A Compact Waveguide Slot Filtering Antenna Based on Mushroom-Type Surface

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***Abstract*—A mushroom-type surface based waveguide slot filtering antenna is proposed herein. First, using a mushroom-type surface replacing the conventional metal plane in the bottom of a rectangular waveguide, a novel filtering waveguide is achieved. This filtering waveguide functions as a bandstop filter when the surface performs as a perfect magnetic conductor. Then, a filtering waveguide slot antenna is obtained by cutting radiating slots on the top of the filtering waveguide. Compared with a traditional waveguide slot antenna, the proposed antenna has nearly the same radiation characteristic while realizes an additional filter selectivity with almost no extra volume occupying. A prototype is demonstrated in *Ku*-band with operating in 12.25-12.75GHz and rejecting over 14.0-14.5GHz, which can be a candidate for receiving antenna of satellite communication. The measured results agree well with the designed ones, showing a suppression level stronger than 40dB in the rejecting band.**

***Index Terms*—Filtering antenna, Mushroom-type surface, Waveguide slot antenna, Artificial material.**

I. INTRODUCTION

WITH the prosperous development of wireless communication systems, it is an irreversible trend for the microwave radio frequency (RF) front-end to become compact and multifunctional. As a result, a filtering antenna, integrating the antenna and filter in a single module and having both radiating and filtering functions simultaneously, has been proposed. The filtering antenna is able to effectively reduce the overall size and loss of the RF front-end, and it has attracted extensive research interests.

Many kinds of filtering antennas and their design methods have been reported in the literature [1]-[6]. By adding particular structures to antennas, such as parasitic loops [1] and shorting pins [2], some filtering antennas were realized. Inserting bandpass filter [3] or filtering power divider [4] to the feeding ports of their respective antennas is also an effective design method to conduct filtering antennas. Recently, a co-design approach with synthesizing an antenna as the last stage of a multi-stage filter has been presented [5]-[6]. However, most of these filtering antennas were microstrip antennas based on single- or multi-layer dielectric-slabs, and the dielectric loss become larger for higher frequencies. Additionally, usually the filtering circuits or structures were unpackaged and exposed out in the previous design, which would introduces severe mutual coupling problem among adjacent elements for an array design.

Waveguide slot antenna has been widely used due to its advantages of high efficiency, especially at sub-millimeter or millimeter wave band, low profile, high mechanical strength, and high power-handling capability. There were a few researches about waveguide slot filtering antennas. To realize a filtering response, the waveguide-type filter was integrated into the waveguide cavity natively provided by the power divider feeding waveguide in [7] and [8]. While in [9], a single rectangular grating waveguide with metallic sheets was designed both as radiating cavity and filter. In our previous work [10], bed of metal nails has been embedded into a rectangular waveguide to achieve a bandstop filtering response. However, the height of the nails is about a quarter of the wavelength of the central frequency in the stopband, which is still too thick for some applications, and the structure of bed of nails is still quite complicated for fabrication, so it is necessary to design a more compact and simple structure further.

Mushroom-type surface was first proposed in 1999 [11] and has been widely used to design high-performance antennas [12]. In this study, we use the mushroom-type surface to design a waveguide slot filtering antenna. Compared with our previous work in [10], the proposed antenna here has lower profile, more design freedom, and easier fabrication. This is because that the mushroom-type surface can be achieved based on a thin dielectric substrate and its complex shaped metallization can be easily realized using printed-circuit-board (PCB) technology. The proposed filtering antenna is designed for *Ku*–band, which operates in 12.25-12.75GHz, while possesses the filtering ability to suppress the interference single from 14.0-14.5GHz.

