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TECHNICAL PAPER

Design of compact and wide bandwidth SPDT with anti-stiction torsional RF MEMS series capacitive switch

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Abstract This paper presents a new single pole double throw (SPDT) RF MEMS switch design based on a torsional series capacitive switch. The torsional configuration and use of floating metal reduce the stiction probabilities. Use of a single series capacitive switch compared to the conventional approach of a capacitive and series combination, offers compact size, higher bandwidth and superior reliability. The optimized SPDT topology offers a wider bandwidth of 17 GHz (3–20 GHz) with insertion loss of −0.3 to −0.4 dB and isolation −20 to −44 dB. The proposed structure actuates at 9 V and the contact force varies in the elastic contact regime from 20 to 68 µN for the bias voltage of 10–15 V.

1 Introduction

In recent years, the evolution of wireless communication applications and the specific trend towards miniaturized energy-efficient devices have led to rapid development of RF-MEMS devices such as switches (Bansal et al. 2014; Rangra et al. 2005; Bansal et al. 2012; Rebeiz Gabriel and Muldavin Jeremy 2001; Sukomal and Shiban Koul 2012), antennae (Jitendra Pal et al. 2014; Mahmoodnia and Ganji 2014) and filters (Kok-Yan and Rebeiz 2009; Reines and Rebeiz 2010) etc. RF MEMS components in general offer smaller size, low power consumption, low loss, high linearity, and high Q factor compared to conventional counterpart (Rebeiz Gabriel and Muldavin Jeremy 2001). However, the use of multiple switches for designing SPDT, SP4T, phase shifters (Sukomal and Shiban Koul 2012) and redundancy switch matrix (Du et al. 2013) etc., leads to higher insertion loss and larger size. SPDT switches are the basic building blocks for realizing SP4T (Guangwei Hu et al. 2006; Roy and Rangra 2009; Rebeiz 2003), phase shifters (Tan et al. 2002, 2003; Dv et al. 2008), wireless communication systems (Misran et al. 2012; Kang-Ho Lee et al. 2005; Shairi et al. 2011) and switch matrices (Du et al. 2013; Sinha et al. 2012; Daneshmand and Mansour 2006; King Yuk (Eric) Chan et al. 2009), which constitute the core of wireless communication technology. The robustness and size of SPDT unit are thus crucial for the reliable and economical feasibility above mentioned devices and systems. In this work, a novel compact and reliable design of a RF-MEMS SPDT switch configuration for S-Ku band applications is presented. The single switch based stiction free SPDT is more reliable as compared to the contemporary SPDT or SP4T configurations designed using large number of switches. An area reduction of approximately 85 % is achieved (actual area = 0.88 × 0.68 mm^2) compared to the reported devices where the area ranges from 5 to 15 mm^2; 5.2 × 3 mm^2 (Uno et al. 2009), 3.8 × 1.1 mm^2 (Cheng et al. 2009) and 3.5 × 1.5 mm^2 (Yamane et al. 2010).

The concurrent approach to realize RF MEMS SPDT consists of a combination of series ohmic and shunt capacitive switches or similar types. The shunt capacitive switches have limited bandwidth and placement of the switch at a quarter wavelengths from the T-junction increases the size of SPDT (Cheng et al. 2009; Malczewski and Pillans 2004).

In series ohmic switch smaller bridge-contact area leads to radiative leakage and limit the frequency response to 12 GHz (Yamane et al. 2010; Malczewski and Pillans 2004; Majumder et al. 2003). In addition, realizing an ohmic contact with minimum deformation and pitting is a major issue.

