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A MILLIMETER-WAVE ULTRA-WIDEBAND FOUR-WAY SWITCH FILTER MODULE BASED ON NOVEL THREE-LINE MICROSTRIP STRUCTURE BAND-PASS FILTERS

Z. Wang, Q. Lai, R. Xu, B. Yan, W. Lin, and Y. Guo

School of Electronic Engineering
University of Electronic Science and Technology of China
Chengdu, Sichuan 610054, China

Abstract—This paper presents a millimeter-wave ultra-wideband four-way switch filter module integrating six building blocks including four band-pass filters and two switches. The switch filter module works at whole Ka-band (26–40 GHz) and consists of four wideband band-pass filters and two monolithic microwave integrated circuit (MMIC) single pole four throw (SP4T) switches. The four wideband band-pass filters are realized by a novel three-line microstrip structure band-pass filter. Compared with the traditional three-line filter, the proposed three-line filter not only retains virtues of traditional three-line filter, but also resolves drawbacks of it, which include discontinuities between adjacent sections, many parameters of design, and no effective matching circuits at input/output ports. The proposed three-line filter is validated by electromagnetic simulation. The developed switch filter module is fabricated using hybrid integrated technology, which has a size of 64 mm × 44 mm × 7.5 mm. The fabricated switch filter module exhibits good performances: for four different states, the measured insertion loss and return loss are all better than 8.5 dB and 10 dB in each pass-band, respectively.

1. INTRODUCTION

Recently, millimeter-wave has become important working frequency of electronic technology development and is widely applied to radar, wireless communication and electronic antagonism. Growth of these technologies requires excellent performance and high level of

Corresponding author: Z. Wang (zgwang@ee.uestc.edu.cn).

integration for transmitter, receiver and transceiver modules [1–12]. Switch filter module is the crucial part of some transceivers, especially for transceiver in electronic antagonism, so researches for switch filter module are very important. Obviously, band-pass filters are the most significant components in these modules.

In response to multifarious applications, numerous publications have dealt with the development of diversified filters, such as planar microstrip filters [13], metal cavity filters [14], substrate integrated waveguide (SIW) filters [15], three-dimensional (3-D) low temperature co-fired ceramic (LTCC) filters [16] and dual-mode filters [17]. The microstrip parallel coupled-line filter has been one of the most commonly used filters for several decades [18, 19]. Major virtues of this kind of filters are their planar structure. But, there are also drawbacks for this kind of filter; the most important one of which is the small line spacing of the first and last coupling stage for wideband band-pass filter. Unfortunately, the smallest line spacing is limited by process technology. For overcoming the drawbacks of the traditional parallel coupled-line filters, the three-line filter is proposed [20, 21]. The proposed three-line filter has the following two important features: the tight line spacing of end stages can be relaxed, and the stop-band rejections are also improved. However, the traditional three-line filter has discontinuities between adjacent sections, many parameters of design, and no additional matching circuits at input/output ports resulting in unfavorable pass-band matching performance.

In this paper, a millimeter-wave ultra-wideband four-way switch filter module is proposed. The switch filter module covers whole Ka-band (26–40 GHz) and consists of four band-pass filters and two SP4T switches. In order to meet the requirements of the module, a novel three-line filter is proposed. Compared with the traditional three-line filter, the proposed three-line filter has three important improvements as follows: avoiding the discontinuities between adjacent sections, decreasing parameters of design (especially for many-pole), and enhancing pass-band matching performance by joining matching networks of diamond structure at input/output ports. The proposed filter also retains virtues of the traditional three-line filter. But, the proposed filter structure also has two limitations: firstly, the spurious pass-band could be closer to the working pass-band than the traditional one for adopting the uniform line width adjacent sections; secondly, since the number of design parameters is decreased, this could add the mutual influence among the structure parameters, which leads to greater difficulty of the optimization process. According to requirement of the switch filter module, four three-pole three-line microstrip structure band-pass filters are designed. Employing these four filters and two MMIC SP4T switches, the switch filter module is fabricated, and excellent performances are obtained.

2. DESIGN OF FILTERS

The block diagram of the four-way switch filter module is developed as shown in Fig. 1. It can be seen that the switch filter module is composed of two SP4T switches and four band-pass filters. The two SP4T switches adopt MA4AGSW4 of MA/COM. The four wideband band-pass filters need to include four different pass bands, which are 26–30 GHz, 30–34 GHz, 34–38 GHz and 38–40 GHz, respectively. The selection of passbands is based on the scheme of whole transceiver system. In this paper, the four filters are designed using three-pole three-line microstrip structure.