II. ANTENNA CONFIGURATION, MECHANISM, AND DESIGN

A. Antenna configuration

The structure of the proposed filtering antenna is depicted in Fig. 1. A mushroom-type surface is placed on the waveguide cavity bottom of a common six-slot waveguide slot antenna. The surface is implemented on a RO4003C substrate with permittivity of 3.55 and thickness of 0.813 mm. Printed square patches and via-holes for shorting the center of the patch to the

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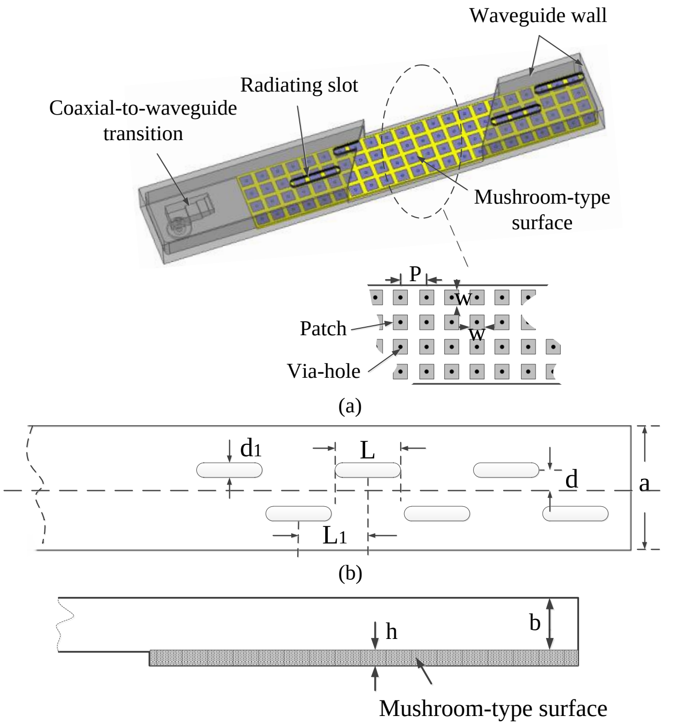


(a)

(b)

(c)

Fig. 1. Configuration of proposed filtering antenna. (a) 3-D perspective view. (b) Top view. (c) Side view.

TABLE I
DIMENSIONS OF THE FILTERING ANTENNA (UNIT: mm)

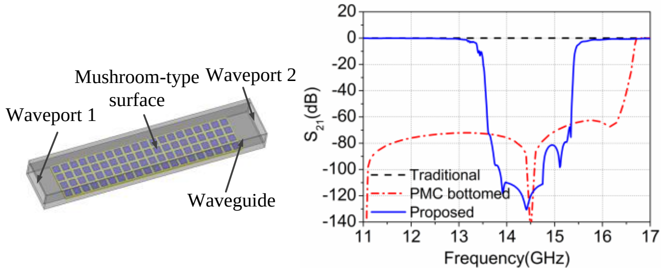
a	b	d	d_1	L	L_1	P	W
16.0	4.5	2.6	2.0	12.8	12.9	4.0	2.9

bottom metallic plane are periodic distributed. And a coaxial-to-waveguide transition is used to excite the filtering antenna. The major structural dimensions of the antenna are symbolized in Fig. 1, numerically determined, and listed in Table I.

B. *Filtering mechanism*

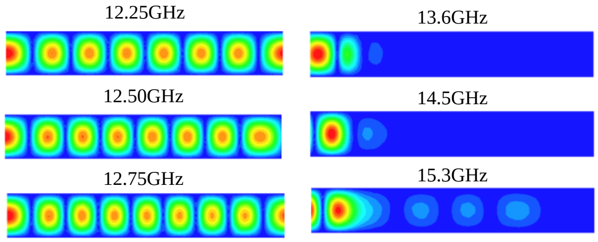
As well known, parallel-plate transmission has a cutoff frequency when one of the two perfect electric conductor (PEC) plates is substituted by a perfect magnetic conductor (PMC). The cutoff performance arrives when the distance between the two parallel plates is shorter than a quarter of the wavelength [13].

Inspired from this cutoff property, it is feasible to achieve a filtering waveguide structure by replacing the bottom stable PEC surface of a rectangular waveguide with a PEC/PMC changeable specially-designed surface, i.e., the mentioned mushroom-type surface. With the change of frequency, the mushroom-type surface transforms its EM function from PEC to PMC. Following this transforming, the filtering waveguide realizes passband and stopband simultaneously for different frequencies. Then a filtering waveguide slot antenna will be conducted by cutting radiating slots on the top of the proposed filtering waveguide.



(a) (b)

Fig. 2. (a) Configuration of proposed filtering waveguide and (b) its transmission coefficient compared with a traditional rectangular waveguide and a PMC bottomed waveguide (These three waveguides have the same cross-section dimensions *a* and *b*).



