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Monolithic Integrated Design of S-Band Switched Filter Bank Based on LTCC Technology

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Abstract—A S-band monolithic integrated switched filter bank has been designed to realize tunable working center frequency, and a tuning range of 12.9% from 2.7 to 3.05 GHz was achieved with interval of 50 MHz. The switched filter bank is designed using 8 eighth-order step impedance resonators (SIR) band-pass filters arranged in parallel rows. Microelectromechanical Systems (MEMS) switched circuit is integrated above filters for monolithic design combined with low temperature co-fired ceramic (LTCC) technology. The SIR bandpass filters are designed to resist Electromagnetic Interference (EMI) between components and introduce cross coupling to bring two transmission zeros and better out-of-band rejection. The monolithic integrated switched filter bank is only 74 mm $\times$ 24 mm $\times$ 2.5 mm, which realizes the monolithic integration of the device and enhances the reliability. The measured results show that the insertion loss and out-of-band rejection are in good working condition.

1. INTRODUCTION

Filter, as an important passive component, is an indispensable part of the RF circuit [1–3]. With the development of communication technology, the requirements of the performance about filters are increasing. Traditionally, filters which work in a single working center frequency are unable to meet the needs of today's rapid development of information technology. Achieving tunable working center frequency is one of the effective ways to improve communication efficiency.

In recent years, the academic study about realizing tunable filter working center frequency has also been one of the important directions for researchers. In 2005, Reines et al. developed a switched Ku-band filter bank using two single-pole triple-throw (SP3T) microelectromechanical systems (MEMS) switching networks and three end-coupled bandpass filters, and a tuning range of 17.7% from 14.9 to 17.8 GHz was achieved with a fractional bandwidth of $7.7 \pm 2.9\%$ and insertion loss ranging from 1.7 to 2.0 dB [4]. In 2011, Schulte et al. changed filter microstrip size by means of Microelectromechanical Systems (MEMS) switches, and a filter with optional frequency was proposed with a center frequency of 630 MHz and a tunable frequency range of 537 MHz–728 MHz, and insertion loss between 2.5 dB and 5.5 dB [5]. In 2013, Inoue et al. introduced a tunable frequency filter with an optional frequency range of 1.4 GHz to 2.7 GHz, and insertion loss is less than 3 dB by adjusting the filter geometry with MEMS technology [6]. In 2015, Arabi et al., who took advantage of the performance of LTCC material by increasing the magnetic winding method to change the electrical parameters of the filter, proposed a filter with frequency modulation of 4% and insertion loss performed better than 2.3 dB [7].

In general, the design of the tunable filters generally has the following four methods: (1) To change the electrical parameters of the filter; (2) To change the geometry of the filter; (3) To change the filter on and off state; (4) To change the transmission phase speed to change the operating frequency. In [3], the

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third one was implemented to tunable filters design. The authors in [5, 6] used the method of changing the geometry of the filter to achieve frequency modulation. By changing the electrical parameters of the filter to achieve the effect of change the operating frequency is presented in [7]. In this paper, the proposed switched filter bank controls filters on-off state to achieve the purpose of frequency selection through the filters' designed upfront. Compared with three other methods, the method in this paper achieves tunable setting filters more easily; the actual operation is easier; the speed of selection is quicker; selection is more accurate for special value. The whole filter bank operates in the S-band, and the structure is simple and uses increasingly mature LTCC process for switched filter bank monolithic integrated design, ensuring the proposed switched filter bank miniaturization feature and enhanced reliability.

2. WORKING PRINCIPLE OF SWITCHED FILTER BANK

The switched filter bank controls filters on-off state to achieve tunable frequency, which consists of input switched chip, output switched chip and filter bank. A schematic diagram of the switched filter bank is shown in Figure 1. Two RF-MEMS (Radio Frequency-Microelectromechanical Systems) switched chips are chosen as the switched chips in this work. RF-MEMS chips are commonly implemented in wireless infrastructure such as a cell phone base station and point-to-point radio frequency (RF) front end with their good characteristic, such as responding time, insertion loss, and switching isolation. In this design, the RF-MEMS chips play an important role as the core control devices to make up the switched system of the switched filter bank. For designing the eight-channel switched filter bank, an SP8T switch is necessary to control radio frequency signals for the eight-way switched circuit, and appropriate chips bring much convenience to perform any on-state in the passband filters according to input chip with high and low power levels. In other words, the filter bank is also indispensable in this work. The filer bank containing eight eighth-order Step Impedance Resonator (SIR) bandpass filters is designed for making frequency tunable. All the center frequencies are differently distracted in S-band range of 2.7 GHz–3.05 GHz. Each filter center operating frequency is separated by 50 MHz, and bandwidth is 200 MHz. For example, when the center frequency of 2.7 GHz is the frequency that we want, setting input channel 1 corresponding to the high and low levels, drive the first input MEMS switch, and the first output switch is turned on correspondingly, so that the other input and output switches are off. At this time, the first switched filter performs in a working state. Due to the corresponding input and output switched settings, the other road filters refuse working and keep in the off state.