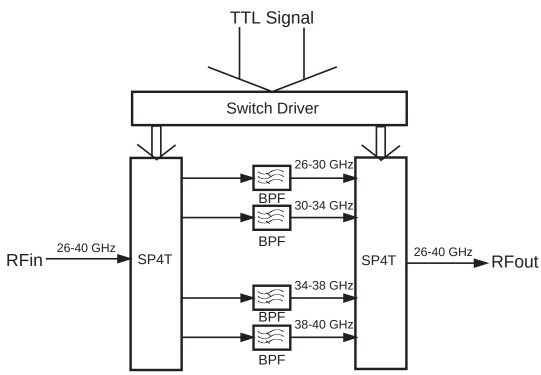


Figure 1. The block diagram of the ultra-wideband four-way switch filter module.

The structure of the three-line filter is shown in Fig. 2. Obviously, the proposed three-line filter has simpler configuration than the traditional three-line filter. It can be easily seen from Fig. 2(b) for the proposed three-line filter that the middle lines of all sections have the same width inducing parameters decreased effectively; conjoint sections have the same line width avoiding discontinuities between adjacent sections; diamond structures are intervened into input/output ports as matching circuits. The diamond structure is used as a compensating of shadowing capacitance for inductance inconsistence existing among the neighboring resonators. The design method of the proposed three-line filter is uniform with that of the traditional three-line filter [21]. The major idea of the design method is transforming six-port network of three-line structure into two-port network and employing the design method of traditional parallel coupled-line filter. The idea of equivalent

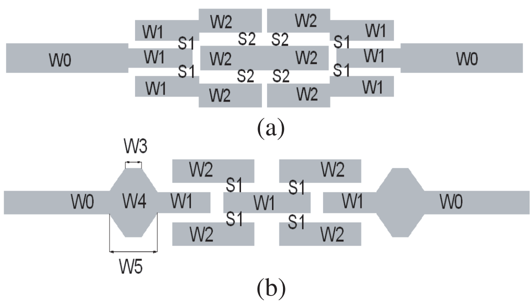


Figure 2. The traditional and proposed three-line filter (a) the traditional three-line filter (b) the proposed three-line filter.

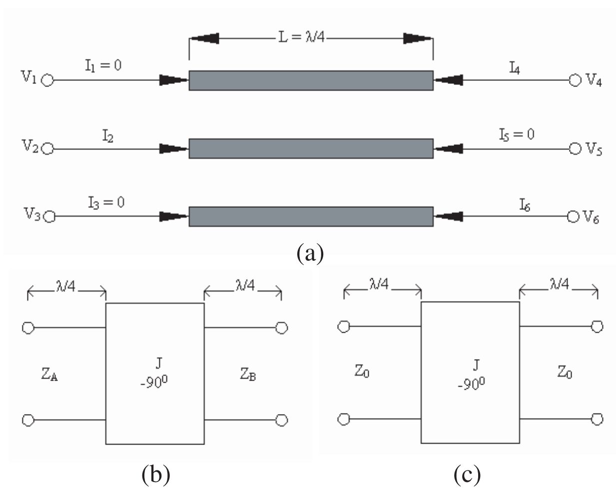


Figure 3. Equivalent circuit transform of the three-line structure (a) three-line structure as a six-port network, (b) equivalent admittance inverter and (c) further equivalent admittance inverter.

transforming is shown in Fig. 3. The design method can be summarized into four steps.

Firstly, the inductance matrix $[L]$ and capacitance matrix $[C]$ per unit length for the structure can be obtained using the spectral domain approach [20, 22]. By the two matrixes, the eigenvotage matrix for dominant modes can be written as

$$[M_V] = \begin{bmatrix} 1 & 1 & 1 \\ m_1 & 0 & -m_3 \\ 1 & -1 & 1 \end{bmatrix} \tag{1}$$

Each vector of $[M_V]$ is the eigenvoltage vector of the matrix product $[L][C]$.