(a) (b)

Fig. 3. Field distribution of the filtering waveguide: (a) in operating band; (b) in stopband.

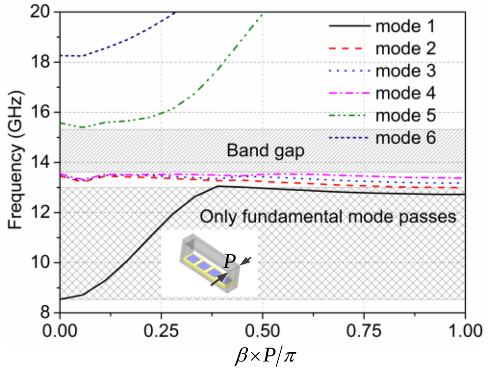


Fig. 4. Dispersion diagram of the 1D-periodic structure in the filtering waveguide.

C. *Design of filtering waveguide*

The filtering waveguide is designed with a section of the proposed mushroom-type surface replacing parts of the bottom metal plane of a rectangular waveguide, as shown in Fig. 2(a).

Fig. 2(b) demonstrates the transmission coefficients (S_{21}) of the proposed filtering waveguide as well as the comparison with the waveguides of pure PEC and PMC bottoms. For the frequencies before 13.0GHz and after 16.0GHz, the S_{21} curve of the filtering waveguide overlaps with that of traditional PEC waveguide. The nearly 0dB performance implies that the wave propagates freely, as illuminated in Fig. 3(a), achieving a passband. While in Fig. 2(b), the stronger than 60dB attenuation during 13.6-15.3GHz brings a stopband for the proposed filtering waveguide, in which the wave deteriorates sharply, as shown in Fig. 3(b). In the stopband, the proposed filtering waveguide works like a PMC bottomed waveguide.

Overall, the filtering waveguide integrates the functions of a traditional PEC waveguide and a PMC bottomed waveguide depending on the PEC/PMC behaves of the mushroom-type surface.

Moreover, Fig. 4 calculates the dispersion curves of the first six modes for the mushroom-type surface based waveguide. As seen in Fig. 4, only mode 1, i.e., the fundamental mode, exists during 8.5-13.0GHz. Any frequencies during this band could be selected as the operating frequencies for the further filtering antenna design. In our work, the operating band is designed to be 12.25-12.75GHz. The field distribution of the filtering waveguide during this operating band has been shown in Fig. 3(a). Clearly, this distribution is very similar to the TE_{10} mode of a common metal rectangular waveguide. Additionally, the entire loss of the filtering waveguide, including reflection loss and insertion loss, is less than 0.5dB for the operating band of 12.25-12.75GHz, as indicated in Fig. 2(b).

Also as observed in Fig. 4, a band gap arises between mode 4 and mode 5, from 13.6GHz to 15.3GHz, in which the wave propagation will be blocked by the filtering waveguide. Absolutely, the gap coincides with the high attenuation area of S_{21} performance shown in Fig. 2(b). And the pre-designed 14.0-14.5GHz rejecting frequencies of the filtering antenna is included in the band gap.

Besides, in our presented design, the location of the stopband can be easily adjusted to meet different demands. Fig. 5 shows the effect of the parameter W of the mushroom-type surface (as labeled in Fig. 1(a)) on the stopband. It is observed that, as W is decreased, the stopband moves to higher frequencies.

D. *Design of filtering antenna*

By carefully designing the offset and length of longitudinal slots on top of the proposed filtering waveguide, a waveguide slot filtering antenna is obtained, and its configuration has been shown in Fig. 1. The operating frequencies of the proposed antenna are centered at 12.5GHz, over 12.25-12.75GHz, and its stopband is designed to cover 14.0-14.5GHz. Since only the TE_{10} like fundamental mode works for the operating band as mentioned above, the design method of radiating slot is the same as that of a traditional waveguide slot antenna [14].

Fig. 6 depicts the simulated reflection coefficient of the proposed antenna. Within the operating band from 12.25GHz to 12.75GHz, good impedance matching with $|S_{11}| < -12.5dB$ is obtained. While S_{11} performs nearly 0dB for the stopband of 14.0-14.5GHz, in which the input signals are almost totally reflected or called rejected.