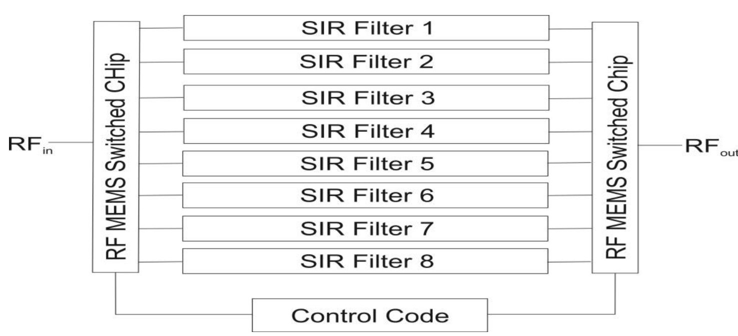


Figure 1. Schematic diagram of the switched filter bank.

3. DESIGN OF SWITCHED CIRCUIT AND MONOLITHIC INTEGRATED

3.1. Design of Switched Circuit

Switched circuit is implemented to control the switched filter bank to select the operating frequency for important components, which has a direct impact on the entire switched filter bank. Response time and insertion loss of the whole switched filter bank always depend on the performance of switched circuit in a large part. Whether a filter is selected correctly or not is also associated with the performance of switched circuit. In order to achieve the best system performance, the proposed switched circuit uses two HMC321LP4 chips as switched chips, and HMC321LP4 chip is an 8-channel controlled switched chip by receiving electrical signals to control RF (Radio Frequency) signal through needed bandpass filter. This switched chip can select only one filter working at a time. The working range of this switched chip contains DC-8 GHz in line with the S-band working requirements, and nanosecond level switched response speed is another highlight. High response speed provides fast frequency selection, so this chip can provide the conditions that we need. In the S-band, the insertion loss of HMC321LP4 chip is less than 2.5 dB, and its curve is very flat as shown in Figure 2. The chip also has excellent switching isolation, and its value is greater than 30 dB from DC to 5 GHz. This switched chip which can be used with LTCC products for surface mounting is small with size of only 4 mm $*$ 4 mm $*$ 1 mm which ensures the ability of high integration. Generally, HMC321LP4 chip is a good choice for the design of integrated switched filter bank.

Figure 3 shows the switched circuit schematic, where N1, N2, respectively, represent two HMC321LP4 chips. The eight bandpass filters are connected by eight pins of the two chips, CH1–

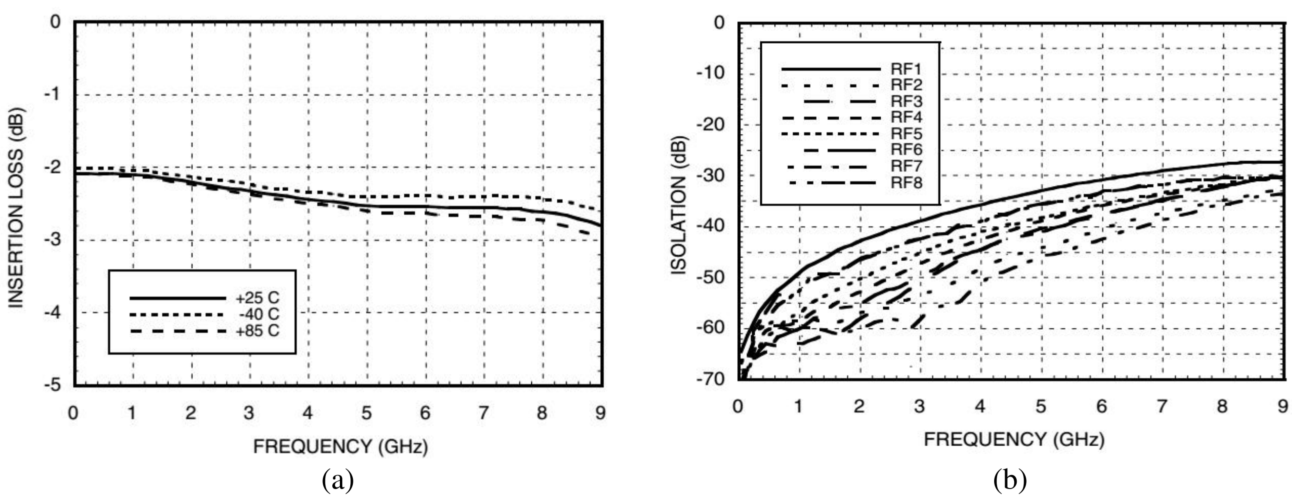


Figure 2. Insertion loss of HMC321LP4 RF MEMS chip. (a) The insertion loss of RF MEMS chip. (b) The isolation loss of RF MEMS chip.