Secondly, by the matrix $[M_V]$, the relation between port voltages and port currents of Fig. 3(a) can be defined as

$$\begin{bmatrix} V_a \\ V_b \end{bmatrix} = \begin{bmatrix} Z_a & Z_b \\ Z_b & Z_a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \end{bmatrix} \tag{2}$$

where $[V_a] = [V_1, V_2, V_3]^T$, $[V_b] = [V_4, V_5, V_6]^T$, $[I_a] = [I_1, I_2, I_3]^T$, and $[I_b] = [I_4, I_5, I_6]^T$, and the impedance matrices $[Z_a]$ and $[Z_b]$ can be derived as in [23]:

$$[Z_a] = [M_V] \operatorname{diag} [-jZ_{mi} \cot \theta_i] [M_V]^T \tag{3}$$

$$[Z_b] = [M_V] \operatorname{diag} [-jZ_{mi} \csc \theta_i] [M_V]^T \tag{4}$$

where $\theta_i = \beta_i L$, β_i the phase constant of the ith mode, L the length of the coupled-line, θ_i the electric length of the ith mode, and Z_{mi} given by

$$Z_{mi} = \frac{Z_{0i}}{m_i^2 + 2} \tag{5}$$

where, Z_{oi} is the characteristic impedance of the ith mode. In (5), $m_2 = 0$.

Thirdly, assume that the electric length of the three model of the coupled-line are approximately the same, and let $\theta_i = \beta_i L = \pi/2$ at the center frequency. Comparing the Z-parameters of the circuits in Fig. 3(a) and Fig. 3(b), several equations can be obtained:

$$m_1 Z_{m1} - m_3 Z_{m3} = J Z_A Z_B \tag{6}$$

$$m_1^2 Z_{m1} + m_3^2 Z_{m3} = Z_A \left(J^2 Z_A Z_B + 1 \right) \tag{7}$$

$$Z_{m1} + Z_{m3} = Z_B \left(J^2 Z_A Z_B + 1 \right) \tag{8}$$

According to [24], assuming $Z_0^2 = Z_A Z_B$, the admittance inverter in Fig. 3(b) can be further approximated by the circuit in Fig. 3(c). To meet this purpose, the product of (7) and (8) is reduced by taking further approximation:

$$m_1^2 + m_3^2 \approx 2 m_1 m_3 \tag{9}$$

Then the following approximation can be obtained

$$m_1 Z_{m1} + m_3 Z_{m3} \approx Z_0 \left(J^2 Z_0^2 + 1\right) \tag{10}$$

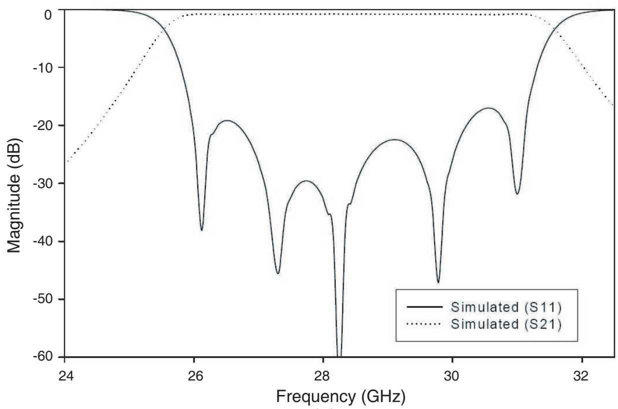
Finally, according to requirements of filter designed, the values of lumped circuit elements of the low-pass filter prototype can be confirmed [25], by which the value of JZ_0 for each admittance inverter can be determined. Once JZ_0 is known, the values of $m_1 Z_{m1}$ and $m_3 Z_{m3}$ can be solved by (7) and (10):

$$m_1 Z_{m1} \approx (Z_0/2) \left(J^2 Z_0^2 + JZ_0 + 1\right) \tag{11}$$

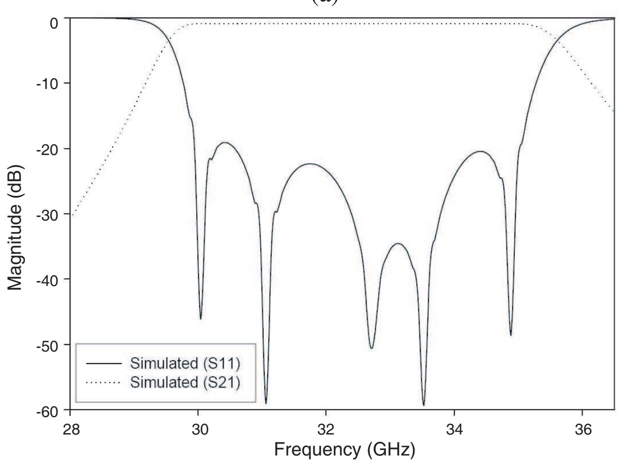
$$m_3 Z_{m3} \approx (Z_0/2) \left(J^2 Z_0^2 - JZ_0 + 1\right) \tag{12}$$

Then the line width and line spacing of coupled-line can be obtained by the graphs established by the quasi-TEM spectral domain approach (SDA) in [22], the vertical and horizontal axes of the graphs are $m_1 Z_{m1}$ and $m_3 Z_{m3}$.