To quantify the filtering ability of the proposed antenna further, a traditional waveguide slot antenna is used as the reference. The referential antenna, as shown in Fig. 7, is well-designed to work in the same operating band as the proposed one and also to have six radiating slots.

Fig. 8 exhibits the simulated gain responses verse frequency for both the proposed antenna and the traditional one. As can be observed, for the proposed antenna, its broadside gain is flat about 13.6dBi in the operating band while varies from -45dBi to -26.5dBi during the rejecting band. Comparing the gain values in these two bands, a suppression level more than 40dB is obtained for our proposed antenna.

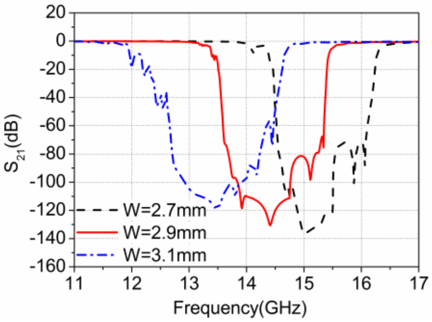


Fig. 5. Stopband characteristics of the filtering waveguide with different printed patch width W .

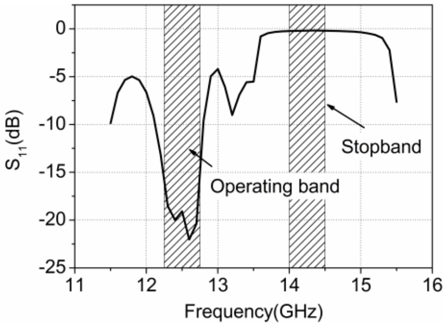
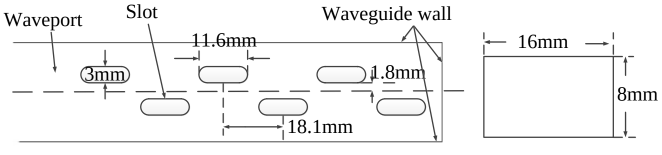


Fig. 6. Simulated reflection coefficient of proposed filtering antenna.



Top view

Cross section

Fig. 7. Configuration of referential waveguide slot antenna.

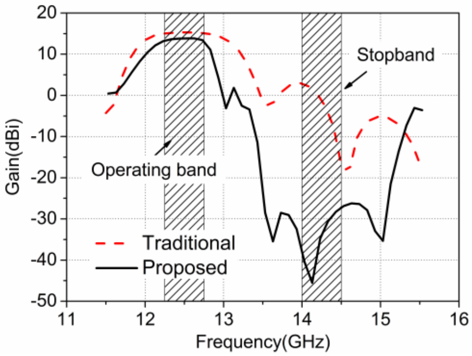


Fig. 8. Comparison of broadside gain response versus frequency between the proposed antenna and the traditional antenna.

Also as shown in Fig. 8, the in-band broadside gain of the traditional antenna is around 15.1dBi. It is 1.5dB higher than that of the proposed antenna mainly due to the larger antenna aperture. The maximum value of the gain in the rejecting band is 2.9dBi for the traditional antenna, which arises at 14.0GHz. Compared with the corresponding value of -26.5dBi for the

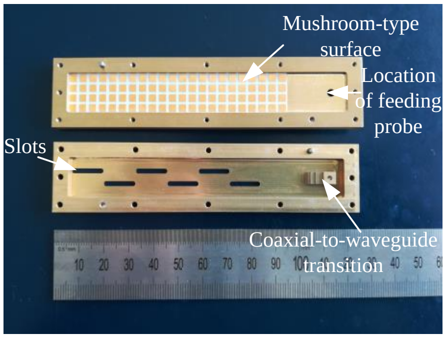
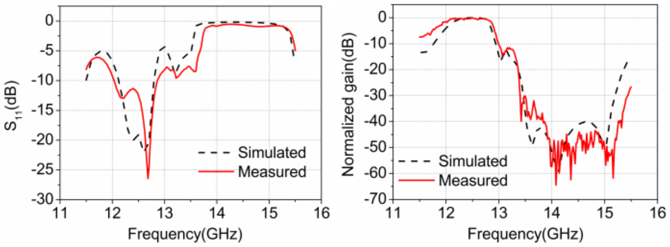


Fig. 9 Inner view of the fabricated waveguide slot filtering antenna.