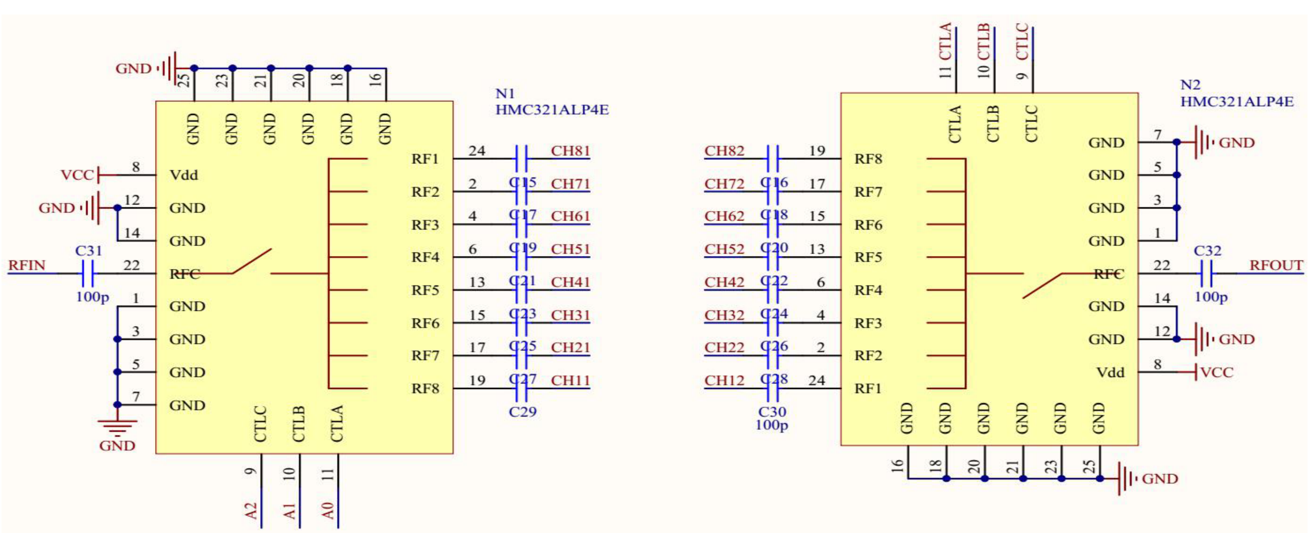


Figure 3. The simple diagram of the switched filters circuit.

Table 1. Control code of switched chip.

Filters		Control Code		
		A	A1	A2
CH1	2600 ∼ 2800 MHz	0	0	0
CH2	2650 ∼ 2850 MHz	1	0	0
CH3	2700 ∼ 2900 MHz	0	1	0
CH4	2750 ∼ 2950 MHz	1	1	0
CH5	2800 ∼ 3000 MHz	0	0	1
CH6	2850 ∼ 3050 MHz	1	0	1
CH7	2900 ∼ 3100 MHz	0	1	1
CH8	2950 ∼ 3150 MHz	1	1	1

CH8. Pin 22 is for the RF signal input and output. With the control voltage level shown in Table 1, 1 is for the high voltage level, 0 for the low voltage level, through the pins 9, 10, 11 input control levels to complete filter channel control. All active devices use +5 V DC power supply, switched chip control for high +2 ∼ +5 V and low level 0 ∼ +0.8 V. Use SN74LVC3G04DCT chip as the inverter, N1 chip control code input to the inverter, converted to N2 chip control code to control the N2 chip gating. So only through the three control codes A0, A1, A2 can simultaneously control the two switched chips and eight switches on or off, thus achieve the purpose of selection in eight filters.

