Single-Pole Eight-Throw RF MEMS Rotary Switch

Suneat Pranonsatit, Student Member, IEEE, Andrew S. Holmes, Member, IEEE, Ian D. Robertson, Senior Member, IEEE, and Stepan Lucyszyn, Senior Member, IEEE

Abstract—The design, fabrication, and measured performance of a novel single-pole eight-throw radio-frequency (RF) microelectromechanical systems (MEMS) rotary switch are described. The concept of this rotary switch is based on the adaptation of the axial gap wobble motor. A prototype switch has been made using separately fabricated stator, rotor, and cap components that are then assembled. A rigorous procedure was set up to investigate the direct current (dc) contact resistance over a total of four million rotor contact closures, with half a million closures made on each of the eight stator contacts. It was found that there was no obvious systematic trend in contact resistance over time. An average contact resistance of 2.5 Ω was recorded; however, values as low as 1.0 Ω were also found. The assembled rotary switch demonstrated an excellent RF performance. With the inclusion of feed lines, the insertion loss was 2.65 dB at 20 GHz, after renormalizing the measurement reference impedance. When the loss of the feed lines is subtracted, the worst-case on-state intrinsic insertion loss of the rotary switch is only 2.16 dB at 20 GHz. A worst-case off-state isolation of 31 dB was also measured over the 20-GHz bandwidth. The effective performance figure-of-merit for this switch in an arbitrary position was calculated to be 10.7 THz. To the authors’ knowledge, this is the first example of a true single-pole multiple-throw RF MEMS rotary switch.

Index Terms—Microelectromechanical systems (MEMS) switch, radio-frequency (RF) MEMS, rotary switch.

I. INTRODUCTION

Radio-frequency (RF) system architectures can be significantly enhanced by increasing the performance and functionality of the RF switches they contain. One important application of the switch is signal routing, which can take many forms. Within RF subsystems, low on-state insertion loss and high off-state isolation signal routing are very important. For example, when implementing redundancy subsystems for a transmitter’s power amplifier (PA) and receiver’s low noise amplifier (LNA), low on-state insertion loss switching is required to minimize degradation in power-added efficiency and noise figure performance, respectively. Whereas, when implementing a transmit/receive (T/R) module or switched-diversity sectorized antenna [1], very high off-state isolation switching is important. Finally, the compact design of high-performance single-pole multiple-throw switches, having good input and output impedance matching, is necessary in digital phase shifters and attenuators.

Over the past few decades, integrated switching in RF circuits has been performed by p-type, intrinsic, n-type (PIN) diodes within hybrid microwave integrated circuits (HMICS), and generally by cold field-effect transistors (cold-FETs) within monolithic microwave integrated circuits (MMICS) [2]. The former can deliver superior broadband RF performance with a single-pole single-throw (SPST) reflective switch. The latter tries to exploit the inherent switching compatibility of FETs operating in their triode region. Unfortunately, even with specially fabricated switching-FETs, performance can be much worse than that obtained with discrete PIN diodes. Also, with both PIN diodes and cold-FETs, intermodulation distortion presents serious limitations at higher RF power levels.

RF microelectromechanical systems (RF MEMS) technology offers the potential for realizing very high-performance components [3]. By far the most important RF MEMS component is the switch. This is because RF MEMS switches have demonstrated orders of magnitude improvement in performance figure-of-merit over conventional PIN diode and switching-FETs [3]–[5]. The first RF MEMS papers started to appear more than a quarter of a century ago, with electrostatically actuated cantilever-type switches [6]. At around that time very little was reported, but over the last decade many papers have been published employing various RF MEMS technologies.

There are two generic types of RF MEMS switch: ohmic contact [or metal-air-metal (MAM)] and capacitive membrane [or metal-insulator-metal (MIM)] [3]. The main advantages of the former are that a very low on-state insertion loss and very high off-state isolation can be achieved. The reason for this is that the ohmic contact area needed for low loss can be relatively very small. At the same time, with such a small area, the parasitic capacitance when the electrodes are separated will be small and, thus, good isolation can be achieved. Unfortunately, considerable force is required to create a good metal-to-metal contact and this may not be possible under certain types of actuation. Moreover, conventional ohmic contact switches are highly susceptible to corrosion, stiction, and microscopic bonding between metal surfaces of contact electrodes.

