Abstract—In this paper, the design and packaging of fully integrated digitally controlled microelectromechanical system (MEMS) filters with low cost, high performance, and compact size are introduced. The four-channel switched filters operating in the frequency range of 11–20 GHz have been developed using MEMS technologies and four five-pole edge-coupled bandpass filters, which are modified from the traditional edge-coupled bandpass filter in the input and output feeders to achieve a better stopband performance. Microwave filters, MEMS circuits, and related packaging are investigated and demonstrated theoretically and experientially.

Index Terms—Bandpass filter, circuit and packaging codesign, digitally switched filters (SFs), microelectromechanical systems (MEMS), software-defined radio.

I. INTRODUCTION

SWITCHED FILTERS (SFs) are widely used for communication systems with multiple-operation frequency band and frequency-hopping radar systems where high isolation between the filter elements is a requirement. SFs are important to determine if the system will meet the required specifications, particularly the purity of the spectrum. Moreover, in many cases, the performance of SFs limits the performance of the communication system, such as noise figure and linearity. Compared with the multiple-band communication systems using a filtering multiplexer [1]–[3], which need certain protection frequency band between two adjacent channels, the multiband communication systems based on SFs do not require the protection frequency band between adjacent frequency channels. Thus, the spectrum of the SF channels can be continuous or overlapping, and the use of the spectrum is more effective. For SF applications, compact size, light weight, and low material and fabrication costs are essential. The conventional approach for SFs is to machine a series of channels in a metal carrier and to place individual filters inside these channels. An input and output (I/O) switching network of PIN diodes selects the filter response. The conventional design technique suffers from several drawbacks. Low-loss substrate for filters combined with active semiconductor substrates for PIN diodes is expensive to assemble. The discontinuity between the filters and diodes also introduces radiation which can degenerate the channel isolation dramatically. We feel that RF microelectromechanical system (MEMS) switches [4]–[10] integrated with planar microwave filters on the single low-loss substrate into a packaging housing are a possible solution to the cost and isolation problem. It also brings advantages in the reduction of insertion loss and size and in protection of the circuit through codesign of the circuits and the packaging.

This paper presents the design and development of the low-cost fully integrated 11–20-GHz wideband digitally controlled SFs as the topology shown in Fig. 1. The adoption of MEMS switches into the SFs brings the advantages of cost, size reduction, and performance improvement. However, the MEMS device itself is electrostatic-discharge (ESD) sensitive and requires a controlling driving voltage of up to 90 V and special assembling process due to the special IC packaging. The electromagnetic compatibility and isolation requirement among the circuits and from outside environment also bring challenges to deal with the microwave, digital, and control signals, particularly when a packaging housing is introduced. The codesign of circuits and packaging housing adopted in this paper demonstrates an effective approach to cope with the aforementioned design challenges. At the same time, the first spurious of the filter can degenerate the performance of the filter dramatically when it is close to the operating frequency of some other channels of the SFs. We also modified the traditional I/O feeders to improve the stopband performance of the SF. This paper is arranged as follows: In Section II, MEMS switch and its characteristics are introduced. The design and implementation of the four edge-coupled bandpass filters are presented in Section III. The modification in the I/O feeders is...
and the RF path is formed, while when the beam does not contact the drain, the switch is in the “off” status, and the RF path is opened. The benefits and applications of the MEMS RF switches as fundamental building blocks, supplanting the PIN diode and the FET RF switches, are numerous because MEMS switches combine the best features of both, having low control power requirements of FETs (the control current is almost zero) and having on resistances and RF insertion losses that are lower than PIN diodes. Furthermore, MEMS switches have lower OFF-state capacitance and, as a result, better OFF-state RF isolation than either FETs or PIN diodes, and, in addition, have inherently high RF linearity. Intended applications include microwave switches that replace the PIN diode and FET switches while providing lower insertion loss, higher isolation, higher linearity, higher radiation resistance, superior tolerance for high temperature environments, and lower prime power consumption. A common perception is that MEMS devices are susceptible to shock and vibration. If care is taken in the design and packaging, this is not the case. Newton’s second law: force = mass * acceleration allows us to quickly understand why MEMS can be built to survive very large shocks. Their mass is typically on the order of micrograms or less; therefore, even shocks of 1000 G produces only millinewton forces, and suspension that can handle millinewton forces are not that difficult to design for most applications.