3.2. Design of Filter Bank

Filter bank is undisputed another important part of switched filter bank. Monolithic integrated design should be considered as the first important point when we start the design. Simple structure becomes the best choice to meet our need. The SIR bandpass filter is preferred because of its simple structure which can be realized based on the LTCC technology. Traditional $\lambda/4$ SIR filter possesses two different impedance transmission lines as shown in Figure 4. The open stub is equivalent to capacitance, and the shorted stub is seen as inductance. Z_1 and Z_2 represent the impedance of shorted stub and open stub in $\lambda/4$ SIR filter, where θ_1, θ_2 represent equivalent electric lengths, respectively. The impedance ratio R_z is described as:

$$R_z = Z_2/Z_1 \tag{1}$$

And the resonance condition of $\lambda/4$ SIR filter is described as:

$$Z_2 - Z_1 \tan\theta_1 \tan\theta_2 = 0 \tag{2}$$

So that:

$$\tan\theta_1 \tan\theta_2 = R_z \tag{3}$$

From Equation (3), smaller size of the SIR filter will be realized if we configure smaller R_z parameter. However, when the value of parameter R_z is changed to smaller, the width of low impedance line is too large relative to the high impedance line width according to Equation (1), and the miniaturization of the eighth-order SIR filter will be affected. In this work, a folded structure is utilized for smaller-sized design, and much high capacitance value can be realized when the two-layer SIR, depicted in Figure 5, is applied. The top layer is an SIR transmission line with one side for ground; another side keeps open stub; bottom layer is a homogeneous impedance transmission line connected to ground side. Moreover, the folded part forms a coupled capacitance, and the value can be calculated by $C = sWl/d$. Compared with traditional SIR structure, this structure has a constant coupled capacitance, so a compact and clear structure is obtained.

Figure 6 shows the 3D structure of the eighth-order filter designed with the three-dimensional electromagnetic field simulation software HFSS. Each order is designed with the folded structure SIR mentioned above. The high order of eight orders also provides a good out-of-band rejection for the filter. The method of increasing the cross-feedback capacitance to the first and last steps introduces

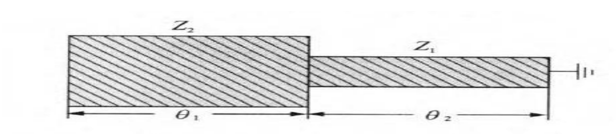
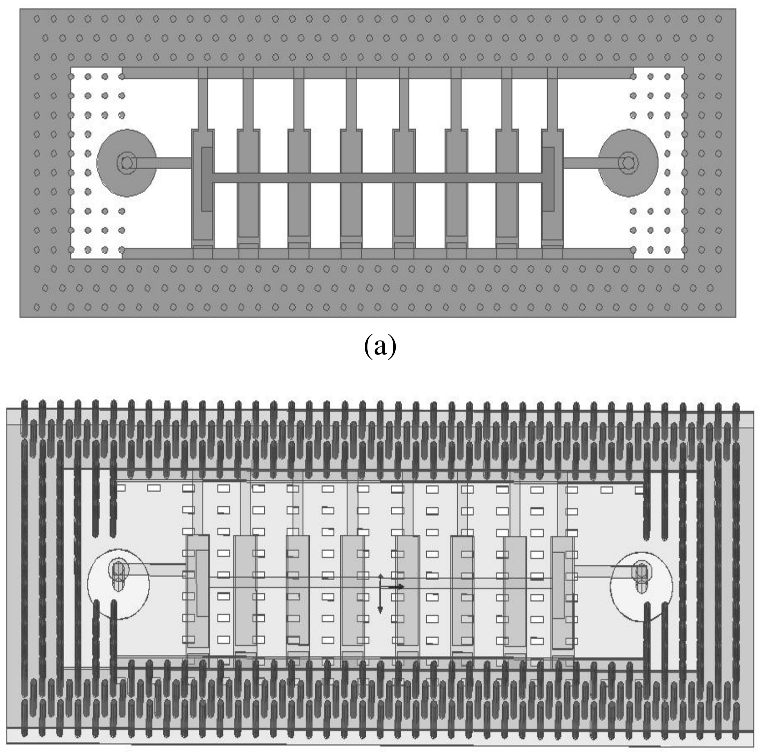


Figure 4. The structure of traditional $\lambda/4$ SIR filter.

Figure 5. The fold structure of $\lambda/4$ SIR filter.



(a)

(b)

Figure 6. Model of eighth-order SIR bandpass filter. (a) Top view of the SIR bandpass filter. (b) Side view of the SIR bandpass filter.

the out-of-band poles which make the effect of out-of-band rejection more obvious. The RF signal is input and output through the left and right two circular electrodes, and the input and output electrodes co-planar design provides a convenient method of the through-hole connection for monolithic integrated design.

In the actual use of the switched filter bank, eight eighth-order SIR filters are placed in a line with the smallest possible room for integrating, and the electromagnetic interference between the filters is a problem which should be taken into account. In this paper, some through-hole columns are added around the SIR filters as shown in Figure 6. The through-hole columns connect the upper and lower plates to act as barrier to prevent electromagnetic interference between the devices, and electromagnetic wave will be constrained in the special area for propagating as shown in Figure 7(a) which depicts the movement of electromagnetic wave in this eighth-order filter. Almost all of the electromagnetic wave is constrained in the cage built by through-hole columns, and it will be good for resisting electromagnetic wave which makes accidental leakage away the filters that affects formal working condition of other filters.