With the capacitive membrane switch, a tradeoff has to be made; increasing the overlapping electrode surface area improves the on-state insertion loss, but compromises the off-state isolation. As a result, electrode separation needs to be maximized and this may not be possible with certain actuation mechanisms. Also, low-frequency operation is not possible.

Electrostatic actuation is, by far, the most common, as it can produce small components that are robust and relatively simple to fabricate. They are also relatively fast and tolerant to environ-

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S. Pranonsatit, A. S. Holmes, and S. Lucyszyn are with the Optical and Semiconductor Devices Group, Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, U.K. (e-mail: s.lucyszyn@imperial.ac.uk).
I. D. Robertson is with the Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, U.K.
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mental changes. In principle, they consume power only when switching between states, although in practice some residual energy is required to hold them in the actuated state. The main disadvantage with electrostatic actuation is that it is difficult to combine low-actuation voltage with high isolation, because of the small spatial separation distances between electrodes. Moreover, self-actuation by the RF signal being switched can be a serious problem.

Nearly all RF MEMS switches are based on out-of-plane electrostatically actuated cantilever-type or suspension bridge designs. In order to achieve a high performance, even simple SPST switches can be rather large. For this reason, the implementation of compact broadband single-pole multiple-throw switches is traditionally seen as a challenge. For example, Tan et al. [7] recently demonstrated an RF MEMS single-pole four-throw (SP4T) switch, with excellent RF performance from dc to 3 GHz, employing a network of four SPST series switches.

An alternative approach to RF MEMS switch design is to adopt the principles used in electrostatic motors, giving the obvious advantage of compactness with a multiple-throw design. Here, at least two basic configurations are available: radial gap and axial gap. With a radial gap electrostatic motor, the rotor is always oriented parallel to the stator. An actuating bias potential is applied between the rotor and stator electrodes placed around its periphery. The resulting electrostatic force drives the necessary angular displacement. As an example, a side-drive rotary switch on GaAs was presented by Larson and Hackett [8]–[10]. In their design, the input signal can only travel diagonally across the rotor. This limits the configurability of the switch to multiple SPST operation. Moreover, since the dc bias and RF signal line electrodes are common, this side-drive rotary switch is prone to self-actuation from the RF signal power. The authors also highlight problems with contact repeatability with their design [8].

With the axial gap configuration, the rotor sits at an angle to the stator, with its center supported by a raised bearing, and with a point on its periphery resting on the stator surface. Translational motion of the rotor is prevented by an axle passing up through a hole at its center. This type of device is commonly known as an axial gap wobble motor [11]–[15]. The stator electrodes are positioned underneath the rotor, and exert a downward force on the rotor, causing it to perform a precessional motion, similar to that of a coin flipped onto a table top. This design offers many advantages in performance when used to implement a single-pole multiple-throw switch. To this end, and for the first time, we describe the design, fabrication and measured performance of a novel single-pole eight-throw (SP8T) RF MEMS rotary switch based on this principle. It will be seen that our approach has the benefits of good RF insertion loss and isolation characteristics, robustness to stiction, and advantages of size, yield, and reliability.

II. SP8T RF MEMS ROTARY SWITCH DESIGN

With reference to Fig. 1, the novel rotary switch is an adaptation of the axial gap wobble motor previously reported by Holmes and Saidam [15]. A microstrip or coplanar waveguide (CPW) transmission line is employed to feed the input RF signal directly to the bearing (or post) and axle (or shaft). The input RF signal then makes its way onto the rotor, via the inherent rotating physical/ohmic contact that exists between the touching gold surfaces of the bearing and the tilted rotor. An arbitrary number of output contacts are located on the stator, around the periphery of the device where the outer edge of the tilted rotor makes physical contact with the stator. Each output contact is centered on a stator electrode. Consequently, when a bias voltage is applied to any single electrode, the stable equilibrium position for the rotor is with its physical contact point perfectly aligned to the corresponding output contact. The selected output RF signal path can again employ either a microstrip or CPW line as the interconnect between the switch and the outside world.

