A Metal-Strip Integrated Filtering Waveguide

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Abstract **─** In this paper, a metal-strip integrated filtering waveguide is proposed. The overall structure consists of a traditional rectangular waveguide and a metal-strip surface which is loaded at the bottom wall of the waveguide. The customized surface can be considered as a meta-surface, the working property of which can be transformed between perfect electric conductor (PEC) and perfect magnetic conductor (PMC) depending on its operational frequency. When the surface acts as a PEC, the filtering waveguide works at pass-band and electromagnetic waves can freely travel inside the waveguide like a conventional one. When the surface plays a role as a PMC outside the interested frequency band, a stop-band can be created where the propagation of electromagnetic waves could be effectively prevented. By integrating the band-pass and band-stop functions into the same waveguide, a compact filtering waveguide structure can be obtained. The proposed filtering waveguide operates in Ku-band with pass-band of 12 GHz~15.1 GHz and stopband of 15.8 GHz~17.4 GHz. Experimental results show a favorable consistency with the simulation results and verify the proposed concept. Moreover, the proposed structure also possesses a compact size and characterizes for easy-fabrication, having a promising practicability in advanced satellite communication system applications.

Index Terms **─** Filtering waveguide, metal-strip surface, meta-surface, PEC, PMC.

I. INTRODUCTION

Satellite communication (Satcom) technology is of great significance for global ocean, land and meteorology monitoring and surveillance. As an important front-end device for the Satcom wireless communication systems, antenna is responsible for transmitting and receiving radio frequency (RF) signals. However, most of the antennas are "passive" and receive signals without any distinction [1]-[7]. Therefore, these signals may cause certain interference to the RF transmitting and receiving systems. Waveguide-based components are frequently adopted in Satcom communication due to its excellent resistance to cosmic radiation and great electrical and structural performance. Traditionally waveguide-based antenna and filters are bridged via waveguide channels, which usually causes a bulky size of the RF front-end. Hence, it is always a requirement that if the signal propagation and filtering function can be properly integrated into a waveguide, not only the loss caused by the waveguide cascade topology can be avoided, but also the size of the overall RF front-end can be greatly reduced.

In recent years, various integrated filtering waveguide have been proposed [8]-[10]. A waveguide band-pass filter is introduced in [11], which is built on a dielectric substrate and applies a new type of microstrip to waveguide transition. In [12], an end-coupled band-pass filter based on the micro-bandgap waveguide technology is demonstrated. The designed filter has a planar structure and is therefore suitable for integration with active and passive components. A rectangular waveguide band-pass filter designed in [13] is made by deep reactive ion etching micromachining on a silicon wafer. On the other hand, an idea of integrating a metamaterial-based surface in a waveguide antenna is presented in [14] to achieve a filtering slotted antenna.

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As the height of its internal metal nails is about a quarter wavelength at the center frequency of the stop-band, a perfect ideal magnetic conductor characteristic can be obtained. By utilizing this feature, the antenna can possess better attenuation characteristic in the stop-band, thereby the filtering function can be realized. This surface is usually integrated on the bottom layer of the waveguide to implement the filtering function of the antenna. However, loading such metallic metamaterial surface can be considered as adding a "thick" plate below the bottom of the waveguide which would increase the profile of the whole structure.

In this paper, a metal-strip surface is integrated in a rectangular waveguide for Ku-band communication application. Its operational frequency band is around 12-15.1 GHz with a stop-band of around 15.8-17.4 GHz so as to achieve good anti-interference characteristic. The proposed design adopts the metal-strip meta-surface to be realized by low-cost printed circuit board (PCB) technique. By changing the structural configuration of the metal-strip surface, the stop-band and pass-band characteristics of the filtering waveguide can be customized. The paper consists of the following parts: Section II introduces the structure of the proposed filtering waveguide. The design details and analysis are discussed in Section III. Section IV demonstrates the simulation and the measurement results with favorable comparison. A conclusion of the work is drawn in Section V.