Although there are many advantages of the MEMS switch, there are several challenges that need to be handled for the application of the MEMS switch. First, RF MEMS switches are ESD sensitive and can be damaged by static electricity. Using proper ESD precautions is important when handling these devices. Second, since the $V_{TH}$ voltage is very high (up to 90 V), conversion from standard control voltages, such as TTL and CMOS, to high voltage is needed. Introduction of charge-pump circuits is necessary to provide the high $V_{TH}$ but, on the other hand, it affects the switch speed. Third, power handling and switch modes of either cold switching or hot switching are important to determine the lifetime of the MEMS switches. The longest lifetime of the devices and best contact-resistance stability will be achieved under cold-switched and low RF power conditions. The devices are usually operated at a contact force of 200 μN and have a single contact resistance of 3 Ω. The switches typically have eight contacts in parallel to yield a total on-resistance, including interconnects, of less than 1 Ω at dc and low frequencies. The device lifetime is generally measured at a current of 10 mA or less, with the current applied only during switch closure (to avoid hot “breaks” and “makes,” i.e., “cold switched”). Under these conditions, the switch lifetime exceeds $10^{10}$ cycles. Finally, as the dimensions show in Fig. 3, the MEMS switch is an attractive alternative to other mechanical and solid-state switches. As shown in the photograph in Fig. 2(a) and (b), the MEMS switch is fabricated using an all-metal (drain, gate beam, and source are all metals) surface-micromachining process on high-resistivity silicon (substrate below the metals). The main beam is formed by a cantilever, which is a moving part controlled by driving voltage at the gate. When a dc bias voltage is applied between the “gate” and “source,” an electrostatic force deflects the beam toward the substrate. When the bias between the gate and source exceeds the threshold voltage $V_{TH}$, the contacts on the beam touch the drain and complete the circuit between the source and “drain.” When the bias voltage is removed, the beam acts as a spring, generating sufficient restoring force to open the connection between the source and drain, thus breaking the circuit. When the beam contacts the drain, the switch is in the “on” status, and the RF path is formed, while when the beam does not contact the drain, the switch is in the “off” status, and the RF path is opened. The benefits and applications of the MEMS RF switches as fundamental building blocks, supplanting the PIN diode and the FET RF switches, are numerous because MEMS switches combine the best features of both, having low control power requirements of FETs (the control current is almost zero) and having on resistances and RF insertion losses that are lower than PIN diodes. Furthermore, MEMS switches have lower OFF-state capacitance and, as a result, better OFF-state RF isolation than either FETs or PIN diodes, and, in addition, have inherently high RF linearity. Intended applications include microwave switches that replace the PIN diode and FET switches while providing lower insertion loss, higher isolation, higher linearity, higher radiation resistance, superior tolerance for high temperature environments, and lower prime power consumption. A common perception is that MEMS devices are susceptible to shock and vibration. If care is taken in the design and packaging, this is not the case. Newton’s second law: force = mass * acceleration allows us to quickly understand why MEMS can be built to survive very large shocks. Their mass is typically on the order of micrograms or less; therefore, even shocks of 1000 G produces only millinewton forces, and suspension that can handle millinewton forces are not that difficult to design for most applications.

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Fig. 3. Dimensions and the performance of adopted MEMS IC. (a) Top view of SP4T. (b) Side view. (c) Measured performance of switches.

