A Waveguide Slot Filtering Antenna Based On Metamaterial Surface Approaches

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***Abstract*—**A novel design of waveguide slot filtering antenna based on metamaterial surface approaches is presented. This filtering antenna consists of a common waveguide slot antenna with longitudinal slots cut on the top broad wall of its rectangular waveguide and a metamaterial surface embedded in the bottom broad wall. The metamaterial surface replaces the conventional metal plane in the form of a bed of nails. In the operating band, the surface functions as a perfect electric conductor (PEC), so the antenna radiates just like the traditional ones. While in the interference band, the surface performs as a perfect magnetic conductor (PMC) to stop the propagation of electromagnetic wave in the waveguide cavity, so the interference signal is rejected and a filter function is achieved. To show the design process and verify its feasibility, a filtering antenna prototype working at C-band and having a bandstop filtering function at X-band is designed, fabricated and tested. Good agreement between simulation and measurement has been obtained, demonstrating an efficient radiation at working band and a strong suppression more than 35dB in the stop band.

***Index Terms*—Filtering antenna, metamaterial surface, waveguide slot antenna, filter**

I. INTRODUCTION

The current developments of wireless communication systems demand the radio frequency (RF) front-end to be compact, lightweight, low cost, multi-functional and anti-interferential, especially when the equipments are installed on the space-confined platforms such as car, ship, plane and satellite. The antenna and filter are two crucial components in the RF front-end, and the filter is usually cascaded right after the antenna. Traditionally, the antenna and filter are designed individually with common 50-Ω ports and then connected directly by a section of 50-Ω transmission line. However, this design usually causes an impedance mismatch, increases the insertion loss and makes the front-end cumbersome. To meet the demand of prosperous developments of wireless communication, filtering antenna, i.e. a module having radiating and filtering functions simultaneously, has been proposed and attracted significant research interests [1]-[7].

Many kinds of design methods of filtering antennas have been reported in the literature. Several filtering antennas have been realized through adding particular structures into antennas [8]-[12]. In [8], metal posts were inserted into a horn antenna. In [9], coupled cavities were created into the waveguide of a leaky antenna. A parasitic loop was placed at the top of a printed antenna in [10]. In [11], four shoring pins were embedded into a via-fed monopole ultra-wideband antenna. In [12], H-shaped coupling lines and a stacked patch were adopted for a dual-polarized patch antenna. These antennas exhibit satisfying filtering performances. However, it is very difficult to tune the filtering specifications of them, which limits the application range of these filtering antennas.

Various approaches have been discussed for intergrating the filter into the feedline of the antenna [13]-[16]. Based on multilayer low-temperature cofired ceramic (LTCC) technology, a quasi-elliptic filter was integrated into a microstrip line of a series-fed antenna array in V-band [13]. A three pole coplanar strip (CPS) filter was connected with a CPS-fed loop antenna to obtain a ultra wideband (UWB) antenna-filter system [14]. In [15], a bandpass filter was designed into the balun of a quasi-Yagi antenna. In [16], a third-order

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filtering power divider was used to fed a microstrip antenna array. In our previous work [17]-[18], evanescent mode filters were integrated into the feeding waveguide of a broadband slotted ridge waveguide antenna array [19]. Nevertheless, in these designs, the feeding network must provide enough space to include the filtering circuit, which may make the front-end size large. What's more, this space requirement is not able to be satisfied sometimes since it is conflict with the demand of miniaturization.

Recently, a synthesis process for filtering antenna design has been presented. In these designs, the antenna not only radiates, but also serves as the last resonator or the load impedance of the filter. So far several different forms of this kind of filtering antennas have been described, such as slot antenna with 3-D cavity filter [20], microstrip filtering antennas [21]-[22], and substrate integrated waveguide filtering antenna [23]. However, due to the lack of the exact extraction of the antenna's equivalent circuit, these filtering antennas did not show good filtering perfomance, especial at the band edges.

