high-Q, especially at mm-wave frequencies, high linearity (IIP3), and compatibility with low-cost MMIC fabrication processes. However, MEMS varactors have not reached a mature level yet, mostly because of their low capacitance ratio in analog designs and their low resonant frequencies.

This paper presents two designs of MEMS varactors using the parallel-plate approach. The first one demonstrates a continuously tunable capacitance with a ratio of 1:1.46. The second design is a discrete-position (up-down) varactor switching between two capacitances with a ratio of 1:1.87. These designs have both demonstrated good measured performances over 5–35 GHz, with an excellent quality factor at 35 GHz and a resonant frequency beyond 80 GHz, making them suitable for applications such as tunable filters, tunable matching networks or phase shifters at millimeter-wave frequencies.



(b)

Fig. 1. Wide tuning range varactor; side view (springs and anchors not represented)(a) and top view (b).

II. EXTENDED TUNING RANGE MEMS VARACTOR

Fig. 1 shows an extended tuning range varactor designed using the same approach as Zou et al. [3]. The capacitance area is at the center of the bridge, between the bridge and the CPW center conductor. The varactor is actuated by two electrodes included in the ground plane on both sides. The height of the bridge is g_{cap} = 1.5 µm in the capacitance area (140 × 140 µm) which results in a total capacitance (parallel-plate and fringing) of 130 fF. The height of the bridge above the electrodes is g_{el} = 2.5 µm. A DC voltage applied between the electrodes and the bridge permits to decrease the height of the bridge by $g_{el}/3$ before the bridge is pulled down [6]. Thus, the gap between the parallel plates is tunable in the range [g_{cap} - $g_{el}/3$; g_{cap}] resulting in a parallel-plate capacitance ratio of 1:2.25 (115–260 fF).

The fabrication process is described in Fig. 2. The varactor is fabricated on a 20 mil-thick quartz substrate (ε_r = 3.8) using an 88 Ω CPW line with dimensions of

83/133/83 μm. The electrodes are connected to external bias pads with SiCr lines not shown in the figure. The sacrificial layer is a 2.5 μm-thick PECVD SiO_2 layer which is partially etched in the middle of the bridge to reduce its thickness to 1.5 μm. The bridge is fabricated by sputtering 0.8 μm of gold and electroplating 2.5 μm in the center of the bridge. The sacrificial layer is removed using a buffered HF solution and the varactor is released using a critical point dryer.

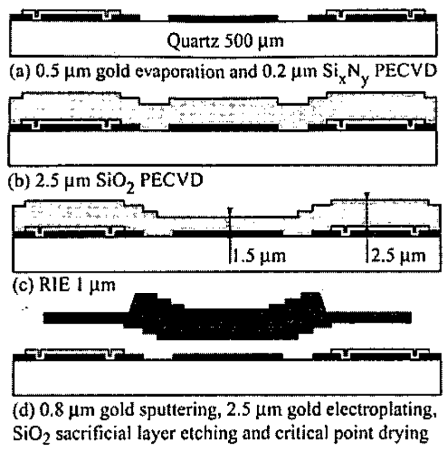


Fig. 2. Fabrication process of the extended range varactor.

The varactor is modelled by an LC series circuit and the values are fitted to the measured S-parameters at 5–35 GHz (Fig. 3a). The losses are negligible in these measurements and will be examined in Section IV. The inductance is independent of the bias and is mostly due to the springs, which are 30 × 90 × 0.8 μm. The extracted capacitance varies from 82 fF to 120 fF which is a ratio of 1.46 (Fig. 3b). The capacitance values are smaller than expected because of the stress gradient in the electroplated gold which bows up the bridge, resulting in a bridge height of 3–3.5 μm at the center. The tuning voltage is 24 V and the extracted spring constant is k = 15 N/m. The operating range of this varactor is expected to extend far beyond 35 GHz since the resonant frequency is 83 GHz (L = 30 pH, C = 120 fF).

III. Discrete-Position MEMS Varactor

A similar process can be used to fabricate a discrete-position MEMS varactor. In this design, the PECVD SiO_2 sacrificial layer is partially etched on both sides of the bridge, resulting in g_{el} = 1.5 μm above the electrodes while the central gap is g_{cap} = 2.5 μm (Fig. 4a). This component is basically a switched capacitor: in the up-state, the gap in the capacitance area is g_{cap} = 2.5 μm, corresponding to C_{pp} = 69 fF, while in the down-state, the bridge is pulled down over the electrodes resulting in a gap of 1 μm at the center ($g_{cap} - g_{el}$) leading to C_{pp} = 172 fF. The capacitance has been extracted from S-parameters measurements following the same procedure described previously (Fig. 4b). The measured up-state capacitance (V_{bias} = 0 V) is 94 fF. The measured down-state capacitance is 176 fF for V_{bias} = 40 V. This represents a capacitance ratio of 1:1.87. The bridge is pulled down at V_{bias} = 18–22 V. In both states, the capacitance is nearly constant, varying by less than 10 %.