The rotary switch described in this paper was designed with a single input and eight possible outputs, all interconnected to the outside world using 50-Ω CPW lines. In order to minimize the attenuation of the CPW interconnects, a 500-μm-thick quartz substrate was chosen. Even with such a thick substrate, strong coupling between the quasi-transverse electromagnetic (quasi-TEM) mode of the CPW line and the lowest order transverse magnetic (TM1) mode is not expected below the corresponding theoretical cutoff frequency of approximately 106 GHz.

The rotor itself was designed to be either a cartwheel or solid disc. The key mechanical design parameters of the rotary switch were intentionally made similar to those of the wobble motor in [15], in particular the rotor diameter of 1 mm and tilt angle of 0.02 rad. This approach was taken in order to produce devices with approximately known drive characteristics. Some additional design effort was required, however, to determine acceptable ranges for the dimensions of the cutouts in the stator electrodes, and for the thickness of the dielectric spacer. To this end, numerical simulations were carried out to determine the variation of the drive torque with these parameters. A dielectric spacer layer with a relative permittivity of 4.0 was assumed throughout.
Detailed dynamic models for axial-gap wobble motors have been reported previously by several groups (see [13] and [14]), and here we include only a brief outline of our approach to facilitate a discussion of the design tradeoffs with our device. The driving torque in an axial-gap wobble motor is generated by the electrostatic closure force between the rotor and whichever electrodes are activated on the stator. Because the rotor tilt angle is small, and the rotor-stator gap is much less than the rotor diameter, a simple parallel plate approximation can be used to calculate the force per unit area $f$ at any point on the rotor, giving

$$f \approx \frac{\varepsilon_0 V^2}{2(g + t_d/\varepsilon_r)^2} \mathbf{e}_x. \quad (1)$$

Here, $t_d$ and $\varepsilon_r$ are the thickness and relative permittivity of the dielectric, respectively, and $g$ is the air gap between the rotor and the dielectric, which varies with position due to the rotor tilt. $V$ is the voltage applied to the region of the stator immediately below the point where $f$ is evaluated, and $\mathbf{e}_x$ is a unit vector normal to the rotor surface. The total torque due to electrostatic forces can then be obtained as

$$M = \int \int \mathbf{r} \times f dA \quad (2)$$

where the vector $\mathbf{r}$ denotes the position relative to the rotor center, and the integral extends over parts of the rotor surface that lie above activated electrodes.

Following [13], we resolve the total torque $M$ into two components $M_d$ and $M_n$, along axes lying in the plane of the rotor. These axes are labelled $x'$ and $y'$, respectively, in Fig. 2. The component $M_d$ acts along the $x'$-axis, which passes through the rotor center $O'$ and the contact point $P$. This torque component is responsible for driving the rolling motion of the rotor on the stator, and is accordingly referred to as the drive torque. The orthogonal component $M_n$, known as the adhesion torque, prevents slipping and determines the contact force at the physical contact point $P$. Both torque components are important for correct device operation, and either can be used to illustrate the design considerations in adapting the wobble motor for switching. In the following sections, we focus on the drive torque.