In this study, a novel design method of a waveguide slot filtering antena array is proposed. Different from the previous reported filtering antennas, additional filter circuit is not necessary in our approach, the filtering function here is obtained utilizing the metamaterial surface embeded in the waveguide cavity. And the filtering band can be easiy controlled and changed by adjusting the parameters of the metamaterial surface. The designed filtering antenna has almost the same radiating performance as the common waveguide slot antenna in the working band while possesses a strong attenuation property in the interference band.

The paper is organized as follows. Section II shows the structure of the proposed filtering antenna. Section III presents the filtering mechnism and the design process of the proposed filtering antenna. Section IV gives the experimental results. Then a conclusion is followed in section V.

II. STRUCTURE OF FILTERING ANTENNA

The structure of the proposed filtering antenna is depicted in Fig. 1. The configuration is as same as the conventional waveguide slot antenna, except that the smooth metal plane in the bottom of the rectangular waveguide is replaced by a metamaterial surface. The surface is composed of periodic metal nails. And the

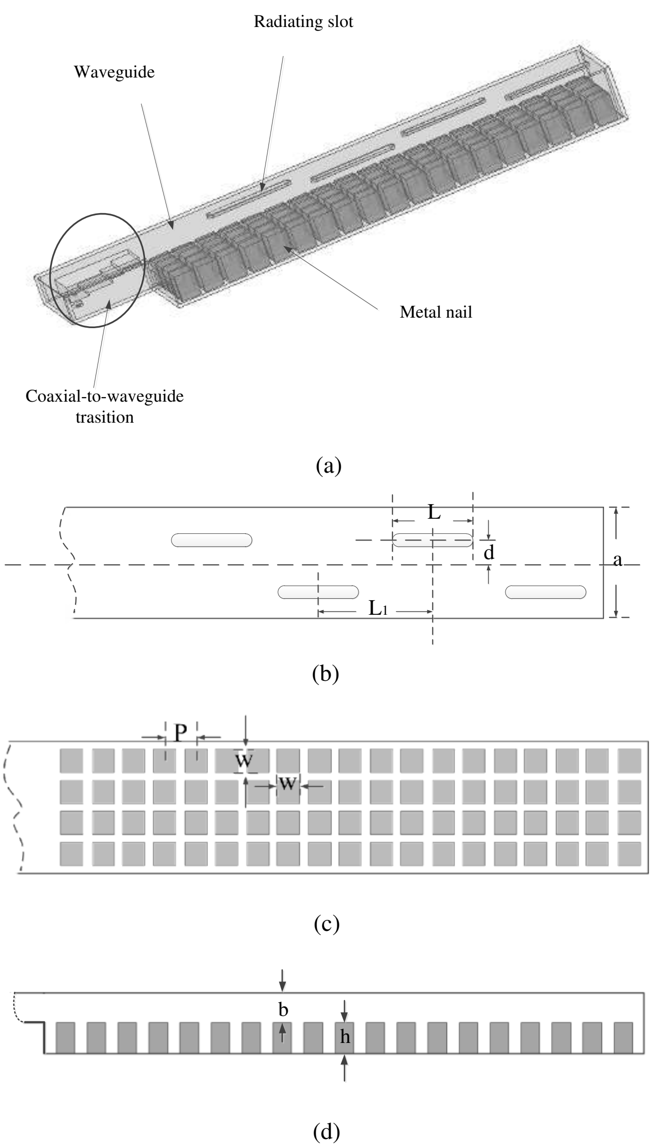


Fig. 1. Configuration of the proposed filtering antenna. (a) 3-D view of the whole filtering antenna. (b) Top view of the filtering antenna. (c) Top view of the nails surface. (d) Side view of the nails surface.

Table 1. Dimensions of the filtering antenna (millimeters)

a	32.0	d	4.0
b	7.6	P	7.6
L	27.5	W	6.1
L_1	32.0	h	8.1

filtering function is realized through the surface.

In this study, a prototype is designed to operate at C-band with filtering capacity at X-band. As shown in Fig. 1, to simplify the design without lossing the generality, four longitudinal radiationg slots are adopted.

