Design of Ku-band Size-reduced Waveguide Slot Filter Antenna Loaded with Metal Ridges

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Abstract. A filter antenna based on waveguide structure is proposed in this paper, which reduces the size of the resonator by loading a metal ridge in the rectangular waveguide resonator to produce a capacitive effect. The filter antenna integrates the waveguide filter and the waveguide slot antenna radiation array, and achieves a better matching of filtering characteristics and impedance. The simulation results show that the centre frequency of waveguide filter antenna is 15GHz and the relative bandwidth 2%; the return loss is more than 16.78dB; the peak gain of waveguide filter antenna reaches 12dBi. To summarize, the performance is excellent under the case of simple structure. The proposed filter antenna lays the foundation for the realization of integrated communication system and can be used in satellite and radar communication system.

1. Introduction

With the rapid development of wireless communication technology, the receiver front-end system tends to be integrated, multi-functional and low-cost. The filter antenna with radiation and filtering functions has become a research hotspot[1]. The traditional design method of filter antenna only considers the performance of the device itself and cascades through matching network. It is not considered from the overall scope. The proper integration of the antenna and filter turns out to be an efficient way in reducing the cost and the size of the functional block for a microwave system[2]. The filter antenna can make the antenna have both radiation and filtering functions, which reduce effectively the size and area of three-dimensional packaging. It can make the filter antenna have the advantages of compact structure, lightweight and low cost[3]. This method can reduce the size of equipment and realize the miniaturization of wireless communication system. It can avoid the influence of impedance mismatch on the system. On the one hand, the filter antenna exhibits the radiation characteristics of the antenna; on the other hand, it has good filtering and frequency selective characteristics of the filter[4]. Waveguide slot antenna is widely used in radar antenna because of high power capacity, low loss and easy integration[5]. Therefore, the study of waveguide filter antenna is of great significance for the realization of integrated receivers.

The waveguide filter antenna is designed by using the waveguide structure in this paper. The size of the resonator is reduced by loading metal ridges into the rectangular waveguide resonator to produce capacitive effect, which makes the structure of the filter compact. Then, the waveguide filter and the waveguide slot antenna radiation array are integrated and designed, which eliminates the impedance matching structure and reduces the size of the filter antenna. Therefore, it has good radiation characteristics and filter frequency selection characteristics, which can well suppress spurious signals outside passband.
2. Design of waveguide filter antenna

2.1. Waveguide bandpass filter
The centre frequency of the waveguide bandpass filter is 15GHz with the relative bandwidth of 2%, and the return loss is 20dB. In this paper, a 4-order Chebyshev low-pass filter prototype is used to design the bandpass filter. The 4-order low-pass prototype elements of 0.01dB ripple Chebyshev band-pass filter are obtained by looking up the table. The values are as follows:

\[ g_0 = 1, \quad g_1 = 0.7128, \quad g_2 = 1.2003, \quad g_3 = 1.3212, \quad g_4 = 0.6476, \quad g_5 = 1.1007 \]

According to the obtained low-pass prototype element values, the coupling coefficients of the filter and the external quality factors of the input and output can be calculated by using the following coupling formulas, and its parameters are shown in Table 1.

\[
W_{FBW} = \frac{w_2 - w_1}{w_0} \\
(Q_e)_A = \frac{g_0 g_1}{W_{FBW}} \\
(Q_e)_B = \frac{g_2 g_{x+1}}{W_{FBW}} \\
k_{j,j+1} = \frac{W_{FBW}}{g_j g_{j+1}}
\]

where \( w_2 \) and \( w_1 \) are the upper and lower cut-off frequencies of the 3dB passband of the filter. \( W_{FBW} \) is the relative bandwidth of the filter. \((Q_e)_A\) and \((Q_e)_B\) are the external quality factors of the resonators at the input and output. \( k_{j,j+1} \) are the coupling coefficients between the adjacent resonators.

| \((Q_e)_A\) | \(k_{12}\) | \(k_{23}\) | \(k_{34}\) | \((Q_e)_B\) |
|---|---|---|---|---|
| 35.64 | 0.0216 | 0.0159 | 0.0216 | 35.64 |