II. WAVEGUIDE STRUCTURE

The configuration of the filtering waveguide proposed in this work is shown in Fig. 1. Unlike a conventional rectangular waveguide, a metal-strip layer is integrated at the bottom wall of the waveguide. In this design, the metal-strip meta-surface is composed of 22 rectangular metallic strips and shorted to the bottom metal plane through vias. The shorted metal-strip surface is finally realized on a RO4003C substrate with dielectric constant of 3.55 and thickness of 0.813 mm. In order to facilitate the measurement, the meta-surface consisting of the metal-strips is fixed to the bottom wall of the waveguide with conductive adhesive, and two WR-62 standard coaxial-to-waveguide adaptors are mounted to the two ports of the filtering waveguide. The overall dimensions of the proposed waveguide are tabulated in Table 1.

III. DESIGN AND ANALYSIS OF FILTERING WAVEGUIDE

A. Design fundamental

According to waveguide theory, when two parallel plates are perfect electric conductors (PECs), the vertical electric field can be freely propagated between the plates. However, when one PEC plate is replaced by a perfect magnetic conductor (PMC) plate, the propagation of the electric field is highly relevant to the distance between the two parallel plates. If the distance is less than $\lambda/4$, the vertical electric field cannot propagate successfully, where λ corresponds to the wavelength at the operating frequency [15], [16]. The abovementioned propagation characteristics are shown in Fig. 2. It can be seen that once the spacing between the PEC and PMC plates is less than $\lambda/4$, neither the electric field nor the magnetic field is able to propagate through the waveguide, therefore a stop-band can be generated in this structure.

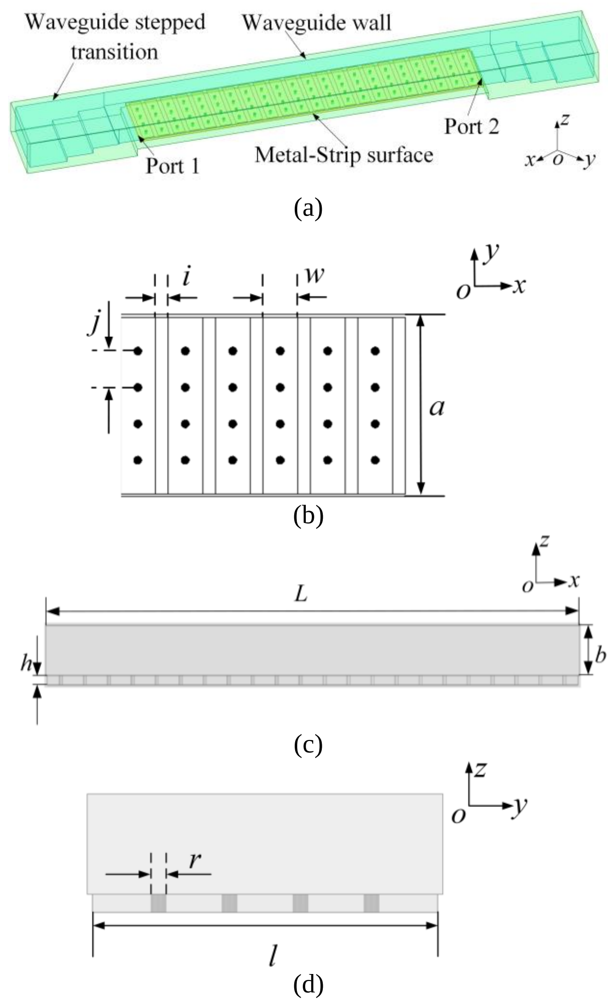

Fig. 1. Configuration of the proposed filtering waveguide. (a) 3-D perspective view of the complete filtering waveguide. (b) Top-view of the metal-strip surface. (c) Front-view of the filtering waveguide. (d) Side-view of the filtering waveguide.

B. Design of filtering waveguide

According to the fundamental mentioned in last section, it is key to construct a meta-surface to perform a frequency-dependent PEC/PMC layer in the waveguide. In this design, a metal-strip layer is adopted as the PEC/PMC meta-surface, which is able to generate a pass-band characteristic in the bandwidth of 12~15.1 GHz while a stop-band in the frequency range of 15.8~17.4 GHz. The proposed metal-strip surface is printed on a PCB board with size of L × a × h, where the length and width of the metal-strip is *a* and *w* respectively. The distance between the adjacent metal-strips is *i*. A ground plane is designed at the bottom of the PCB, shorted with the metal-strips at the top layer by vias. The radius of the vias is *r*. The PCB layer is finally embedded in the bottom wall of the waveguide to achieve filtering performance.

