Abstract — This paper reports on area-efficient, ultra-wideband, MEMS-reconfigurable directional couplers, whose coupling is tuned by mechanically changing the geometry of 3D-micromachined coupled transmission lines, utilizing integrated MEMS electrostatic actuators. Devices have been fabricated in an SOI RF MEMS process. Furthermore, to the best knowledge of the authors, we report for the first time on couplers which are reconfigured by changing the geometry of the ground-plane coupling, either alone or including the conventional tuning of the direct coupling between the signal lines. This results in a very uniform and well predictable performance over a very large frequency band as proven in this paper. Two different concepts are presented and compared, along with measured RF performance and actuator characterization of fabricated devices.

I. INTRODUCTION

There is an increasing need for reconfigurable RF/microwave circuits due to the increasing complexity of multi-standard RF frontends in modern telecommunication systems [1]. RF MEMS components are especially of interest for reconfigurable/tuneable circuits for frequency-agile front end applications, due to their near-ideal signal handling behavior, ultra-low power consumption, large bandwidth and easiness of integration, since fabrication is compatible to integrated circuits. The parallel-plate capacitive tuning principle is very widely used implementation for RF MEMS tuneable devices. Parallel-plate designs are easily implemented with standard surface micromachining thin-film technology [2]. The electrostatic actuation is the most commonly used actuation principle. Electrostatic actuation offers virtually zero power consumption, a response in microseconds and fabrication compatibility, as no nonstandard clean-room materials are needed.

RF power dividers/combiners are key elements in modern communication systems, including beam forming networks, MIMO systems, and adaptive antenna feedback mechanisms, which are getting more and more common to achieve high data throughput at limited power [3]. Switching/tuning of such couplers is necessary especially for future architectures. Previous attempts of tuneable couplers mainly comprise PIN-diode switched hybrid couplers [4]. One of the few MEMS examples is a very space-inefficient branch-line coupler with large MEMS phase-shifters [5]. To our knowledge, so far only one research paper has reported on a compact MEMS-switched directional coupler concept [6].

The present paper reports for the first time on a directional coupler whose coupling is tuned by mechanically changing the geometry of 3D-micromachined coupled transmission lines, utilizing MEMS electrostatic actuators, completely integrated into the sidewalls of the ground planes and signal line of a micromachined 3D coplanar waveguide.

II. CONCEPT AND DESIGN

The basic principle of tuning the designed directional couplers proposed in this paper can be seen in Fig. 1. RF power is coupled between two unshielded transmission lines due to the interaction of the electromagnetic field when the lines are in close proximity [7]. These lines are called coupled lines and consist usually of three conductors i.e., two signal lines and a common ground layer. These lines are assumed to operate in the TEM mode and their electrical characteristics can be completely determined by the effective capacitances between the lines. Even and odd mode excitation of the coupled lines reveal that both the even and odd mode capacitances are strongly influenced by the capacitance to ground of each signal line [7]. The even and odd mode capacitances can be represented as [7].

\[ C_e = C_{11} = C_{22} \] (1)
This results in a strong dependence of the characteristic impedances of the even and odd modes on capacitance of each line to ground [7].

\[
Z_{oe} = \frac{\sqrt{L}}{C_e} = \frac{1}{v_p C_e}
\]  

\[
Z_{oo} = \sqrt{\frac{L}{C_o}} = \frac{1}{v_p C_o}
\]  

where \(v_p\) is the phase velocity of propagation on the line.

Since the overall coupling can be represented in terms of even and odd mode impedance [7] so the total coupling between the lines can be changed by changing the coupling to the ground.

\[
C = \frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}}
\]  

Fig. 1(a) shows the principle of the conventional way for changing the coupling between two coupled lines in a directional coupler by varying the distance between the lines. Fig. 1(b) and Fig. 1(c) show how the coupling can be varied by using the proposed novel method of changing the distance of the signal lines to the ground either without changing the distance between the signal lines (Fig. 1(b)) or by using a combination of the above described approaches (Fig. 1(c)).