The size of this eighth-order SIR bandpass filter contained through-hole columns is $22\,\mathrm{mm} * 9.6\,\mathrm{mm} * 2\,\mathrm{mm}$. With three-dimensional electromagnetic simulation through the HFSS software, the simulation

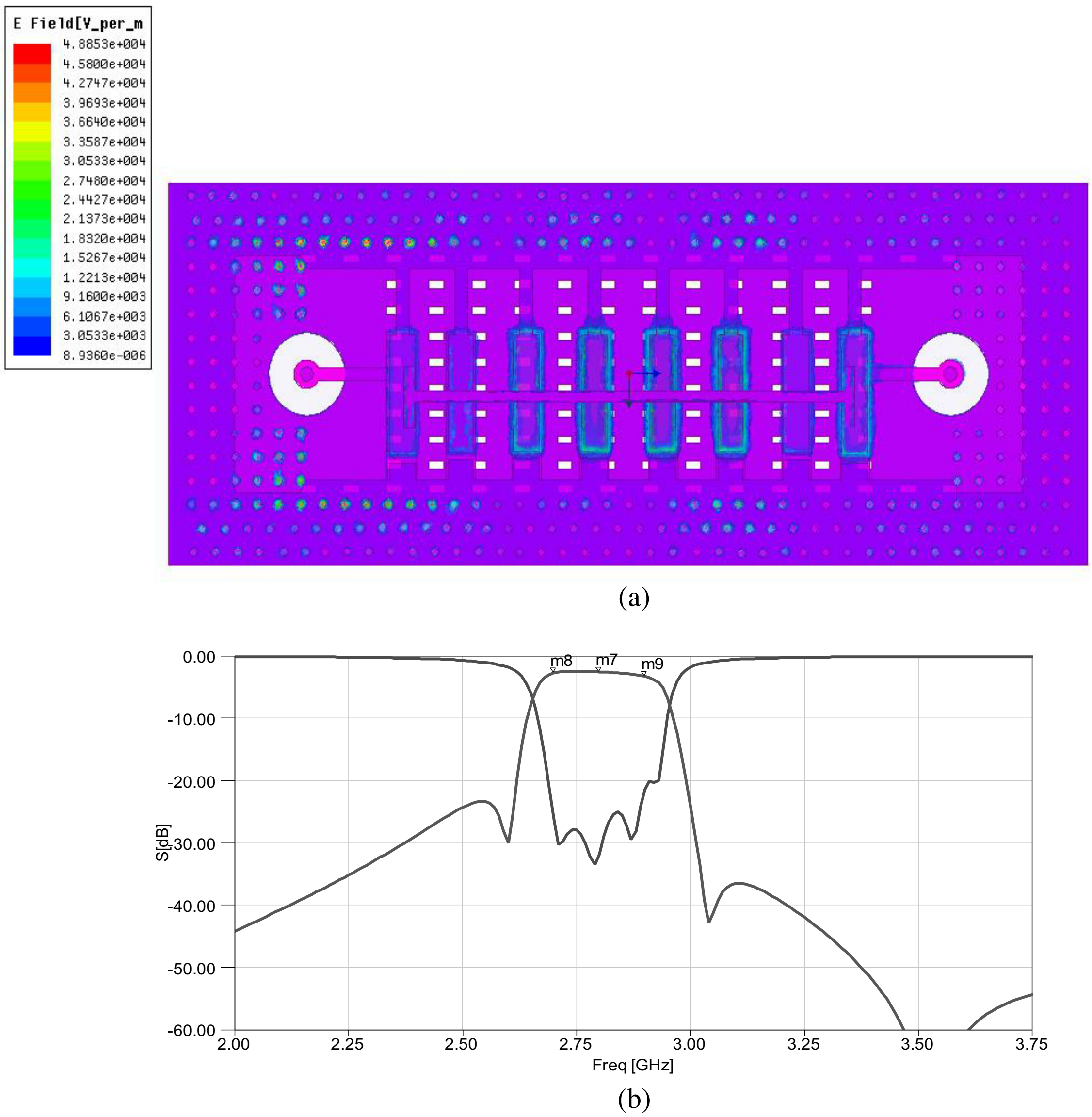


Figure 7. Simulated results of eighth-order SIR bandpass filter. (a) The diagram of electromagnetic field distribution. (b) The S parameters simulated results of eighth-order SIR bandpass filter.

data are shown in Figure 7(b). The center frequency is 2800 MHz, passband insertion loss less than 2.2 dB, bandwidth 200 MHz, out-of-band rejection 29.6 dB@2600 MHz, 42.8 dB@3040 MHz, and in-band return loss greater than 20 dB.