Fig. 4. Filter configurations. (a) Filter layout of traditional I/O feeders. (b) Filter layout with modified I/O feeders.

III. FILTER DESIGN AND RESULTS

Filters are fundamental components in digitally controlled SFs. The stopband characteristics of the digitally controlled SFs are mainly determined by the stopband performance of the filters. There are many kinds of filter topologies in the publications [1]–[3], [11]–[15]. We chose the half-wavelength edge-coupled or parallel-coupled filters with open ends, as shown in Fig. 4(a). The advantages of this type of filters are the via-free layout, relative small size, and good quality factor of the resonator. The design equations for this type of filters are given by [2] and [3]. Odd and even impedance values [4] of the parallel-coupled lines are obtained from the admittance inverter or $J$-inverter parameters $J_{j,j+1}$

$$(Z_{oe})_{j,j+1} = \frac{1}{Y_0} \left[ 1 + \frac{J_{01}}{Y_0} + \left(\frac{J_{01}}{Y_0}\right)^2 \right]$$

$$(Z_{oo})_{j,j+1} = \frac{1}{Y_0} \left[ 1 - \frac{J_{01}}{Y_0} + \left(\frac{J_{01}}{Y_0}\right)^2 \right]$$

where

$$J_{01} = \frac{\pi \omega}{\sqrt{2g_0 g_1}}$$

$$J_{j,j+1} = \frac{\pi \omega}{2\omega_1 \sqrt{2g_j g_{j+1}}}$$

$$J_{n,n+1} = \frac{\pi \omega}{2g_n g_{n+1}}$$

$g_0, g_1, \ldots, g_n$ are the elements of a ladder-type low-pass prototype with a normalized cutoff frequency $\Omega_c = 1$ [2], and $\omega$ is the fractional bandwidth of the filter. $n$ is the number of the filter order, and $Y_0$ is the characteristic admittance of the terminating lines. The initial design results of the coupled line parameters are used as the input parameters for the schematic circuits in the circuit simulator of the Advanced Design System (ADS) 2005 from Agilent Technologies. As an example, a five-pole filter (BPF 1 in the first channel of SFs) with a passband of 11–13.6 GHz is designed. The calculated parameters are the following: $\omega = 0.21, g_0 = g_5 = 1, g_1 = g_6 = 1.1468, g_2 = g_4 = 1.3712,$ and $g_3 = 1.9752.$ Following (1) and (2), the even- and odd-mode impedances for the coupling lines can be determined. For the microstrip filter constructed on the substrate with a relative dielectric constant of 2.2 and thickness of 10 mil, the dimensions of the coupling microstrip lines and the related effective even- and odd-mode dielectric constant of $\varepsilon_{re}$ and $\varepsilon_{ro}$, respectively, can be determined [2]. The actual length of each coupled line section are then determined by

$$l_j = \frac{\lambda_0}{4 \left(\sqrt{(\varepsilon_{re})_j \times (\varepsilon_{ro})_j}\right)^{1/2}}.$$ 