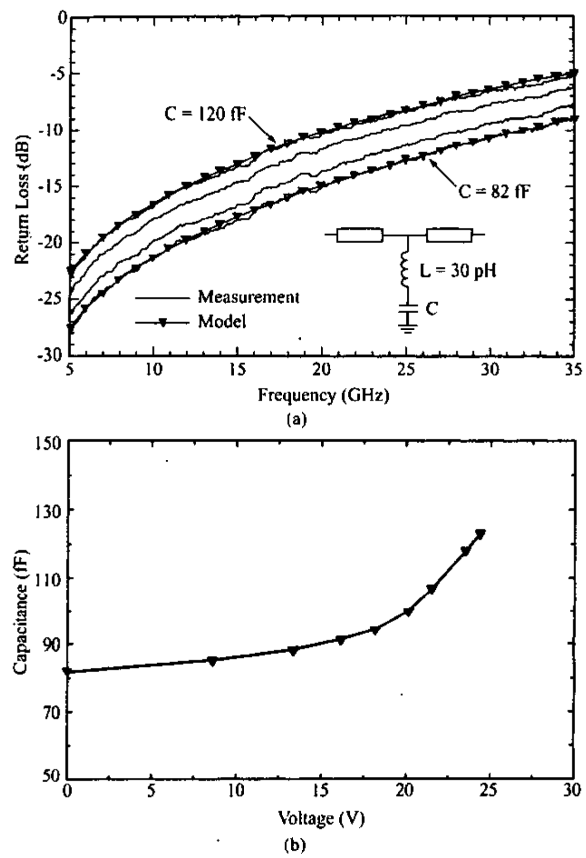


Fig. 3. Measurements of the extended tuning range varactor: return loss (a) and capacitance (b).

III. Q Measurements

The varactors presented in this paper are expected to be high-Q components because of the metal-air-metal parallel-plate structure. The quality factor is thus limited only by the metallic and radiation losses. The losses can be included into the model of Fig. 3a by adding a resistor in series with the LC circuit. In order to measure this resistance, a tunable CPW series resonator has been designed at 33–35 GHz (Fig. 5a). The resonator includes two extended-range varactors identical to the devices described in Section II.

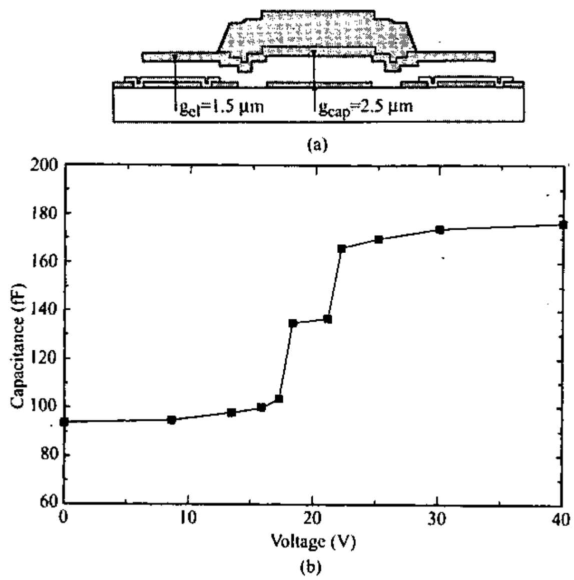


Fig. 4. Discrete-position varactor: side view (a) and measured capacitance (b).

A circuit model of the tunable resonator is shown in Fig. 5b. The fixed resonator parameters were extracted using weakly-coupled resonator measurements and result in an unloaded Q of 94 at 34 GHz. The tunable-resonator model was then used to extract the varactor series resistance R_s. The measured tuning range is 33.4–35.4 GHz (5.8 %) with an unloaded Q of 58–64 (Fig. 5c). The extracted series resistance is $R_s = 0.6\ \Omega$ corresponding to a Q of 95–100 at 34 GHz for C = 80 fF. The series resistance is attributed mostly to the ohmic losses in the narrow springs, to the CPW center conductor which is not electroplated below the bridge for a length of 200 μm, and to radiation from the CPW line. The Q of the discrete-position varactor of Section III was not measured but is expected to be very similar to the values measured above.

V. Conclusion

This paper presented extended-range and discrete-position high-Q millimeter-wave MEMS varactors. The main advantages of these varactors over previous designs are a high quality factor (Q = 95–100 at 34 GHz). The discrete-position varactor is expected to provide a capacitance ratio of 2–4 in future designs, with the use of a shallower RIE etch of the sacrificial layer. Also, the discrete-position varactor can be used in a multiple-capacitor configuration to result in a tunable quasi-analog capacitance range of 2–4. These MEMS varactors are ideal for tunable filters, tunable matching networks, VCOs or phase shifters.

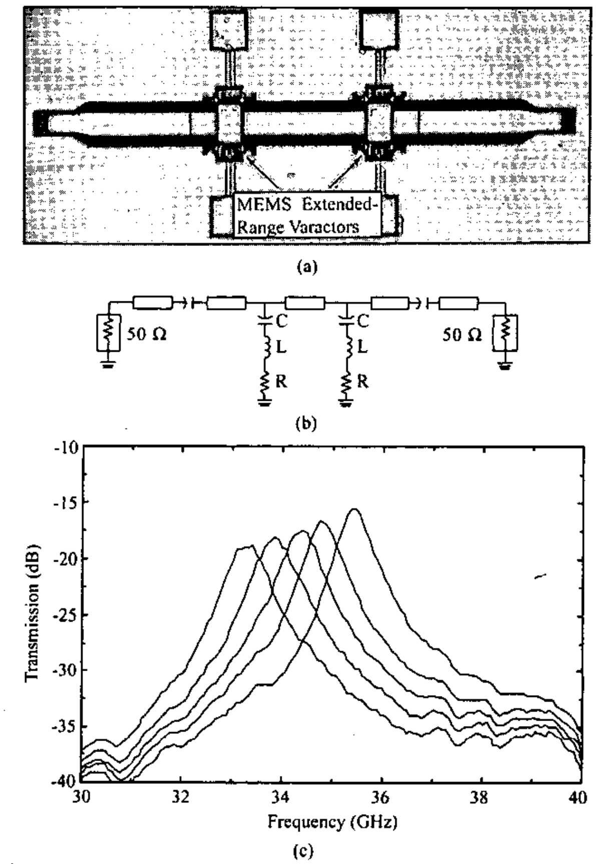


Fig. 5. Tunable CPW series resonator: top view (a), model (b), and measurements (c).

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