When sizing the cutout for each switch contact, it is necessary to consider the tradeoff between drive torque and RF performance. As the cutout becomes smaller, the associated transmission line needs to be tapered to ever smaller dimensions, leading to higher ON-state insertion loss with lower switch contact area. On the other hand, increasing the cutout size reduces the effective area of the drive electrode, lowering the drive torque for a given applied voltage. Fig. 3(a) illustrates the latter effect in our device, by comparing the drive torque characteristics for electrodes with cutouts corresponding to 0, 11%, 19%, and 40% of the electrode area. Each curve shows the variation of drive torque, as a function of angular position $\Psi$, as the physical contact point passes over a single activated electrode with an applied voltage of 100 V. In all cases, the drive torque tends to pull the rotor towards a stable equilibrium position at $\Psi = 0$, where the contact point is centered on the electrode (see Fig. 2). However, as the cutout size increases, the peak drive torque falls off, implying a higher drive voltage for a given dynamic performance. In this paper, we chose a cutout 75 $\mu$m long in the radial direction by 120 $\mu$m wide, corresponding to 19% of the electrode area. This was sufficient to accommodate a 27-$\mu$m-wide RF signal line with a 30-$\mu$m-wide earth strap around the end (to suppress the unwanted slot-line mode). The peak drive torque was about 65% of that of an electrode with no cutout, implying a modest increase of around 24% in drive voltage.

A second feature of the curves in Fig. 3(a) is that when the cutout size becomes a significant fraction of the electrode area, the restoring torque around $\Psi = 0$ becomes disproportionately weaker, reducing the ability of the switch to hold the rotor at the...
desired position. This effect also depends on the dielectric thickness, as illustrated in Fig. 3(b). For very low dielectric thicknesses, the equilibrium at $\Psi = 0$ actually becomes unstable, with two stable equilibrium points appearing on either side. This occurs because the electrode appears increasingly like two separate electrodes as the dielectric becomes thinner. This effect is undesirable if the aim is to hold the rotor at $\Psi = 0$. In this paper, it was avoided by choosing a dielectric thickness of 2.5 $\mu$m.

Compared with the work reported by the Hughes Research Laboratories [8]–[10], our rotary switch has output RF signal line stator contacts that are approximately a third smaller and having greater spatial separation. The resulting reduced adjacent contact parasitic capacitances will inherently give a much greater RF isolation between output signal lines.

III. FABRICATION

The importance of electrodeposition in microfabrication is well known [16], and many studies have been carried out to explain critical issues associated with current distribution and mass transportation during the electroplating process [17]. Along with other high aspect ratio fabrication techniques, the use and continual development of electroplating offer possibilities to step from planar to three-dimensional (3-D) micromechanical structures. In this section, details of the multilevel electroplating process used to fabricate the rotary switch components are briefly described.

With reference to Fig. 4, for the stators, the process starts by the sputter deposition of Ti and Cu seed layers onto 4-in-diam-
eter quartz substrates. Photolithography is used to create a photosist mould for electroplating the ground plane metallization layer. Next, the SU-8 spacer layer is deposited with the use of an adhesion-promotion layer. The multilevel electrodeposition processes of the other metal structures (i.e., signal lines, bearing, and axle) are subsequently undertaken. After the resist mould for the axle is removed, the seed layers are etched with a procedure that has been optimized to minimize lateral under-etching. A scanning electron micrograph of a finished stator is shown in Fig. 5(a).

The rotor fabrication process begins with the deposition of a photosist sacrificial layer. The thickness, curing time, and temperature have been optimized to ensure compatibility with the subsequent process steps. A Cr/Cu seed layer is then deposited by thermal evaporation. The next step is the electrodeposition of the structural metals, which is the same as for the stators. The seed layers are removed and the rotors are released from the substrate by dissolving the sacrificial photosist layer in acetone. Each rotor is then transferred to a stator to form a switch.

To ensure the rotor remains captive on the stator, a nickel-gold cap is attached to the top of the axle, using a novel transfer bonding process. The caps are fabricated in a similar manner to the rotors, except that the final release step is omitted. The transfer bonding operation is performed using a thermosonic bonder, developed for earlier flip-chip assembly work [18]. The switch is mounted on the heated sample stage of the bonder, while the cap, still attached to its fabrication substrate, is held overhead by the ultrasonic bonding tool (see Fig. 6). The two are aligned and brought into contact with a controlled contact force. A short burst of ultrasonic energy is then applied that leads to bonding of the cap to the axle. Under the correct process conditions, the combination of ultrasonic excitation and high temperature also causes the cap to separate from its fabrication substrate, via delamination at the interface between the sacrificial layer and the substrate. Under these conditions, the cap fabrication substrate can simply be lifted away after bonding. Fig. 5(b) shows a scanning electron micrograph of an assembled SP8T rotary switch with a cartwheel rotor and a cap applied using the aforementioned process.