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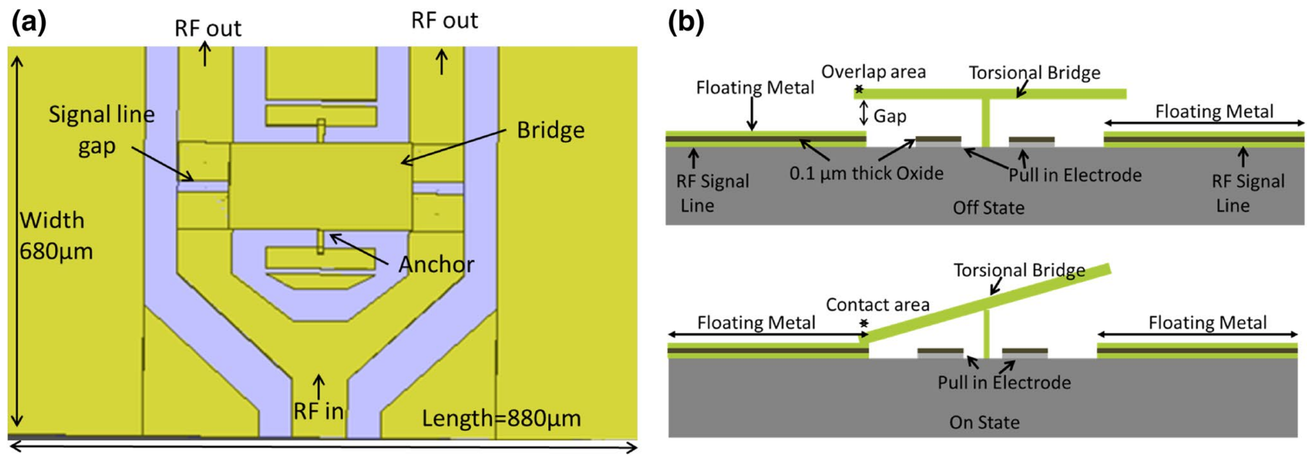

Fig. 1 Series capacitive switch based compact SPDT structure. **a** *Top view* and **b** *cross sectional view*

A large number of SPDT configurations using ohmic and capacitive switches placed at T-junction have been reported in the literature (Dinardo et al. 2006; Sergio Dinardo et al. 2006; Malmqvist et al. 2011). The ensuing larger size with two or more constituent switches undermines the reliability and yield. It also leads to increased insertion loss as two switches operate in series. The proposed SPDT based on a single series capacitive switch overcomes the above mentioned problems.

2 Design parameters

The proposed SPDT design consists of a series capacitive switch in torsional configuration; preferred over conventional fixed–fixed beam or cantilever based structures as stiction is better tackled in a torsional configuration (Bansal et al. 2014). Stiction is caused by capillary forces, hydrogen bonding, capacitive charging and Van der Waal forces between two surfaces in proximity or contact and magnitude of the stiction is directly proportional to contact area. In the present design the reduction in the contact area by a factor of 18 by using floating metal layer and the pull-up action of torsional structure (Fig. 1b) is used to obviate stiction.

The transmission line is a standard gap-signal-gap (55–90–55 µm) 50 Ω CPW, with tapering at the T-junction to minimizes impedance mismatch and reflection. As shown in Fig. 1a the signal line is split into two parts by a gap of 20 microns. The gap dimensions have been optimized for S and Ku band operation. The larger gap in the transmission line implies low up-state capacitance, which further limits the bandwidth of the device by shifting the lower operating frequency point to a higher value. On the other hand, smaller gap in the signal line leads to deterioration in off-state isolation.

The optimized design parameters for the switch are given in Table 1. Bridge dimensions determine the pull-in voltage and are optimized accordingly using Coventorware®. The optimized overlap area between the bridge and transmission line in the off-state is fixed at 5 µm, it is in conjunction with the fabrication limitations and RF response. Also, overlap area <5 µm is difficult to align as torsional movement further reduces the margin. Higher overlap area (>5 µm) results in poor isolation. The proposed fabrication process flow illustrated in Fig. 2 is similar to symmetric toggle switch fabrication discussed in details in (Rangra et al. 2005). The SPDT is a highly compact device measuring 880 × 680 µm^2 only; approximately a reduction of 85 % in size compared to the reported devices (Uno et al. 2009; Cheng et al. 2009; Yamane et al. 2010).