The standard waveguide WR62 working in Ku-band is selected as the simulation model. The length of the wide side of the waveguide is 15.8mm and the length of the narrow side is 7.9mm. Inductive diaphragms are used to achieve coupling between the input/output port of the waveguide filter and the resonant cavity. The couplings between resonators can be adjusted by controlling the coupling window of the inductor diaphragm. Figure 1 shows a waveguide bandpass filter model without metal ridges, which consists of the inductive window composed of the inductive diaphragm and the resonant cavity. The total length of the filter is 60.7mm. The relation between the frequency of the rectangular cavity and the length of each side is shown in formula 5\(^{(6)}\), TE\(_{101}\) mode and TM\(_{nnp}\) mode frequency of the resonant cavity is \(f_{nnp}\). Respectively, \(a, b, l\) are the width, height and length of the resonant cavity. The resonant frequency of the TE\(_{101}\) mode in rectangular waveguide resonator is determined by its physical size.

\[
f_{nnp} = \frac{c}{2\pi\sqrt{\epsilon\mu}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{P\pi}{l}\right)^2}
\]

Figure 2 is a waveguide filter model loaded with metal ridges. The capacitive effect can be produced by loading a metal ridge in the resonator. It can be equivalent to the transmission line structure with parallel capacitors on the waveguide transmission line. Compared with the waveguide cavity resonator, the method of loading metal ridges shortens the size of the waveguide cavity, which makes the structure of the waveguide filter compact. For consideration to meet the requirement of processing technology
and the convenience of processing, the width of the metal ridge is set to 2mm; the distance between the metal ridge and the edge of the resonator is 2.5mm, and the total length of the waveguide filter is 46mm. The resonant frequency of the resonator can be controlled by adjusting the length and height of the metal ridges. When the waveguide filter without the metal ridge and the waveguide filter loaded with the metal ridge have the same s-parameter response characteristics, it can be seen from Figures 1~3 that the length of the waveguide filter without the metal ridge is 60.7mm, whereas the length of the metal ridge waveguide filter is only 46mm. The simulation results verify the feasibility of reducing the size of the filter by loading the metal ridges.

2.2. Waveguide slot antenna radiation array
Figure 4 is the structure model of waveguide filter antenna. The waveguide filter antenna is designed on the basis of the waveguide filter. Due to the weak directivity of single waveguide slot antenna, in order to improve the directivity of the antenna, a waveguide slot antenna array can be formed by opening multiple slots on one wall of the waveguide at the same time. By changing the position of the slot to change the excitation intensity of the antenna, the desired amplitude distribution can be obtained. Based on this, six longitudinal slots with wide sides are periodically opened on both sides of the midline of the wide wall of the waveguide to cut off the surface current on the inner wall of the waveguide to realize the antenna radiation, and then the waveguide slot antenna array is formed. Finally, the integrated design
of the waveguide filter and the waveguide slot antenna array is realized. All the six slots have resonance characteristics. The distance between adjacent longitudinal slots operating in resonant mode is 18mm, and the short circuit is achieved at the distance of 7mm from the last slot. Since each slot is half-waveguide wavelength apart, the equivalent input conductance of slot antenna array is the sum of the conductance of each slot. The slot antenna array can realize the radiation characteristics of the filter antenna. The lengths, widths and deviations from the waveguide center line of all the slots in Figure 4 are identical.

![Figure 4. Waveguide filter antenna model.](image)

3. Simulation results and analysis
In this paper, the waveguide filter antenna model is simulated and optimized by full-wave commercial simulation software HFSS. and the filter performance of the designed waveguide filter antenna is verified. Figure 5 shows the reflection coefficient and gain simulation of the waveguide filter antenna simulated in three-dimensional electromagnetic simulation software HFSS.

![Figure 5. Reflection coefficient and gain simulation results of waveguide filter antenna.](image)

From the simulation results of Figure 5, it can be seen that the waveguide filter antenna works in the frequency range of 14.85GHz to 15.15GHz. The reflection coefficient in the band is better than -16.78dB. The gain flatness of the waveguide filter antenna is consistent and the peak gain is 12dBi. The simulation results show that the waveguide filter antenna has good filtering characteristics and good gain flatness. Figure 6 to Figure 8 show directional pattern of waveguide filter antenna.
4. Conclusions
In this paper, a filter antenna based on waveguide structure is designed, which is loaded with metal ridges to produce capacitive effect to shorten the size. The waveguide filter and waveguide slot antenna radiation array are designed in an integrated way to avoid the influence of impedance mismatching on the system performance. HFSS software is used to simulate the waveguide filter antenna. The simulation results show that the waveguide filter antenna has a working frequency of 15GHz, a relative bandwidth of 2% and a return loss of 16.78dB. The gain flatness in the passband is good, and the maximum achievable gain is about 12dBi. The filter antenna has the radiation characteristics of the antenna and the filtering characteristics of the filter. It can well suppress the spurious signals outside the passband, which has a good application prospect in the communication system.

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