Although placement of the rotors was done manually in this paper, the rotor fabrication process was designed for compatibility with the batch transfer assembly process described previously by Holmes and Saidam [15]. This process was shown to be capable of assembling arrays of wobble motors by parallel laser-driven transfer of rotors between two aligned substrates. The same process could be applied, without modification, to the devices described here, eliminating the need for a delicate manual assembly operation. The capping process could also be extended to arrays of devices, allowing for batch assembly of arrays of devices without manual intervention.

IV. DC CHARACTERIZATION

DC contact resistance measurements were made to verify correct operation of the switch and to obtain some preliminary reliability data. The experimental setup, shown schematically in Fig. 7, allowed individual four-probe resistance measurements to be made between each output signal line and the common input signal line. The switch was driven continuously by a sequence of nonoverlapping, rectangular 100-V drive pulses. A low clock frequency of 400 Hz/4 × 100 Hz was used to ensure that the dwell time at each contact position (10 ms) was sufficiently long, compared to any switching transients due to contact bounce.

Each output contact from a prototype rotary switch was assigned an A/D channel. A 4× faster clock was used to trigger the data acquisition system, so that four-switch resistance measurements could be made at each position during this 10 ms. One recorded data point is made from an average over 16 consecutive measurement samples at the same contact (i.e., a group of four measurement samples during 10 ms, followed by 360° rotation and then another four measurement samples during 10
ms, etc.). After a measurement-free period of 2 or 10 min of continued rotation, the acquisition sequence is repeated to produce the next resistance data point. Fig. 8 shows the resulting contact resistance data, obtained continuously over almost half a million rotations, i.e., a total of four million rotor contacts closures where made, with half a million closures on each of the eight stator contacts. The graph shows the variation, over a continuous 10-h period, in the contact resistance for one particular contact position (RF2). The scatter on the data is quite low, although on a few occasions the contact resistance rises well above the average value. The reason for this is currently unclear, but we believe it may be attributable to surface asperities on the electroplated gold contacts, which will cause the contact area to vary semirandomly over time as the rotor rotates. Alternatively, the high-peak values may result from particulate contamination of the device. The tests were carried out in a normal laboratory environment, and the devices were not packaged or protected from dust. Overall, the results obtained are very encouraging, in that there is no obvious systematic trend in the contact resistance over time and the average resistance over all measurements is as low as 2.5 Ω (with a minimum value of 1.0 Ω). From simple calculation, which takes into account the multicomposition nature of the metal, the center conductor for each tapered CPW feed line has an effective series loss resistance contribution of approximately 0.1 Ω. Therefore, the average intrinsic series loss resistance is 2.3 Ω at dc.

RF characterization of the rotary switch was carried out using the microwave measurement facility within the Institute of Microwaves and Photonics, University of Leeds, U.K. A functional schematic of the measurement setup is given in Fig. 9. Here, an Agilent 8510C vector network analyser (VNA) is used with a Cascade Microtech probe station. In order to protect the sensitive RF mixers within its test-set, from any high-voltage transients, 10-dB attenuators were inserted between the VNA and the corresponding RF port of the rotary switch under test. These attenuators are made from a T-network of resistors, which allow the input voltage to be divided down considerably. Moreover, an additional bias-tee was inserted between the attenuator and the corresponding RF port of the rotary switch, to prevent any dc from entering the VNA. As a result, the useful dynamic range of the measurement system was limited to operation above approximately 0.5 GHz. Therefore, even though the rotary switch operates down to dc, only its measured performance above 0.5 GHz can be given.

Fig. 7. DC contact resistance measurement setup.

Fig. 8. Measured variation of dc contact resistance at one switch position (RF2) over many switching cycles.

