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Two-state reconfigurable miniaturized low-pass filter using micromachined double-contact RF switches

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ABSTRACT

This paper presents a compact micromachined two-state reconfigurable low-pass filter (LPF). Frequency tunability of the proposed LPF could be efficiently and precisely achieved by ON/OFF actuations of two types of single-crystal silicon (SCS) double-contact RF MEMS switches. The use of the SCS double-contact switches as frequency-tuning elements on the reconfigurable filter has two main advantages: the number of the tuning elements required can be reduced by half, and mechanical robustness and reliable filter operations can be provided owing to the deform-free properties and stable actuating behavior of the SCS actuators. The proposed filters and switches were monolithically fabricated using a robust silicon-on-glass (SiOG) process. A frequency tuning ratio of 2.5:1 was successfully obtained and the average insertion losses on the passbands were changed only by 0.05 dB between the two reconfigured filter states.

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1. Introduction

Over the past few decades, frequency-tunable radio frequency microelectromechanical system (RF MEMS) technologies have been emerging in reconfigurable RF filter applications because of their promising advantages, such as low loss, low power consumption and high linearity compared to their electrical counterparts. For these reasons, many attempts have been made to apply them to practical RF filter devices in the micro- and millimeter-wave regions, and a number of miniaturized versions of reconfigurable RF filters using several RF MEMS components have been reported [1–11]. Several monolithic RF reconfigurable filters have been demonstrated; they are configured by changing the capacitance of the filter circuits using implemented tunable MEMS elements [1–5]. In addition, resonators with specific center frequencies and RF MEMS switches to select the targeted resonators have also been monolithically fabricated on a single substrate [6–8]. In other approaches, hybrid-type filters, which imply that RF MEMS switches are externally integrated with the filter banks to select the specific filter bank, have also been presented [9–11]. In these cases, the reconfigurability of the filters strongly depends on the number of MEMS elements implemented. Therefore, one or more MEMS elements are needed to achieve at least one reconfigured state with respect to their initial state. The use of multiple-contact MEMS switches makes it possible to reduce the number of MEMS elements required to change the filter states, resulting in improvements in the loss characteristics and structural simplicity of the filter circuits. A reconfigurable LPF based on multiple-contact metallic thin-film switches was introduced [12]. Although a prototype of the reconfigurable LPF was successfully demonstrated, the practicability of the filter is unclear because of unresolved issues related to the structural deformation of the metallic structure, such as bending and/or buckling of the metallic thin-film actuating parts, mainly due to thermal and residual stresses. In this concept of reconfigurable filter, stable contact behavior of multiple-contact switches at each contact point is desirable for obtaining a stable filter response because the electrical contacts at each point are made only by single actuation of the multiple-contact switch. Several studies have reported that the structural deformation of the metallic moving structure due to residual stress makes it difficult to obtain the uniform actuating status of the switches and predict the precise dynamic characteristics such as the driving voltage [13–15]. Therefore, stable actuating behavior and structural stability of the implemented switching elements

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are essential for realizing a stably operating reconfigurable filter.

This paper reports a two-state reconfigurable LPF using mechanically robust double-contact SCS RF MEMS switches as the frequency-tuning elements. This approach is suitable for realizing a simple and stably operating miniaturized reconfigurable filter because the number of tuning elements can be reduced efficiently, and the mechanical and operating stability of the tuning element can also be achieved due to the superior stress-free property and reliable actuating behavior of the SCS switches [16].

2. Design and simulation

2.1. Design of filter structure

Fig. 1 presents a schematic view of the two-state reconfigurable LPF using two sets of series- and parallel-type double-contact switches. The proposed LPF is mainly based on the quasifractal low-pass transmission structure with three parts of the signal line (one center line and two outer lines). Two parallel-contact switches are located on the outer side, while two series-contact switches are shown on the inner side of the filter circuit. Therefore, the role of 8 individual switches is performed by only 4 double-contact switches consisting of two sets. In the first reconfigured state, two parallel-contact switches are actuated simultaneously while maintaining the OFF states of the two series-contact switches; hence, the center and outer lines of the signal line are electrically connected in parallel. As a result, a three-cell cascade low-pass filter structure is obtained, as shown in Fig. 1(b). On the other hand, the three-cell cascade structure is changed into the one-cell low-pass filter configuration, which is three times longer, by activating the two series-contact switches, as shown in Fig. 1(c). Therefore, two different frequency responses of the LPF can be obtained by the different actuating status of the switch sets. The actuating parts of the double-contact switch implemented in the proposed LPF are composed of a stress-free SCS, and the displacement of the switch depends only on the deformation of the four mechanical springs in the *z*-direction, which support the switch body (top electrode) as shown in Fig. 1, due to the applied bias voltage. Therefore, the moving part, including the contact region, can be actuated without undesirable stress-related structural deformation such as bending and buckling, resulting in both mechanical stability and uniform contact behavior.