The calculated coupling dimensions and lengths are used as the initial input for ADS optimization. The optimized result is shown in the curve marked as traditional in Fig. 5. The bandpass filter operates in the 11–13.6-GHz range, and the first spurious appears to be two times the fundamental frequency, i.e., around 22–27.2 GHz with bad attenuation. To improve the rejection in the first spurious, a cross-stub feeder, as shown in Fig. 4(b), is introduced in the I/O feeders. From the simulation results shown in Fig. 5, the cross stubs in Fig. 4(b) have two functions, i.e., I/O matching and suppression of the spurious. In contrast, the two filters shown in Fig. 4(a) and (b) have the same dimensions except for the cross-stub portions in Fig. 4(b) with the dimensions of $W$ and $L$ shown in Fig. 5. It can be seen that the cross stubs have high rejection on the first spurious of up to 56 dB. Fig. 6 shows the simulation and the measurement results of BPF 1 in the first channel or Channel 1 of the SFs.
in Fig. 1. The filters inside the digitally controlled SFs consist of five edge-coupled bandpass filters with modified I/O feeders printed on a Rogers RT5880 substrate with a thickness of 10 mil. Fig. 6 shows the simulation and the measurement results of Filter 1 in the first channel or Channel 1 of the SF in Fig. 4(a). The rejection in the first spurious is improved by 25 dB as compared with that of the traditional design in Fig. 4(a). Filter 1, operating from 11 to 13 GHz, has an insertion loss at the center frequency of 1.9 dB and a flatness of ±0.3 dB. The simulation and measurement results well agreed in both the passband as well as the stopband. It is an acceptable difference between the simulation and measurement when the rejection is more than −40 dB. The differences are from the discontinuities and mutual coupling of the test fixtures (The universal substrate test fixtures WK-3001-B from Microwave Intercontinental Inc. are used for the I/O port connections for measurement of the four bandpass filters.). This can also be seen from the SF results to be given later on. The same design approach is used for the design of the other three filters of the SF in Fig. 1. The center operating frequencies are 14.2, 16.2, and 18.2 GHz, respectively. The measured transmission and reflection results of the four filters are shown in Figs. 7 and 8, respectively. The passbands of Filter 2, Filter 3, and Filter 4 cover the frequencies of 12.6 GHz–15.9 GHz, 14.4–18 GHz, and 16.3–20 GHz, respectively. The middle-band insertion losses for the four filters are better than 2.1 dB. The return losses in the passbands for the four filters are better than 10 dB.

IV. CODESIGN OF SFs AND PACKAGING

The 11–20-GHz-MEMS SF is one of the building blocks in our 2–30-GHz wideband software-defined radio system cofounded by the Defense Science and Technology Agency of Singapore and ST Electronic (SatcomS). The choice of the scheme is based on system requirements obtained from the system-link budget calculation and cost consideration. The block diagram of the filter-bank module is shown in Fig. 1. The filter-bank module consists of four wideband filters as introduced in the previous section and two MEMS SP4T switches. The four different channels are selected by “A” and “B” with TTL logic level of either “0” or “1.” The I/O ports of the filters are connected to SP4T switches. It is found that when the requirements of the stopband is more than 40 dB, there exists an interference among the microwave signal, dc signal, and digital control signal, as well as the interchannel interference. To solve this issue and form a compact module with good performance, codesign of the circuits and packaging is necessary. The perspective view of the designed mechanical housing is shown in Fig. 9. To avoid pickup among the signals, in the mechanical box, the RF portion and dc and control portion are in two different air boxes Ht and Hb, respectively, and separated by a middle metal wall with height of Hm in Fig. 9. The control signals are from the digital board to the RF board through the feed-through capacitors, which is screwed in the mechanical housing, and to avoid the ESD issue from the dc supply and control-circuit parts. Since the SF module is required to have a standard control interface with TTL control
voltages, the conversion from TTL to 90 V for MEMS driving is needed. As shown in Fig. 10, the charge-pump circuits and digital driving circuits are adopted. The 90-V voltage is generated by using the switched regulator together with the Dickson charge-pump circuits, as shown in Fig. 10(a). The digital driving circuits convert the 2-bit TTL control logic to the four output control ports with driving voltages of either 90 or 0 V, corresponding to the on or off statuses of the MEMS switch for the channel selections. The dc and control circuits are designed on the FR4 board and assembled at the bottom side, i.e., Hb side, of the mechanical housing. The implemented circuit board at the bottom side of the mechanical housing is shown in the photograph in Fig. 11. The connection of the dc and digital board to the RF board is through the eight feed-through capacitors assembled on the inner metal wall of the housing.