The initial dimensions of filter can be obtained by the method above. By simulation and optimization using commercial full-wave 3-D FEM simulator (Ansoft HFSS), the final line width and spacing of coupled-line can be obtained, including dimensions of diamond structure. For avoiding cavity effect in millimeter-wave, the size of filter should be small enough. So substrate Al_2O_3 is selected, which has relative dielectric of 9.9, thickness of 0.254 mm and loss tangent of 0.001 (1 MHz). According to the requirements of the switch filter module, the specifications of the four filters are proposed: for the first filter, center frequency 28.6 GHz, the fractional bandwidth about 18.18% (5.2 GHz), and 0.5 dB passband ripple; for the second filter, center frequency 32.5 GHz, the fractional bandwidth about 15.38% (5 GHz), and 0.5 dB passband ripple; for the third filter, center frequency 36.7 GHz, the fractional bandwidth about 14.71% (5.4 GHz), and 0.5 dB passband ripple; for the fourth filter, center frequency 39.6 GHz, the fractional bandwidth about 10.1% (4 GHz), and 0.5 dB passband ripple. For previous measured results exhibit the center frequency moving down compared with simulated results, the four filters designed have higher center frequency and wider bandwidth, compared with requirements. The four filters are designed using three-pole three-line microstrip structure by the method described above, the length of each coupled line section is approximately $\lambda_g/4$ (λ_g is the guided wavelength at the center frequency). The initial values of the four filters are approximate: for filter one, $W_0 = 0.24$ mm, $W_1 = 0.22$ mm, $W_2 = 0.23$ mm, $S_1 = 0.2$ mm; for filter two, $W_1 = 0.21$ mm, $W_2 = 0.19$ mm, $S_1 = 0.21$ mm; for filter three, $W_1 = 0.21$ mm, $W_2 = 0.3$ mm, $S_1 = 0.25$ mm; for filter four, $W_1 = 0.28$ mm, $W_2 = 0.28$ mm, $S_1 = 0.23$ mm. After simulation and optimization by Ansoft HFSS, the geometric dimensions are determined as follows: for filter one, $W_0 = 0.24\,\mathrm{mm}$, $W_1 = 0.2\,\mathrm{mm}$, $W_2 = 0.22\,\mathrm{mm}$, $W_3 = 0.14\,\mathrm{mm}$, $W_4 = 1.23\,\mathrm{mm}$, $W_5 = 0.52\,\mathrm{mm}$, $S_1 = 0.23\,\mathrm{mm}$; for filter two, $W_1 = 0.21\,\mathrm{mm}$, $W_2 = 0.2\,\mathrm{mm}$, $W_3 = 0.18\,\mathrm{mm}$, $W_4 = 1.2\,\mathrm{mm}$, $W_5 = 0.56\,\mathrm{mm}$, $S_1 = 0.24\,\mathrm{mm}$; for filter three, $W_1 = 0.22\,\mathrm{mm}$, $W_2 = 0.29\,\mathrm{mm}$, $W_3 = 0.165\,\mathrm{mm}$, $W_4 = 1.31\,\mathrm{mm}$, $W_5 = 0.545\,\mathrm{mm}$, $S_1 = 0.27\,\mathrm{mm}$; for filter four, $W_1 = 0.26\,\mathrm{mm}$, $W_2 = 0.28\,\mathrm{mm}$, $W_3 = 0.25\,\mathrm{mm}$, $W_4 = 1.21\,\mathrm{mm}$, $W_5 = 0.65\,\mathrm{mm}$, $S_1 = 0.24\,\mathrm{mm}$. The size of the designed filters is $8.1 \times 3 \times 0.254\,\mathrm{mm}^3$. The simulated results of the four filters are shown in Fig. 4. It can be seen from Fig. 4 that all results meet the pass-band requirement of the switch filter module.