Table 1: Parameters of the filtering waveguide

Parameter	Value
a	16 mm
b	4.5 mm
h	0.813 mm
L	93.5 mm
w	3.1 mm
i	1.1 mm
j	2.5 mm
r	0.35 mm
l	15.7 mm

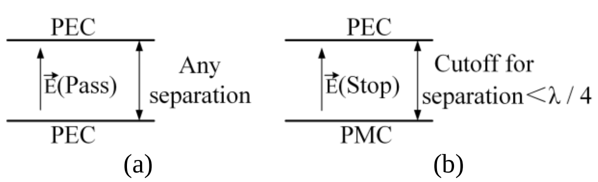

Fig. 2. Electric field propagation inside two parallel plates: (a) model with two PEC plates, and (b) model with a PEC plate and a PMC plate.

C. Analysis of filter waveguide

The reflection and transmission coefficients of the proposed filtering waveguide is shown in Fig. 3, characterized by S_{11} and S_{21} respectively. It can be seen that the S_{11} coefficient is less than -20 dB in the band of 12~15.1 GHz, indicating the metal-strip surface can be used as a PEC layer for electromagnetic (EM) wave propagation in this bandwidth. While in the frequency range of 15.8~17.4 GHz, S_{11} is close to 0 dB and S_{21} is below -60 dB, which shows that the EM wave in this frequency band is almost totally reflected. In this case, the metal-strip surface acts as a PMC layer to prevent signal propagation. Therefore, the proposed filtering waveguide can generate a pass-band of 12~15.1 GHz for target signal propagation, while there is a stop-band existing in 15.8~17.4 GHz for interference signal rejection. Note that when the metal-strip layer acts as PMC, the cut-off frequency appears at around 15.8 GHz as the spacing (*b*) between the top and bottom plate of the waveguide is close to a quarter wavelength at this frequency. All the signal below 15.8 GHz under this condition will be rejected.

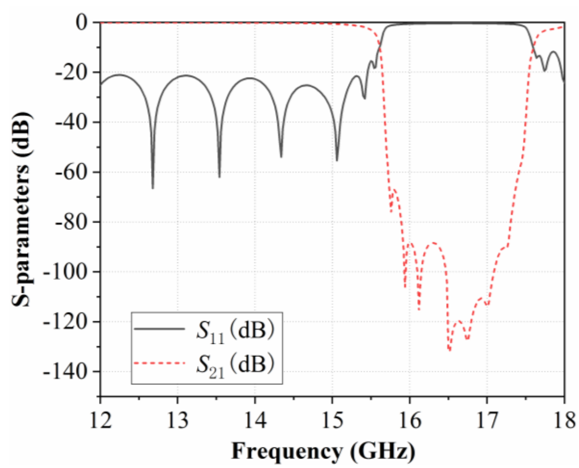

Fig. 3. S-parameter results of the proposed filtering waveguide.

D. Parametric analysis

The frequency response of the metal-strip surface can be changed by some key structural parameters, which could make it easily customize to different anti-interference requirements with specified pass-band and stop-band.

Two typical parameters are studied in this work. Figure 4 shows the effect of the vias' height (*h*) on the frequency response of the stop-band. As the height increases, the stop-band shifts to lower frequencies and the corresponding bandwidth is also affected. Figure 5 shows the influence of the via spacing of metal strips (*j*) on the waveguide stop-band performance. As the spacing increases, the stop-band has similar response as the vias' height that shifts to lower frequency band while the bandwidth of the stop-band is also affected. Figure 6 shows the effect of the width (*w*) of the metal-strip on the stopband performance, from which it can be seen that as the width increases, the stopband slightly shifts to a lower frequency band Parametric studies on other parameters are not necessary to present as similar effect can be expected. Based on the above analysis, it can be seen that the filtering response could be easily adjusted by changing the corresponding parameters of the metal-strip layer, and therefore the proposed filtering waveguide can be flexibly designed for various applications.