To facilitate the measurement, a coaxial-to-waveguide transition is used to excite the filtering antenna. The main dimensions of the prototype are listed in Table 1.

III. DESIGN AND ANALYSIS OF FILTERING ANTENNA

A. FILTERING FUNDAMENTAL

It has been well known that, a vertical electric field propagates freely between two parallel metal plates (or PEC plates) regardless of their separation, as illustrated in Fig. 2. However, there is no propagated field (i.e., all modes are below cut-off) between a PEC plate and a PMC plate when their separation is smaller than $\lambda/4$, where λ is the wavelength. This parallel-plate cut-off property has been utillized in the ridge gap waveguide (RGW) technology [24]-[26]. In RGW, the metal ridges are surrounded by a PMC surface. Providing a waveguide cavity height smaller than $\lambda/4$, the PMC surface stops waves in all directions, then in such a way, the waves have to follow the metal ridges. The ridges can bend, split, make corner and so on to design microwave circuits.

In this work, inspired from the parallel-plate cut-off property, replacing the metal bottom plane of a rectangular waveguide by a appropriate designed metamaterial surface, a bandstop filter function at specified frequencies can be obtained. As shown in Fig. 3, the upper and bottom plane are seperated a distance less than $\lambda_S/4$, where λ_S is the smallest wavelength of the stopband. The response of metamaterial surface varies with frequency. At the operating frequencies, the metamaterial surface is designed to perform as a PEC plane, so the waves can propagates in the cavity, while in the stopband, the surface functions as a PMC plane, with the seperation less than $\lambda_S/4$, the wave propagation is rejected, as a result, a filtering function is achieved.

B. DESIGN OF FILTERING WAVEGUIDE

In this section, a filtering waveguide is designed based on the principle described above. The geometry of the proposed filtering waveguide is illustrated in Fig. 4. As seen, the metamaterial surface is embeded into the bottom of the waveguide in the form of bed of periodic nails. The nails have a square cross section with side length W, a height h and a distance P between two adjacent nails, as shown in Fig. 1(c) and Fig. 1(d).

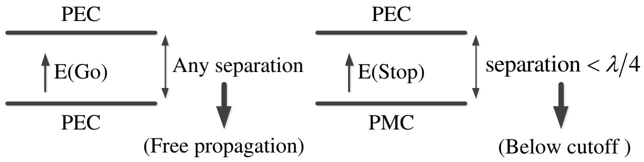


Fig. 2. Field propagation within two parallel plates: one consists of two PEC plates; the other consists of a PEC plate and a PMC plate.

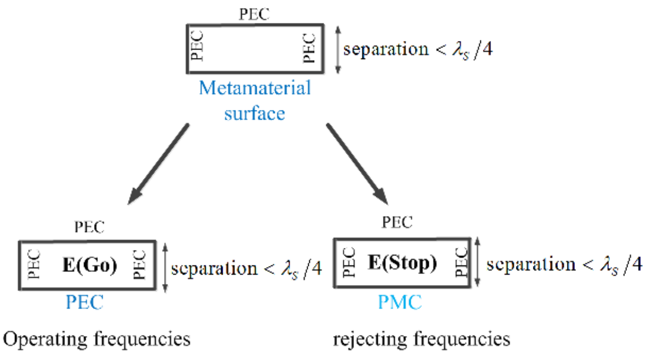


Fig. 3. Field propagation in a metamaterial-based waveguide: the metamaterial surface works as a PEC plane at operating frequencies while a PMC plane at rejecting frequencies.