V. RF MEASUREMENTS
A. Performance Within a 50-Ω Reference Impedance Environment

The same rotor drive setup used in the dc characterization was adopted for the static RF measurements. It can be seen in Fig. 10 that the rotary switch operates up to 20 GHz. This figure represents a summary of the basic RF measurements, after on-wafer calibration of the complete system has been performed with a 50-Ω reference impedance. The ON-state insertion loss smoothly increases with frequency, up to a maximum value of 4 dB at 20 GHz.

It can also be seen from Fig. 10 that the level of OFF-state isolation is better than 31 dB across the entire 20-GHz frequency bandwidth of the rotary switch. There are two reasons for this high level of isolation. The first is a combination of the large spatial separation of the corresponding rotor section and small OFF-state stator contacts. The second is the relatively high shunt capacitance between the rotor and the upper CPW ground planes. An even higher level of OFF-state isolation was found with the solid disc rotor, but this performance came with a higher ON-state insertion loss penalty.

B. Performance Within a Simultaneous Complex Conjugate Impedance Matched Environment

The basic switches were not designed to operate at any particular frequency. Therefore, no impedance matching circuits were employed and, as a result, the switch exhibits a higher than normal level of mismatch loss within a 50-Ω environment, due to impedance mismatch reflection losses. To assess the significance of this effect, the insertion loss of the switch having a cartwheel rotor was renormalized to find the inherent attenuation (i.e., without any mismatch losses). To this end, the identical measurement port impedances were optimized, at 20 different frequency points, to give simultaneous complex conjugate impedance matching. This is equivalent to performing the $G_{\text{Max}}$ function within some RF/microwave simulation software packages. In so doing, with the closed switch in the ON-state, the insertion loss is minimized, due to the lack of any signal power reflections. The $G_{\text{Max}}$ performance is shown in Fig. 11. It can be seen that the worst-case maximum insertion loss is now only 2.65 dB at 20 GHz.

It should be noted that these results include both the 1-mm-long 50-Ω CPW feed lines. Much longer 50-Ω CPW test lines were included on the same wafer as the switches and subsequently accurately characterized. For example, at 20 GHz, an attenuation of 0.25 dB/mm was obtained from measurements of these test lines. Since both the input and output feed lines are approximately 1 mm long, the combined attenuation from these feed lines is 0.5 dB. Therefore, it can be concluded that the intrinsic loss of the switch having the cartwheel rotor is 2.16 dB at 20 GHz.

Fig. 11 also shows the $G_{\text{Max}}$ performance with both the feed lines removed. It can be seen that the intrinsic losses are 0.02 dB at 3 GHz, 0.06 dB at 5 GHz, 0.22 dB at 10 GHz and 2.16 dB at 20 GHz. This can be compared with the measured performances of the side-drive rotary switch, presented by Larson and Hackett [8]–[10], which shows insertion losses of approximately 0.10 dB at 3 GHz, 0.10 dB at 5 GHz, 0.19 dB at 10 GHz, and 0.30 dB at 20 GHz. Our loss results can also be compared with the Tan et al. SP4T switch network, having a measured insertion loss of 0.15 dB at 3 GHz [7].

C. Effective Performance Figure-of-Merit

From the accurate characterization of the 50-Ω CPW test lines, a model for the 1-mm-long 50-Ω CPW feed lines was made. The intrinsic equivalent circuit model of an RF switch is commonly represented as a resistor in the ON-state and a capacitor in the OFF-state. Therefore, by embedding these crude lumped-elements between models for the feed lines, values for the ON-state resistance, $R_{\text{on}}$, and OFF-state capacitance, $C_{\text{off}}$, can be extracted using the measured data. The effective performance figure-of-merit can then be calculated from $f_{\text{ce}} = (1/2\pi R_{\text{on}} C_{\text{off}})$ [3]. Using this parameter extraction technique, for an arbitrary switch position, the following values for $R_{\text{on}} = 18.6 \, \Omega$ and $C_{\text{off}} = 0.8 \, \text{pF}$ were found. The corresponding effective performance figure-of-merit is calculated to be 10.7 THz. By comparison, the hinged RF MEMS switch in [19] exhibited an extracted value of $f_{\text{ce}} = 6 \, \text{THz}$.