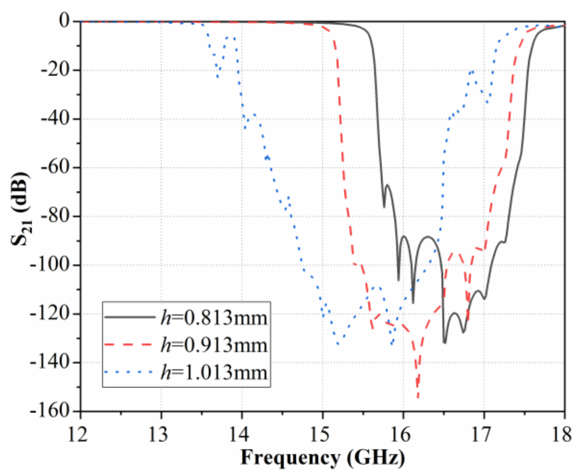

Fig. 4. Transmission coefficient of the proposed filtering waveguide with different heights (*h*) of the vias.

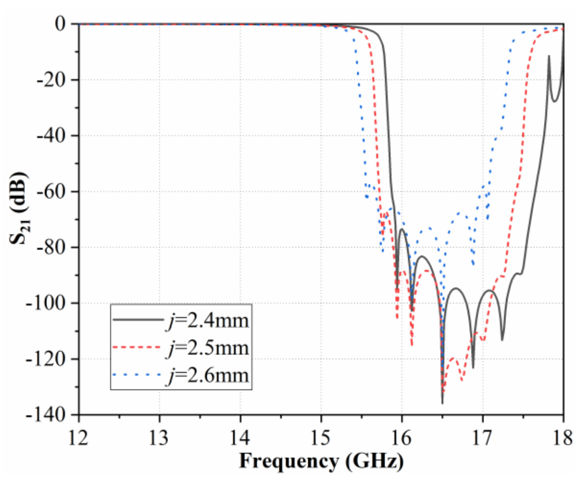

Fig. 5. Transmission coefficient of the proposed filtering waveguide with different vias' spacing (*j*).

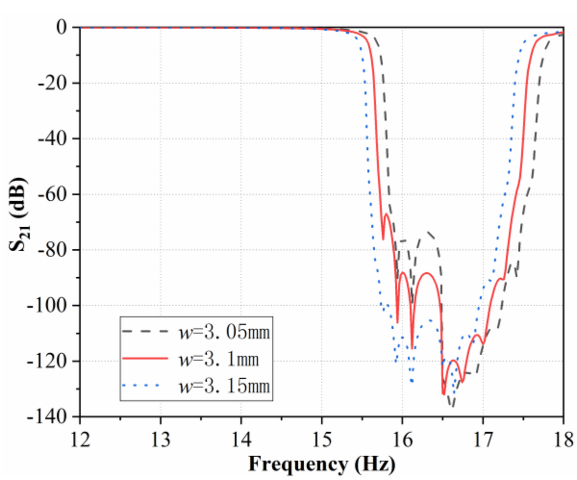

Fig. 6. Transmission coefficient of the proposed filtering waveguide with different width of metal-strip (*w*).

IV. RESULT ANALYSIS

As shown in Fig. 7, the waveguide consists of two parts: a cover and a cavity. The cavity includes a waveguide step transition and an embedded metal-strip surface. The waveguide is assembled by fixing the cover on the top of the cavity with screws.

In order to verify the transmission characteristics of the proposed filtering waveguide, a prototype manufactured by machining technique has been tested with vector network analyzer (VNA). The reflection coefficient (represented by S_{11} in units of dB) and the transmission coefficient (represented by S_{21} in units of dB) of the prototype are shown in Fig. 8 with comparison of simulation results. The experimental results are somehow consistent with the overall trend of the simulation results. The reflection coefficient (S_{11}) of the pass-band is close to -20 dB though the frequency response at lower frequencies deteriorates, and the ability of stop-band to suppress interference signals is better than 30 dB. It is also noticed that the stop-band shifts to higher frequency by about 1.3 GHz and the corresponding bandwidth becomes narrower.