To avoid unnecessary discontinuities, which can increase the passband insertion loss and dramatically affect the stopband performance of the SFs, the whole RF circuitry, including the four filters and two RF MEMS switches, are assembled on the same board which is glued to the surface of the mechanical alumina carrier. As shown in Fig. 3(a) and (b), to keep the board thickness similar to the thickness of the MEMS switch, IC is important for process control of the IC attachment and wire bonding. The MEMS IC is attached to the carrier at the place where the board is cut through according to the dimension of the MEMS IC. At the frequency above 10 GHz, keeping the shortest length of bonding wire and making the bonding pads of the board and IC with the same height are key factors to get good RF performance. On the other hand, there are nine pads, as shown in Fig. 3(a), which need to be bonded to the RF boards. Maximizing the spaces among the RF traces and dc traces on the RF board are important to achieve good isolation among different channels. The inner metal walls among the different channels are designed purposely to reduce interference among the different channels and get good RF spectrum purity. With the characteristics of the filters and MEMS switches known, we design and layout all the RF circuitry, including the four filters and two MEMS SP4T switches, on the same RT Duriod 5880 substrate with thickness of 10 mil in the packaging housing, as the photograph shows in Fig. 12. The control voltage is standard TTL logic voltage. From our investigation, codesign of circuits and packaging is good to avoid unnecessary discontinuities.
among the switches and the filters, pickup noise, and cochannel interferences and make the SFs more compact.

The measured transmission and reflection results of the SFs are shown in Figs. 13 and 14, respectively. The measured insertion losses for the four channels of the SFs are 3.6–4.3 dB for Channel 1, 3.8–4.4 dB for Channel 2, 3.7–4.6 dB for Channel 3, and 3.6–4.7 dB for Channel 4. The rejection in the whole frequency range from 5 to 26 GHz, except for the passband, is better than 45 dB. The return losses in the passband of each channel are better than 10 dB, as shown in Fig. 14. The module can support the dc power supply from 5 to 15 V. The two control digital bits are compatible with the standard TTL voltage. The RF I/O ports are standard 2.92 K connectors. The performance of the MEMS SFs module is summarized in Table I.

V. FURTHER DISCUSSION

Through the comparison between Figs. 7 and 13, it is difficult to see the difference between the filters and the SFs, particularly in the insertion loss. To illustrate these differences for comparison of the losses generated due to the MEMS switches and integration, the transmission characteristics of Filter 4 and Channel 4 of the SFs are compared in Fig. 15. Since the filter in Channel 4 is the same filter as Filter 4, an additional 1.7-dB loss of the SFs is introduced from the integration of the filters with the MEMS switches in a packaging housing. It is reasonable that the two MEMS switches generate the loss of 0.8–1.2 dB, and the other 0.5 dB–0.9 dB is generated from the connectors and the RF trace loss of the board for interconnects. Through the comparison of the stopband performance of the filter and the SFs, it is clearly seen that the integration and packaging keep a very good performance of the filter, particularly in the stopband.

In Fig. 15, the SFs results, which are based on solid-state switches (MMIC switches of HMC347 from Hittite) are compared with the SF with MEMS switches. The insertion-loss improvement is around 8 dB by using the MEMS switches. Fig. 16 shows the photograph of the MEMS SFs and the solid-state filters contrasted against the ruler. The size of the MEMS SFs modules is dramatically reduced (more than 50%) compared with that of solid-state SFs module.

VI. CONCLUSION

In this paper, we have presented the circuit and packaging codesign and implementation of a compact and low-cost high-performance SFs module by using MEMS technologies. The design and consideration of the filter performance improvement and SFs have been extensively investigated. Good results in both passband and stopband for filters and SFs are demonstrated. The measured insertion loss of the designed SFs in the whole band from 11 to 20 GHz is around 3.4–4.7 dB, with passband flatness of less than 1.1 dB. The size of the SF module is only 83 mm × 66 mm × 34 mm.
Fig. 16. Photograph of implemented switch filters: (left) MEMS SFs and (right) solid-state SFs.

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