3.3. Design of Monolithic Integrated

LTCC technology is currently one of the important technical means for small, highly integrated design of passive devices. We combine printed circuit board layered design and LTCC technology, so that the previous circuit in the printed plate can be realized into the LTCC process, the layers of the circuit through the vertical through-hole interconnected, designed monolithic integrated switched filter bank based on the LTCC process.

Monolithic integrated design of the switched filter bank is shown in Figure 8, and the figure shows the layer distribution of monolithic integrated switched filters. Layer_a represents the dielectric layer.

Layer_a_Via_b, where a represents the number of dielectric layers, and b represents the number of layers which vertical through-hole need to pass. Silver_c represents the metal buried layer in the LTCC process. Silver_1 to Silver_4 are metal buried layers for the switched circuit part, and Silver_1 to Silver_4 layers correspond to the printed circuit shown in Figure 6. Silver_4 to Silver_8 are metal buried layers for the filter device part. Eight eighth-order SIR bandpass filters are arranged horizontally. Silver_4 layer is the common ground plate of circuit and filter when it is designed. In summary, the monolithic switched filter bank consists of 28 layers of dielectric layer, 8 layers of metal buried layer, dielectric layer thickness of 93 μm, metal buried layer thickness of 10 μm, and the overall thickness of the device is 2.6 mm.

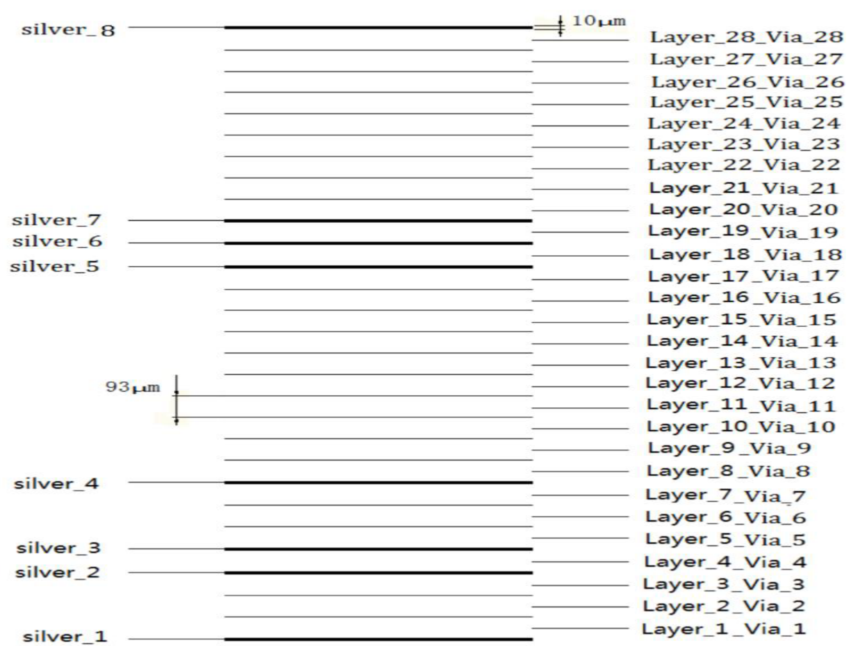


Figure 8. The structure of monolithic integrated switched filters.