Table 1 Parameters used for simulating the torsional SPDT switch

S. No	Design parameter	Values	Units
1	CPW (G-S-G)	55–90–55	µm
2	Anchor thickness	2	µm
3	Oxide thickness	0.1	µm
4	Oxide dielectric constant	3.9	
5	Floating metal thickness	0.1	µm
6	Electrode length	100	µm
7	Electrode width	160	µm
8	Gap between electrode and torsional bridge	2.4	µm
9	Torsion bridge thickness	2	µm
10	Torsion bridge length	300	µm
11	Torsion bridge width	150	µm
12	Signal line gap	20	µm
13	Anchor length	30	µm
14	Anchor width	10	µm

3 Results and discussions

3.1 Electrical analysis

Floating metal concept has been utilized in the present device to reduce stiction and increase on/off capacitance ratio. The air gap between the bridge and t-line is optimized for 2.4 µm, as shown in Fig. 1. With floating metal layer on the t- line and switch in off state position, overlap area (A_{off}) is 650 µm^2 [(bridge width−signal gap) × bridge overlap area = 130 × 5 µm^2], whereas without floating metal, A_{off} is (130 × 90) µm^2. Off state capacitance is reduced from $\varepsilon_o \frac{A_{off}}{d_{off}}$ = 43.1 fF (without floating) to 2.4 fF when floating metal layer is used. The reduction in overlap area also results in higher capacitive reactance ($1/\omega C$, minimum 3.3 kΩ at 20 GHz), offering lower leakage at higher frequencies.

In the down state (switch on state) overlap area using floating metal is 130 × 90 µm^2 with 0.1 µm thick oxide. The on state capacitance of 4 pF gives capacitive reactance <13Ω, at 3 GHz. The RF response of SPDT is analyzed by using a commercial tool (Ansoft HFSS). A wider bandwidth of 17 GHz (3–20 GHz) of the SPDT with insertion loss varying from −0.3 to −0.4 dB is obtained. Isolation varies from −44 dB (3 GHz) to −20 dB (20 GHz) as plotted in Fig. 3. Return loss is better than −12 dB for above mentioned bandwidth.

3.2 Mechanical analysis

The electromechanical parameters such as pull-in and pull-up voltage, contact area, force, and mechanical resonance frequency of the switch are simulated using Coventor-ware, as shown in Figs. 4 and 5. FEM simulations show pull-in voltage of approximately 9 V with pull-up at 6 V as illustrated in Fig. 4a.

Resonance frequency of the structure is 6.8 kHz for bias of 9 V as shown in Fig. 4b with natural resonance frequency of 7.1 kHz. Switching time of the SPDT at bias