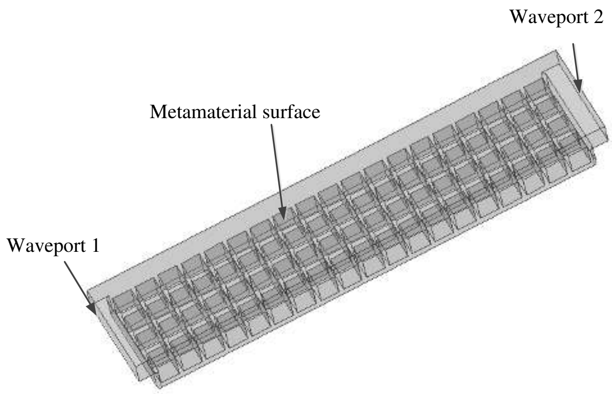


Fig. 4. Configuration of the filtering waveguide

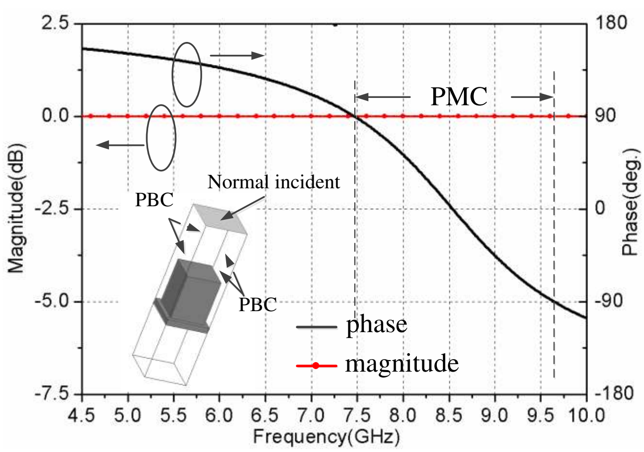


Fig. 5. Simulated reflection magnitude and phase of the metamaterial surface

The characterization of the entire surface can be reduced to that of a single nail as a result of the periodicity. Periodic boundary condition (PBC) is applied to the four side walls of a unit cell, and a normal incidence is considered, as seen in Fig. 5. The dimensions of the nails are as listed in Table 1.

The simulated (using the commercial software HFSS) reflection coefficient of the unit cell is also shown in Fig. 5. A 0-dB magnitude is obtained overall the interesting band. While a 0° phase occurs at the point of 8.5GHz. This corresponds to the frequency where the surface behaves like a PMC. Usually, the useful bandwidth of a PMC is in general defined as +90° to -90° on either side of the central frequency. So the designed surface can be considered as a PMC from 7.5GHz to 9.6GHz. As a comparison, the phase is about 145° around 5.5GHz, where the performance of the surface is similar to that of a PEC.

The transmission coefficient (S_{21}) of the filtering waveguide is shown in Fig. 6. As a comparison, S_{21} performances of a common rectangular waveguide (with four PEC sides) and a waveguide with a PMC bottom are also drawn in Fig. 6. They have the same dimensions of a and b. Here, a and b are set to 32mm and 7.6mm, respectively. For the common waveguide, this corresponds to a cut-off frequency of 4.7GHz, and all the waves above 4.7GHz can propagate through freely. While for the case of the PMC bottomed waveguide, its cut-off frequency is 9.9GHz since b is right the quarter of the wavelength of 9.9GHz, and all the waves below 9.9GHz is rejected, just as predicted by the parallel-plate cut-off property mentioned in the last section.

Overall, as plotted in Fig. 6, from 4.7GHz to 9.9GHz, a PEC bottom supports the wave propogation while a PMC one stops it. So when the metamaterial surface performs as a PEC, the S_{21} response of the proposed waveguide is similar to that of the common one. As a result, the nearby 0-dB performance is obtained over a large frequency range. From 5.2GHz to 6.8GHz, the insertion loss is better than -0.5dB, leading to a passband. Over the passband, the waves go through efficiently. Meantime, a cut-off frequency also arises at 4.7GHz, as same as that of the common one.