(a)



(b)

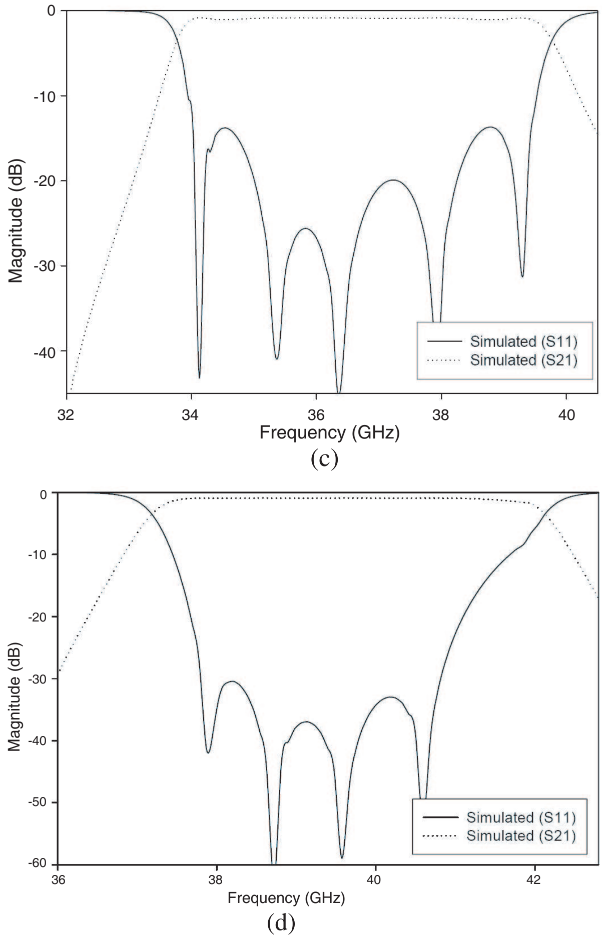


Figure 4. Simulated results of the designed three-line structure band-pass filters (a) filter one (26–30 GHz), (b) filter two (30–34 GHz), (c) filter three (34–38 GHz) and (d) filter four (38–40 GHz).

3. KA-BAND SWITCH FILTER MODULE AND MEASURED RESULTS

Employing the four novel three-line microstrip structure band-pass filters designed in section two and two MMIC SP4T switches (MA4AGSW4), the millimeter-wave ultra-wideband four-way switch filter module is fabricated. The size of entire module fabricated is 64 mm × 44 mm × 7.5 mm. Photograph of the fabricated switch filter module is shown in Fig. 5 (including a pair of test fixture).

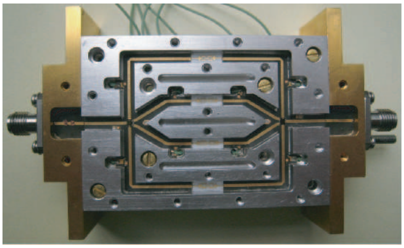
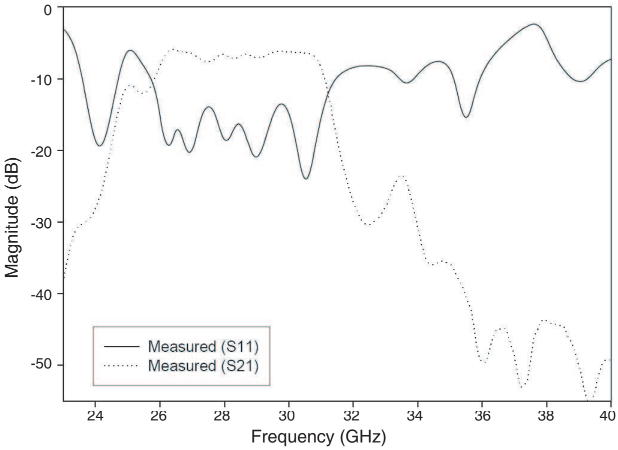
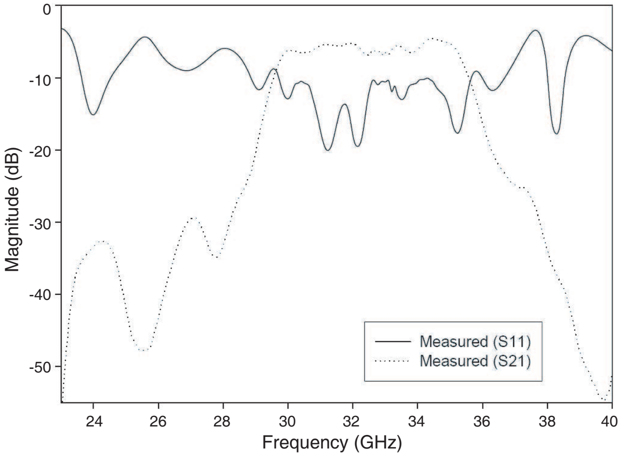