(a) (b)

Fig. 10. Simulated and measured results of the filtering antenna: (a) reflection coefficients; (b) normalized gain.

proposed antenna, a nearly 30dB improvement of out-of-band rejection is obtained for our filtering antenna.

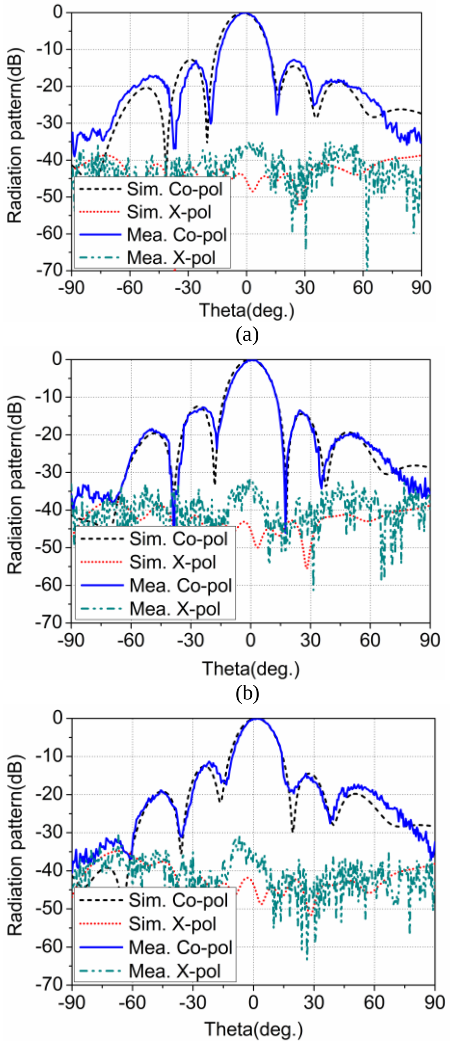
III. MEASURED RESULTS

For demonstration, the *ku*-band prototype antenna has been fabricated and measured. The top metal cover (with etching slots) and the bottom cavity (with embedded mushroom-type surface) are first milled separately, as shown in Fig. 9, and then fixed together with screws surrounding the edges.

Fig. 10(a) describes the simulated and measured reflection coefficient of the proposed antenna. As observed clearly, the measured result agrees well with the simulated one, obtaining an $\left|S_{11}\right| < -10dB$ operating band from 12.1GHz to 12.8GHz. And a predicted nearly 0-dB *S*-parameter performance ($\left|S_{11}\right| > -1.0dB$) realizes a stopband from 13.9GHz to 15.2GHz. Both the measured operating and rejecting bands cover the pre-specified bands. The small discrepancy is mainly due to the fabrication tolerances.

Fig. 10(b) plots the simulated and measured broadside gain responses of the proposed antenna. They agree well with each other. The measured normalized gain in the rejecting band is below -40dB, achieving a suppression more than 40dB.

Fig. 11 shows the simulated and measured *H*-plane radiation patterns of the proposed antenna at 12.25GHz, 12.50GHz and 12.75GHz. The measured radiation patterns show a good agreement with the simulated ones. They are classical patterns of a one-dimensional six-element linear array, and in turn verify the good radiation properties of the designed filtering antenna.



(a)

(b)

(c)

Fig. 11. Simulated and measured H-plane radiation patterns of the filtering antenna: (a) 12.25GHz; (b) 12.5GHz; (c) 12.75GHz.

IV. CONCLUSION

A novel waveguide slot filtering antenna based on mushroom-type surface has been presented in this study. By placing the mushroom-type surface in the cavity bottom of a traditional waveguide slot antenna, an additional stopband filtering function is achieved. Since the mushroom-type surface is achieved on a thin dielectric substrate, almost no addition space is occupied, and then the filtering waveguide slot antenna owns almost the same low profile property as a traditional waveguide slot antenna. A *ku*-band prototype was fabricated and measured for demonstration. The measured results show a suppressing ability more than 40dB in the rejecting band. Moreover, because of the mature PCB technology, more complex metallization can be easily fabricated on the dielectric substrate, to achieve better radiation and filtering performances further.

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