VI. DISCUSSION

The inherent design of the switch, with its small ohmic stator contacts and large physical OFF-state displacements, is ideal for achieving high isolation over extremely large bandwidths. With the use of a solid disc rotor, any associated series inductance can be effectively neglected. Moreover, since the bearing is short and wide, there is no significant series inductance in which to create unwanted resonances. As a result, this switch can have an inherently large instantaneous bandwidth of operation. Moreover, as this is an ohmic contact switch, there is no compromise between OFF-state isolation and ON-state insertion loss, as found with the capacitive membrane switch.

In the ON-state, the electrostatic actuation force helps to achieve a low contact resistance and, therefore, a low insertion loss down to dc. With improvements in the fabrication process (to reduce the surface roughness of the electroplated gold) and
introducing larger contact areas, even lower contact resistances can be achieved. At present, the gold of the signal lines is significantly rougher than that of the surrounding ground plane, as illustrated in Fig. 12. This increased roughness will reduce the effective contact area, and may also explain the relatively high peak-contact resistance values observed in Fig. 8.

The major contributions to the intrinsic insertion loss of the rotary switch at high frequencies can be attributed to the inherent attenuation of the input CPW transmission line, the ohmic resistances associated with both rotor contacts and the use of nickel to create the bearing/axle components. For the OFF-state isolation, the rotary switch has a performance that is comparable to other reported switches, in the range of 30 dB across the dc to 20-GHz bandwidth. The high isolation is due to the large physical displacement between the 0.02-rad tilted rotor and the OFF signal lines.

It should also be noted that, when approaching the self-resonant frequency of the rotor (i.e., when the diameter of the rotor is equal to half the free-space wavelength), then the rotor will radiate like a circular patch antenna. This will result in a dramatic increase in the insertion loss. Fortunately, since the diameter of the rotor is only 1 mm, this would only begin to create problems at frequencies approaching approximately 100 GHz.

Since the switch design is based on the wobble motor principle, it can be driven towards or away from any given position, by applying appropriate bias signals to the stator electrodes. The moveable electrode motion of the rotary switch is deflected downward and is driven to rotate, instead of movements in a vertical direction. For this reason, this rotary switch is less susceptible to the stiction effects that are normally attributed to conven-
tional cantilever and suspension bridge designs, thus improving operational reliability.

While this rotary switch is tolerant to environmental changes and consumes almost no control power, because of the very nature of electrostatic actuation, its present design is susceptible to self-actuation by the RF signal. When the RF signal power is sufficiently large there will be no adverse self-actuation effect when the switch is fixed in any position. Problems may arise, however, when the position of the switch has to be moved. To overcome the holding force created by a large RF signal power, a larger than normal actuation voltage would be needed to rotate the rotor to its new position. Unfortunately, a large-signal measurement facility was not available to us, in order to explore the dynamics of this phenomenon experimentally.

There are few reported single-pole multiple-throw RF MEMS switches. The SP4T switch demonstrated by Tan et al. can be integrated within a circle having a diameter of approximately 1 mm [7]. Similarly, a 1-mm² single-pole six-throw (SP6T) switch was reported by Lee et al. [20]. Both have designs based on a network of multiple SPST switches (i.e., four and six, respectively). If an SP8T switch was required, using a network solution, then a larger overall size would be anticipated. The 1-mm-diameter rotor of our SP8T switch defines its size. When compared with other reported single-pole multiple-throw switches, our rotor design can be considered compact. This offers the additional advantage of processing uniformity across its smaller area. Moreover, with our solution, there is only one moving component in the entire switch. As a result, our rotary switch can be expected to have a higher production yield and improved performance reliability.