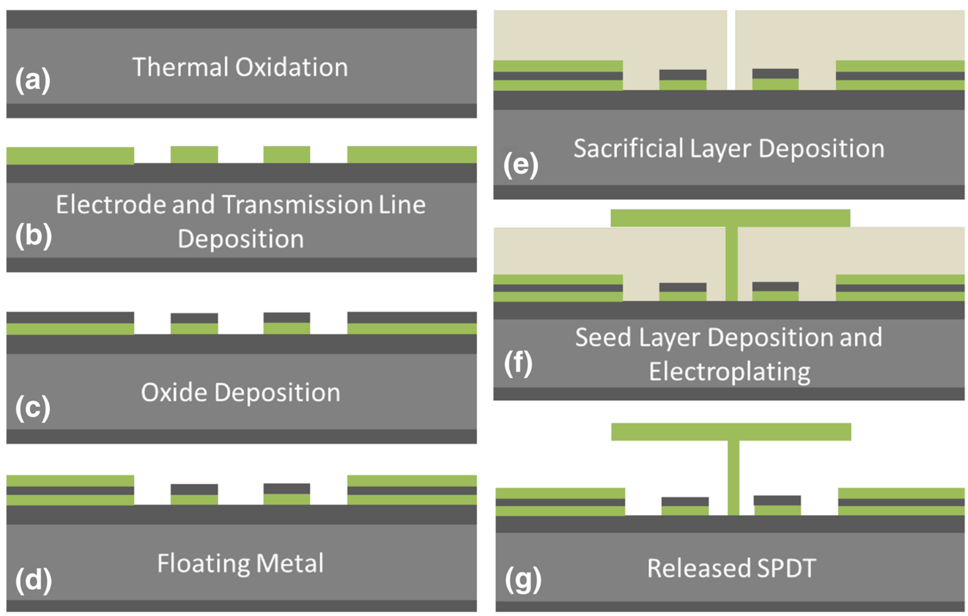

Fig. 2 Proposed fabrication process flow for designed SPDT switch

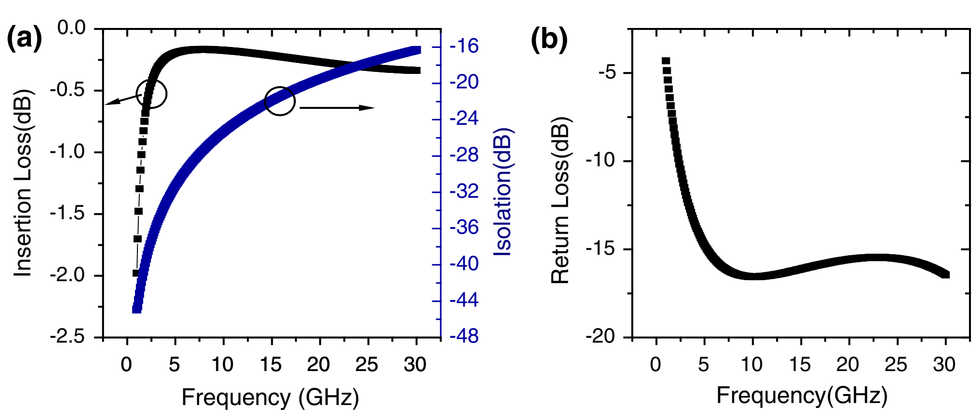

Fig. 3 **a** Insertion loss and isolation **b** return loss of proposed SPDT

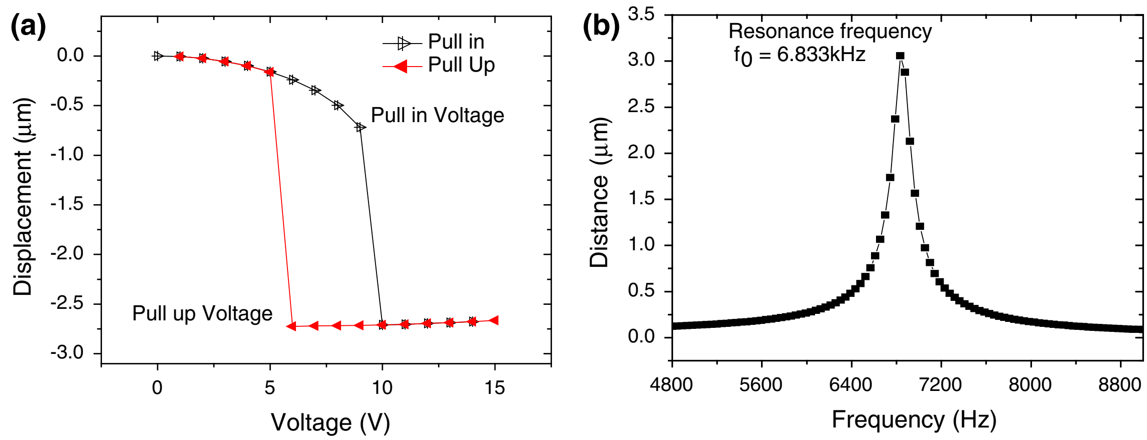

Fig. 4 **a** Pull-in voltage analysis and **b** frequency response of SPDT

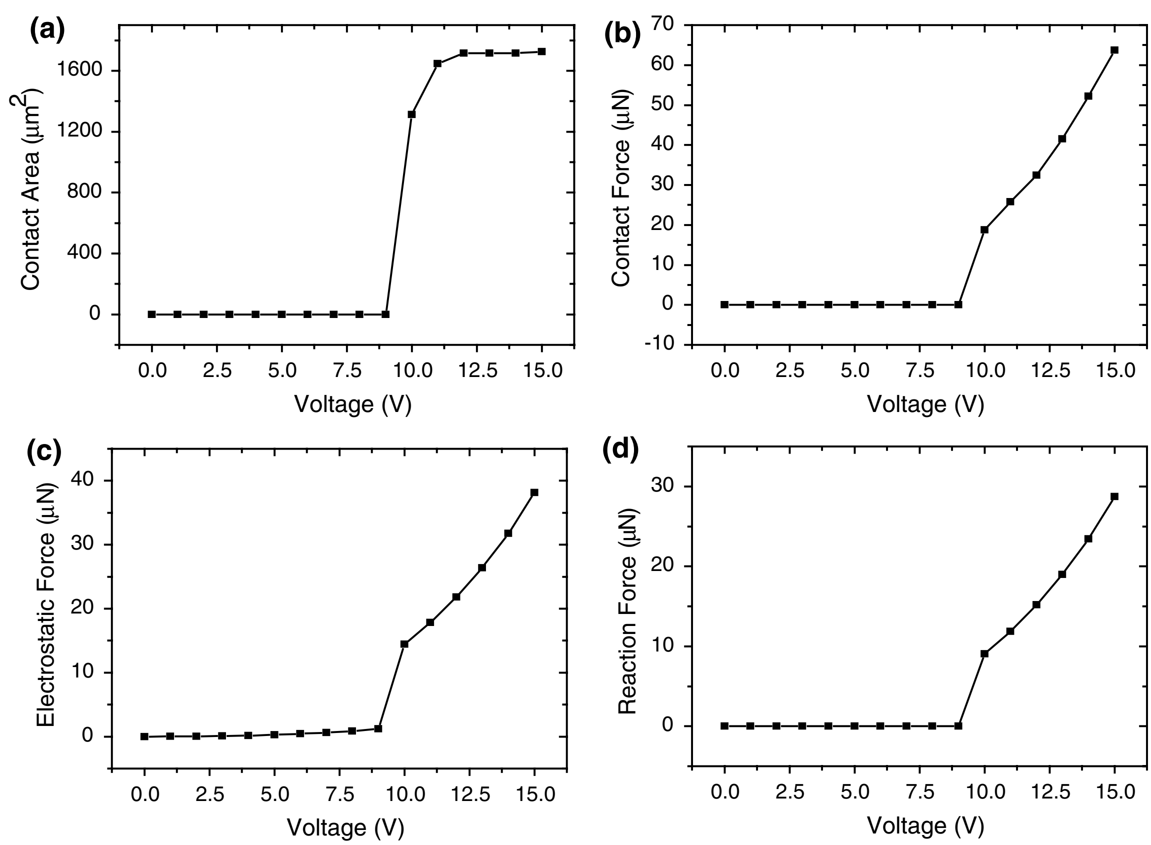

Fig. 5 **a** Contact area, **b** contact force, **c** electrostatic force and **d** reaction force response with respect to bias voltage

voltage of 15 V is 50 μs and can be controlled by altering bias voltage (Rebeiz 2003) as

$$t_s \simeq 3.67 \frac{V_p}{V_s \omega_o}$$

where t_s, V_p, V_s and are switching time, pull-in voltage, bias voltage and resonance frequency of designed SPDT respectively. Switch reliability and problem of stiction are improved by reducing metal to metal contact area; the contact area is 1,700 μm^2 for bias voltage >10 V as shown in Fig. 5a, which is small compared to conventional switches or SPDT without floating metal (Bansal et al. 2014). The optimum value of force required for metal to metal elastic contact is given as 40–200 μN (Rebeiz 2003). In the present case the contact force is in the range of 20–68 μN for applied bias voltage of 10–15 V as shown in Fig. 5b. Contact force is taken as the sum of the electrostatic and reaction force as shown in Fig. 5b–d. Electrostatic force is due to the applied voltage across electrode and bridge, where as, reaction force arises due to Newtonian motion of bridge and is a function of damping. All the simulations are performed at room temperature and 1 atm pressure. Depending upon the contact force requirement, SPDT can be packaged at suitable pressure and reaction forces can be controlled.

4 Conclusions

Single switch based SPDT of size 0.6 mm^2 is designed for a bandwidth of 17 GHz (3–20 GHz). Stiction free torsional configuration of SPDT, using floating metal has pull in voltage of 9 V and contact force of 68 μN for applied voltage of 15 V. Series capacitive switch used for SPDT has advantage of higher bandwidth and compact size as compared to conventional shunt capacitive and series ohmic switches combinations. The optimized SPDT topology has insertion loss of −0.3 to −0.4 dB, isolation −20 to −44 dB and return loss of −12 to −15 dB for frequency range of 3–20 GHz.

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