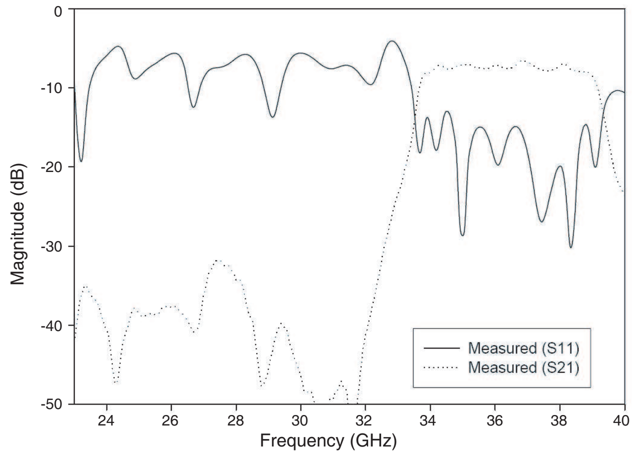
Figure 5. Photograph of the fabricated Ka-band four-way switch filter module.



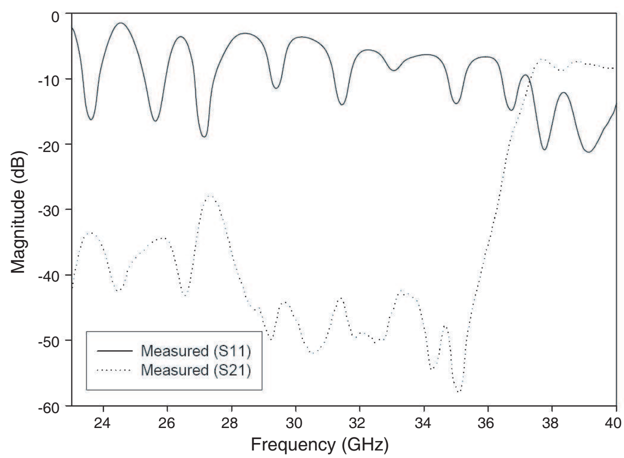
(a)



(b)



(c)



(d)

Figure 6. Measured results of the fabricated Ka-band four-way switch filter module (a) state one (26–30 GHz), (b) state two (30–34 GHz), (c) state three (34–38 GHz) and (d) state four (38–40 GHz).

The measurements are taken using Agilent E8363B vector network analyzer (VNA). For measuring expediently, a pair of test fixture is connected at the input/output ports of the switch filter module by bond wires as shown in Fig. 5. The measured results of the module are shown in Fig. 6. The module exhibits excellent performances. As can be seen: for the first state, the switch filter module exhibits insertion loss and return loss of better than 8 dB and 14 dB in pass-band of

26–30 GHz, respectively, and rejection of better than 24 dB in 34–40 GHz; for the second state, it exhibits insertion loss and return loss of better than 7 dB and 10 dB in pass-band of 30–34 GHz, respectively, and rejection of better than 28 dB in 38–40 GHz; for the third state, it exhibits insertion loss and return loss of better than 8 dB and 13 dB in pass-band of 34–38 GHz, respectively, and rejection of better than 24 dB in lower than 30 GHz; for the fourth state, it exhibits insertion loss and return loss of better than 8.5 dB and 12 dB in pass-band of 38–40 GHz, respectively, and rejection of better than 20 dB in lower than 34 GHz. Compared to the simulation, the center frequency of the filter all moves down, and this could be attributed to tolerance of manufacture and relative permittivity. In addition, switch time measured is smaller than 10 ns, which is controlled by switch driver and switch self.

4. CONCLUSION

In this paper, a millimeter-wave ultra-wideband four-way switch filter module has been fabricated and measured. The switch filter module covers whole Ka-band (26–40 GHz). Based on requirements of the module, a novel three-line microstrip structure band-pass filter has been presented. The filter simplifies the traditional three-line filter, and still retains its virtues and high performance. Four millimeter-wave band-pass filters using this novel three-line structure have been designed. The switch filter module fabricated exhibits excellent performances.

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