VII. CONCLUSION

The design, fabrication, and measured performance of a completely novel SP8T RF MEMS rotary switch have been described. To our knowledge, this is the first example of a true single-pole multiple-throw RF MEMS rotary switch. The basic concept of the switch has exploited the principles of actuation that were demonstrated for the axial gap wobble motor, previously reported by one of the authors of this paper. This natural adaptation of the wobble motor has not only given way to the realization of a true single-pole multiple-throw switch, but also allows for cyclic operation. The authors are currently investigating applications ranging from serrodyne modulators [21] to steerable scanning antennas.

In terms of RF performance, with its SP8T configuration, the switch has demonstrated both low ON-state insertion loss and high OFF-state isolation, over an extremely wide instantaneous bandwidth. With suitable refinements to the basic design, it is possible to improve this performance considerably. Moreover, with its robustness to stiction, and advantages of size, yield, and reliability, this novel rotary switch could be ideal for implementing signal routing functions within high-performance reconfigurable RF front-end architectures.

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REFERENCES

Suneat Pranonsatit (S’05) received the B.Eng. degree from Chulalongkorn University, Bangkok, in 1998, the M.Sc. degree from Ohio State University, Columbus, in 2000, and the Ph.D. degree from the Department of Electrical and Electronic Engineering, Imperial College London, London, U.K., in 2005, all in electrical engineering.

She was a Research Assistant in sensor fabrication at Ohio State University. She was appointed a Lecturer at the Department of Electrical Engineering, Kasetsart University, Bangkok, in 2001. In 2002, she received a scholarship from The Royal Thai Government for her Ph.D. studies. She is now on sabbatical, working as a Postdoctoral Fellow within the Optical and Semiconductor Devices Group, Imperial College London. Her interests are MEMS and microelectronic fabrication processes, sensors, and screen printing technologies.


He is currently a Reader in Microelectromechanical Systems in the Department of Electrical and Electronic Engineering, Imperial College London. He is a Cofounder and Director of Microsaic Systems Ltd., an Imperial College spin-out company started in 2001 to exploit Imperial College MEMS research. His research interests are in the areas of micropower generation and conversion, MEMS devices for microwave applications, and laser processing for MEMS manufacture.

Ian D. Robertson (M’96–SM’05) received the B.Sc. (Eng.) and Ph.D. degrees from King’s College London, London, U.K., in 1984 and 1990, respectively.

From 1984 to 1986, he worked in the monolithic microwave integrated circuit (MMIC) Research Group at Plessey Research Caswell, U.K. Since then he held academic posts at King’s College London and the University of Surrey, Surrey, U.K. In June 2004, he was appointed to Centenary Chair in Microwave and Millimeter-Wave Circuits at the University of Leeds, Leeds, U.K. He edited the book MMIC Design (IEE: London, U.K., 1995) and coedited the second edition RFIC & MMIC Design and Technology (London, U.K., 2001). He has published over 350 papers in the areas of MIC and MMIC design.

He is currently the Editor-in-Chief of IET Proceedings—Microwaves, Antennas & Propagation. He has organized many colloquia, workshops, and short courses for both the IEE and IEEE.


He joined Imperial College London, London, U.K., in June 2001, within the Optical and Semiconductor Devices Group, as a Senior Lecturer and was promoted to Reader in 2006. Prior to this, he was a Senior Lecturer at the University of Surrey, Surrey, U.K., within the Microwave and Systems Research Group. Following 12 years of RFIC/MMIC research, he has spent the past five years focusing on RF MEMS. He represents Imperial College within the European Union’s Framework VI Network of Excellence on Advanced MEMS for RF and Millimeter Wave Communications (AMICOM). During summer 2002, he worked as a Guest Researcher, within the MEMS laboratory of the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan. In 2004, he published a review paper on RF MEMS technology, which won an IEE Premium Award in 2005. In recent years he has given five invited presentations on RF MEMS research at international conferences/workshops. He coauthored over 100 publications in the areas of applied physics and engineering.

Dr. Lucyszyn has been an Associate Editor since November 2005, and serves as a Member of the Editorial Board for the IEEE/ASME JOURNAL OF MICROELECTROMECHANICAL SYSTEMS. In 2005, he was elected Fellow of the Institution of Electrical Engineers and a Fellow of the Institute of Physics.