2.2. FEM analysis of switching elements

The double-contact switches implemented in the proposed LPF are electrostatically actuated by an electrostatic force induced by the bias voltage applied between the top and bottom electrodes, and the switch can be simply modeled by the parallel-plate actuator model, as shown in Fig. 2(a). The electrostatic force of the parallel-plate electrostatic actuator model can be estimated easily using Eq. (1):

$$F_e = \frac{\varepsilon_0 wWV^2}{2(g_0 - d + (t_d/\varepsilon_r)^2} \quad (1)$$

where ε_0 is the vacuum dielectric constant and $w \cdot W$ is the electrode area. V and g_0 are the applied voltage and initial gap between the electrodes, respectively. ε_r and t_d are the relative dielectric constant and thickness of the dielectric layer, respectively. d is the vertical displacement due to the applied voltage. The electrostatic forces of the parallel and series double-contact switches due to the applied voltage were simulated using Eq. (1) and the vertical displacement was calculated using a finite element method (FEM), as shown in Fig. 2(b). In addition, the spring stiffness of the mechanical

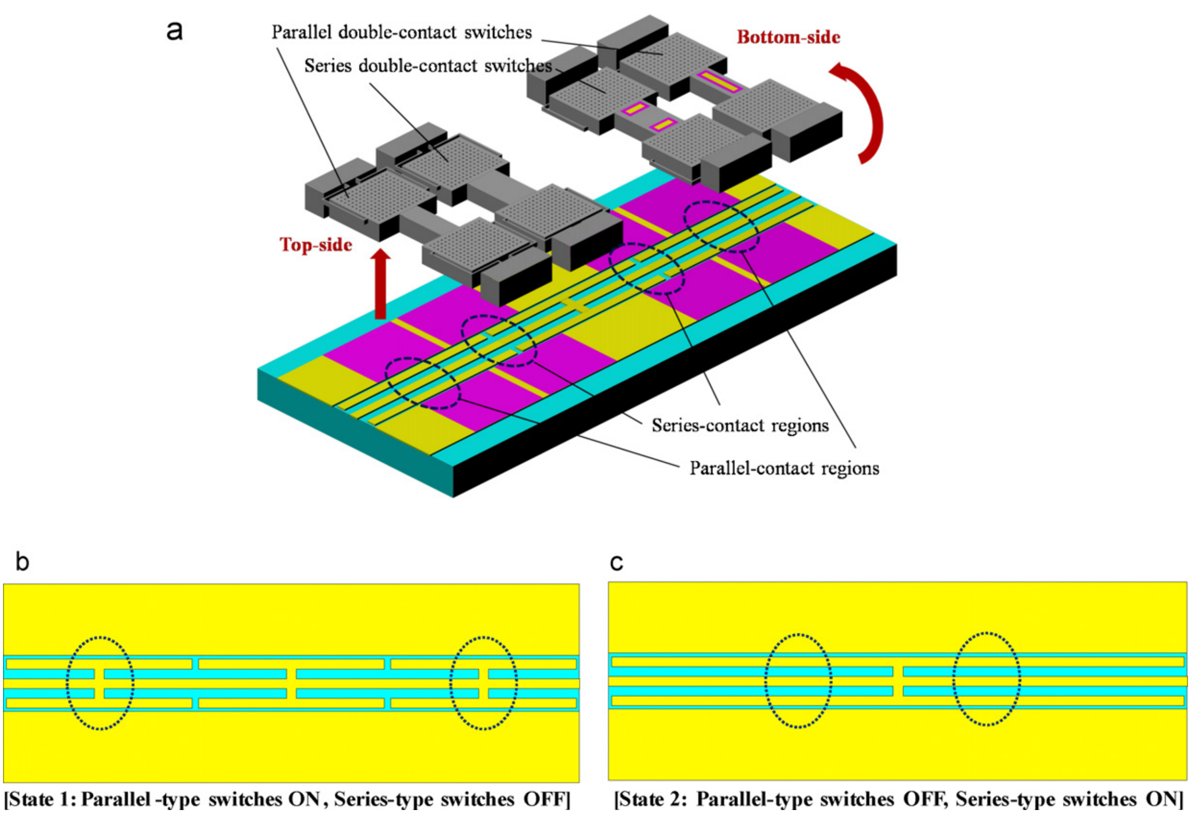

Fig. 1. The proposed two-state reconfigurable LPF. (a) Schematic view of the LPF, (b) first reconfigured state (parallel-contact switches ON, series-contact switches OFF), and (c) second reconfigured state (parallel-contact switches OFF, series-contact switches ON). Dotted circles in (b) and (c) indicate the contact regions.

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