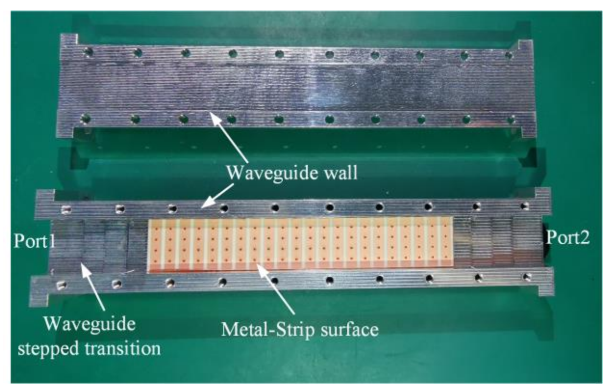

Fig. 7. Photograph of the proposed waveguide.

After a careful inspection, there are several reasons causing the difference between the measured and simulated results: (1) The actual thickness of the dielectric substrate becomes smaller after copper coated on both sides of the substrate. According to the previous parametric analysis, this error would cause a frequency-shift to higher frequency in the stop-band and also changing the bandwidth; (2) In addition, the dielectric constant of the actual substrate is around 3.38 instead of the dielectric constant 3.55 set in the simulation; (3) All the metallic materials of the filtering waveguide are set to PEC in the simulation environment without considering the actual conductive loss. After reducing the thickness and dielectric constant in the design model, the simulation is re-run to investigate the change and the result is shown in Fig. 9. Now the experimental results are basically consistent with the simulation ones though the bandwidth of the stop-band still has deviation.

Furthermore, it should be noted that as the WR-62 standard coaxial-to-waveguide adapter operates from 12.4 GHz up to 18.0 GHz, it might affect the reflection coefficient of the filtering waveguide at lower frequency during the measurement.

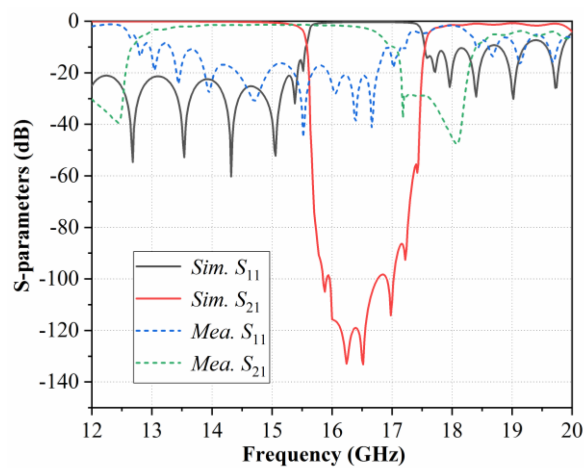

Fig. 8. Simulated and measured S-parameters of the filtering waveguide.

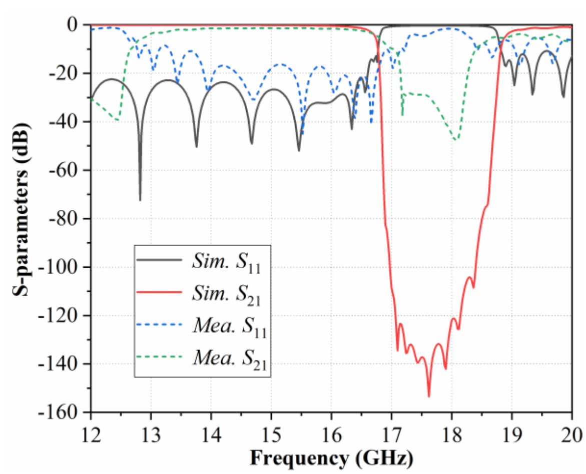

Fig. 9. Simulated and measured S-parameters of the filtering waveguide.

V. CONCLUSION

A new metal-strip integrated filtering waveguide is investigated in this paper. The structure simply consists of a traditional waveguide and a metal-strip meta-surface embedded at the bottom of the waveguide. The meta-surface can act as a PEC layer in the pass-band while exhibit PMC characteristic in the stop-band. After simulation analysis and experimental verification, the filtering waveguide is able to meet different design requirements. The metal-strip surface is realized on the PCB, the design process of which is relatively simple and convenient for practical implementation and easy for size miniaturization.

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