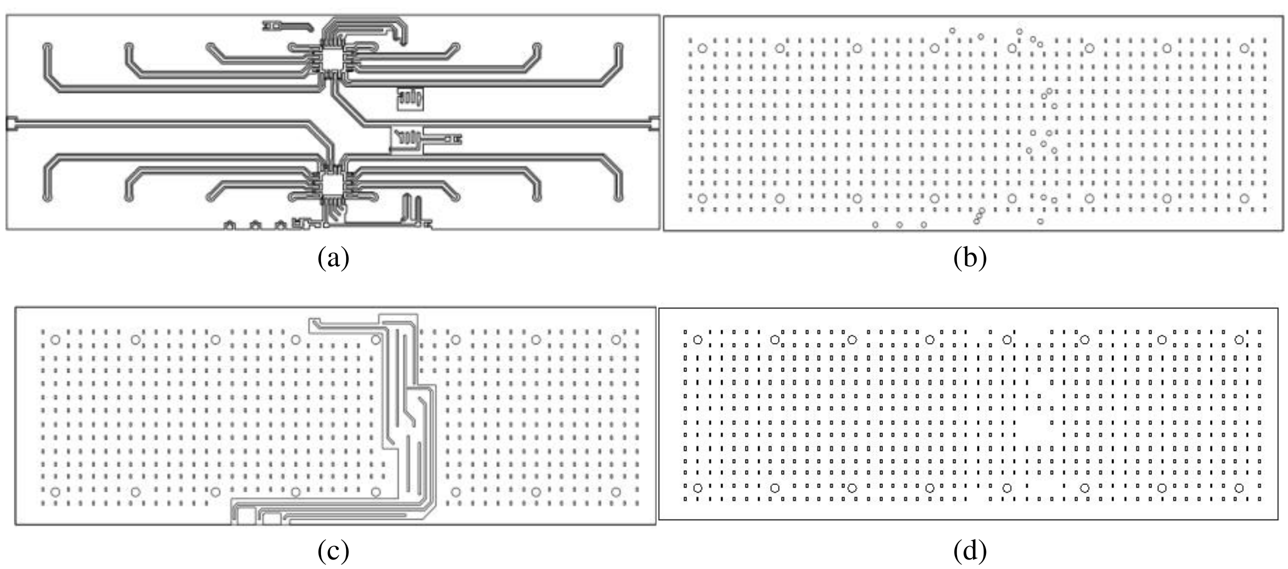
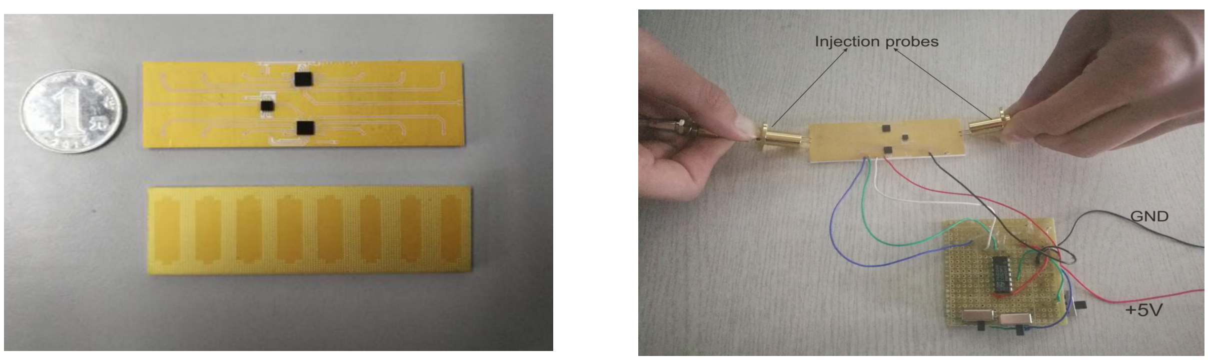


Figure 9. Layout of four layers printed circuit. (a) Layout of Silver_1 printed circuit. (b) Layout of Silver_2 printed circuit. (c) Layout of Silver_3 printed circuit. (4) Layout of Silver_4 printed circuit.

4. TEST AND ANALYSIS

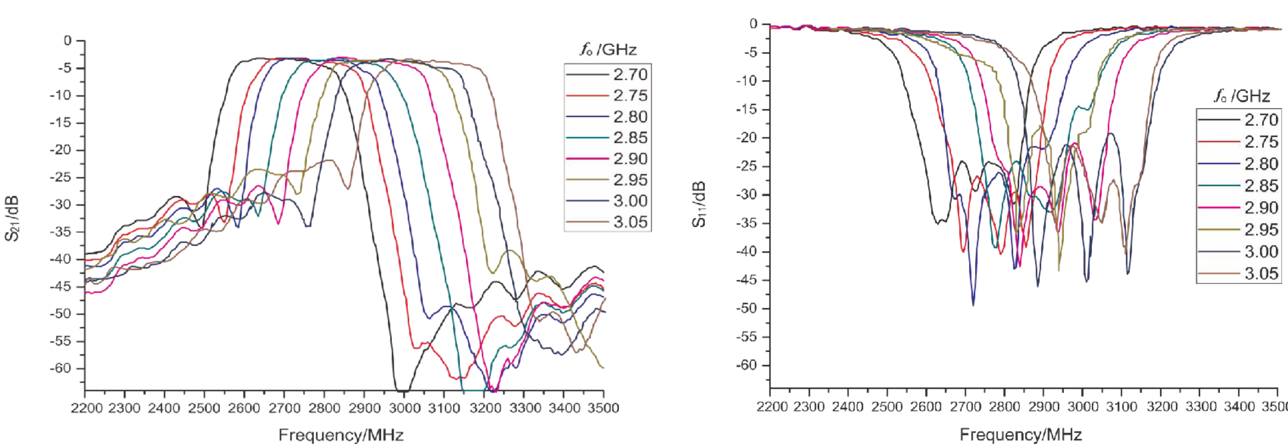
Combined with the design method mentioned above, we design a monolithic integrated eight-channel switched filter bank. Using dielectric material Ferro-A6 as a ceramic material for actual processing, this ceramic material thickness is 93 μm after sintering. Au has better conductivity and reliability than silver, so we choose Au as the metal buried layer for circuit design. Based on the actual processing of the LTCC technology, the monolithic integrated design of the switched filter bank integrates eight SIR bandpass filters. Switched circuit is shown in Figure 10, and the integrated size is 74 mm × 24 mm × 2.5 mm. This monolithic switched filter bank enables miniaturization of the filters and enhances the reliability of the filter bank. With the chips labeled on the surface, monolithic integrated switched filter bank is achieved.