In this paper we demonstrate both novel concepts shown in Fig. 1(b) and Fig. 1(c). The reconfiguration is achieved for both the ground layer and the signal lines by using 3D coplanar waveguide transmission lines and switching on and off different floating elements. In a 3D micromachined coplanar waveguide the major part of the electric field lines is concentrated above the substrate, which decreases dielectric losses and radiation losses into the substrate. The metallization is only applied on top of this 3D topography.

The 3D illustration and the working principle of the concept shown in Fig. 1(b) and Fig. 1(c) are shown in Fig. 2. For the tuneable-coupler Design 1 (Fig. 2(a)), the ground-coupling between the lines is varied by laterally moving the ground-sidewalls of the coupled coplanar waveguide thereby changing the nominal coupling from 3 dB in State 1 to 6 dB in State 2. For Design 2 (Fig. 2(b)), two narrow intermediate floating lines are switched to the signal lines of the two coupled lines, and simultaneously the ground-line sidewalls are moved apart for compensating the ground coupling, which allows to design for a much larger coupling range variation by maintaining uniform performance over a large bandwidth thereby varying the nominal coupling from 20 dB in State 1 to 10 dB in State 2. Design 1 only needs actuation voltage for one state (active pull, passive release), whereas Design 2 needs actuation voltages to be applied for both states, as two independent actuators are operated alternatively for maintaining the two states.
III. FABRICATION

All structures are fabricated in a single-mask SOI RF MEMS process, by deep-reactive-ion-etching of the structures into the 30µm deep device-layer of an SOI (silicon on insulator) wafer followed by free-etching of the moving structures by underetching the BOX (buried oxide layer) in hydrofluoric acid. The chips are dried using supercritical drying setup and metallized by high-directivity e-beam evaporation. Finally a selective electrochemically assisted etching step is performed to remove unwanted gold areas in the slots. The fabrication is summarized in Fig. 3.

IV. EVALUATION AND RESULTS

Fig. 4(a) shows a SEM picture of the fabricated device Design 1. Similarly the SEM picture of Design 2 is shown in Fig. 4(b). Fig. 4(c) shows the close up of the actuator designs showing the restoring springs, fixed electrodes and moving walls which can be switched for the desired coupler configuration.

Table 1 show the measured actuation and release voltages of the designed actuators. For Design 1, State 1 is passive meaning that no actuation voltage is required to maintain the coupler in State 1. Whereas for Design 2 both states are active; it requires actuation voltage to maintain both State 1 and State 2. The actuation voltages are very reproducible and no stiction was observed, as these devices comprise all-metal designs without dielectric isolation layers.

<table>
<thead>
<tr>
<th>STATE 1</th>
<th>DESIGN 1</th>
<th>DESIGN 2</th>
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<tbody>
<tr>
<td>ACTUATION [V]</td>
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<td>27</td>
</tr>
<tr>
<td>RELEASE [V]</td>
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<td>24</td>
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<table>
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<th>STATE 2</th>
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<td>34</td>
</tr>
<tr>
<td>RELEASE [V]</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

TABLE I

ACTUATION AND RELEASE VOLTAGES FOR DESIGN 1 AND DESIGN 2 OF THE DIRECTIONAL COUPLER.

Fig. 5 shows the RF measurement results. The couplers are ultra-wide band (57% bandwidth) from 10 to 18 GHz. Design 1, utilizing reconfigurable ground-plane coupling, is designed as a two-state 3-to-6 dB reconfigurable directional coupler. Design 2 is designed as a two-state 10-to-20 dB reconfigurable coupler. Here, the measurements show extraordinarily good agreement with the design values, and the overall excellent performance of the device is emphasized by the through-port being better than 2 dB, the isolated port being better than 40 dB, and the return loss being better than 15 dB, uniformly for the whole spectrum and for both states. These excellent results prove the performance benefit of the novel method of combined tuning of both ground-plane and signal-line coupling of Design 2.

V. CONCLUSION

A novel concept of RF MEMS ultra-wideband 10 to 18 GHz tuneable directional coupler has been presented. Two different tuning concepts involving tuning the distance of the signal lines to ground were compared. Designs were fabricated and evaluated using the measured RF performance and actuator characterization. The most suitable technology is.

REFERENCES

Fig. 5. Measured S parameters in the two coupling states: (a) Design 1; (b) Design 2

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