The testing preparation is made as shown in Figure 10(b). The power supply is offered by a DC voltage source and the injection probes is connected to the network analyzer Agilent 8753ES by coaxial cable to get measured results. After the actual testing, the given actual tested results are shown in Figure 11. All the states are selected. Measured results show that the center working frequency of all eight filters remains stable from 2.7 GHz to 3.05 GHz with interval of 50 MHz, and bandwidth keeps 200 MHz for each filter. The insertion loss of all the bandpass filters almost remains less than 5 dB as shown in Figure 11(a), and the in-band return loss is greater than 15 dB as shown in Figure 11(b). The



(a) (b)

Figure 10. The prototype and testing preparation of switched filter bank. (a) The prototype of switched filter bank. (b) The testing preparation of switched filter bank.



(a) (b)

Figure 11. Measured results of switched filters. (a) S_{21} curve of eight bandpass filter. (b) S_{11} curve of eight bandpass filter.

out-of-band rejection in lower frequency is almost better than 25 dB for each filter, and the out-of-band rejection in higher frequency is better than 40 dB. In summery, no significant changes appear compared with the expected results, and the insertion loss of the actual measured results is 3 dB higher than those of the simulation. This is because the RF-MEMS switched chip itself has insertion loss, which can be learned from Figure 2(a), and welding inserts loss becomes another reason of insertion loss. Overall, the switched filter bank presents high reliability; performance remains stable; no serious electromagnetic interference phenomenon appears between the components.

Little research of monolithic integrated design of S-band switched filter bank based on LTCC technology has been reported. So firstly the design in this paper is compared with the the designs of tunable filters using different methods in [4–7]. The design in this paper offers more channels for selecting than the three-channel switched filter bank based on MEMS technology, but the size of MEMS design is the advantage that LTCC cannot achieve. Compared with the designs in [5–7], the design in this paper has fast switched response speed. More accurate selection can be made with larger tunable range, and the good out-of-band rejection can be obtained. This monolithic integrated design of S-band switched filter bank based on LTCC technology creates a more convenient and accurate condition for the research topic of tunable filters.

In Table 2, the design in this paper is also compared with four other switched filter banks. The switched circuits of the four switched filter banks in [8–11] are designed using RF MEMS chips or PIN diodes, and the whole switched filter banks are designed based on silicon substrate or PCB technology. Compared with the four other switched banks, the design in this paper offers 8 channels for frequency selection, and more selections can be realized by using this filter bank. The size of this design is smaller than those four filter banks, and a more monolithic integrated design can be obtained. The method in this paper creates a smaller size for the monolithic integrated design of switched filter bank. This design fully confirms the practicality of the monolithic integrated switched filter bank based on LTCC technology.

Table 2. The comparison of the design in this paper with another four switched filter banks.

Reference	Methods	Channel Number	Size (mm)	Tuning Range (MHz)
[8]	RF MEMS + PCB	2	$66 * 30 * 30$	2393–2503
[9]	RF MEMS + PCB	3	$71.1 * 1.6$	740–1644
[10]	RF MEMS + Silicon	3	$38 * 27 * 10$	6700–9700
[11]	PIN + PCB	4	$95 * 101.6$	4050–4470
This paper	RF MEMS + LTCC	8	$74 * 24 * 2.5$	2700–3050

5. CONCLUSION

A monolithic integrated switched filter bank based on LTCC technology is designed. The switched filter bank integrates the switched circuit and SIR band-pass filters of S-band to realize the single-chip integrated design of the switched filter bank. Through labeling RF-MEMS chips on the surface to realize switched control, any filter of the eight filters in band of 2700 MHz–3050 MHz can be selected to work according to the needs. The design of the bandpass filter solves the problem of serious electromagnetic interference between components. In this paper, the bandpass filters design is not limited to 2700 MHz–3050 MHz frequency band, and other filters can be chosen according to your need for filter selection. More suitable switched chip can also be selected according to the actual needs for the design of a multi-channel switched circuit.

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