We can also see in Fig. 6 that a large attenuation stronger than -60dB happens from 8.1GHz to 8.9GHz for the proposed case, which is similar to that of a PMC

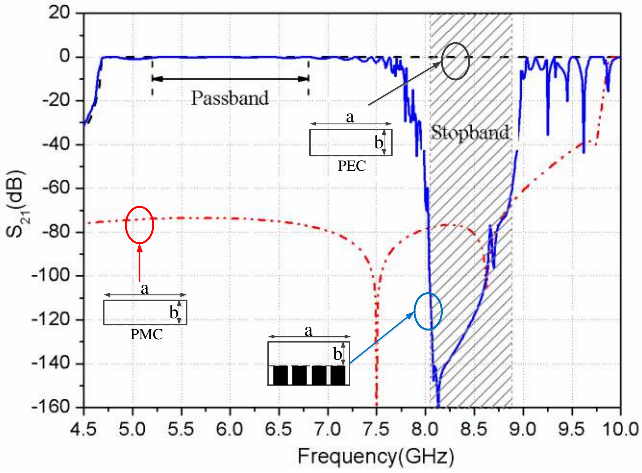


Fig. 6. Transmission coefficient of three kinds of waveguides: a common rectangular waveguide; one with a PMC bottom; one with the proposed surface.

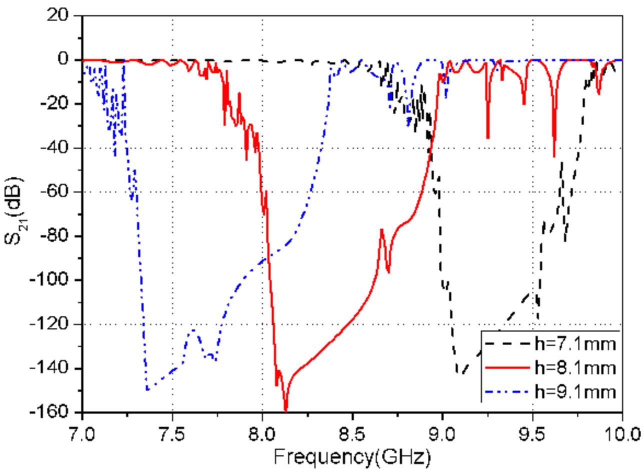


Fig. 7. Effect of the nail height on the central frequency of the stopband.

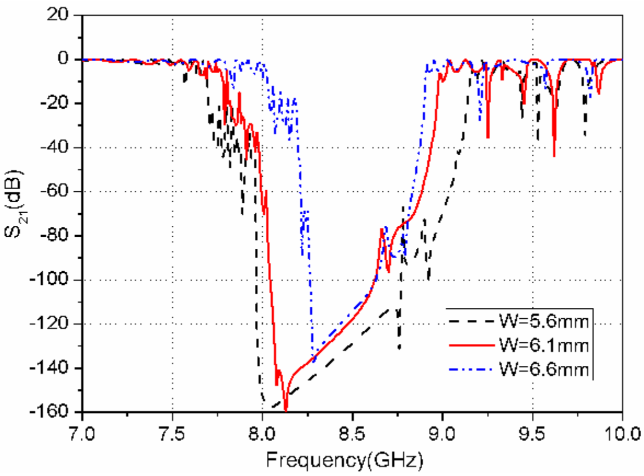


Fig. 8. Effect of the nail width on the bandwidth of the stopband.

bottomed waveguide, resulting in a stopband. The stopband is obtained because the proposed surface functions as a PMC in this band. The central frequency 8.5GHz of the stopband agrees well with the 0° phase location in Fig. 5. But the bandwidth of the stopband is narrower than that of the general defined +90° to -90° as shown in Fig. 5. It corresponds to the bandwidth of +50° to -50°.

Besides, the central frequency and the bandwidth of the stopband can be easily controlled to meet different anti-interference demands. Fig. 7 and Fig. 8 show the effect of the nail height and width on the central frequency and bandwidth of the stopband, respectively. As observed, the central frequency and bandwidth change significantly for different nail parameters. Since the central frequency and bandwidth of the stopband are consistent with that of the PMC band of the surface, the effects of the nail parameters on the stopband characteristic is inherently achieved by adjusting the PMC performance.

C.DESIGN OF FILTERING ANTENNA

This section exhibits the simulated results of the proposed filtering antenna. The structure of the proposed antenna has been shown in Fig. 1. Four slots are designed on the top broad wall of the proposed filtering waveguide. The design method of slots is as same as that of the traditional waveguide slot antenna. The offset and length of the slots are carefully adjusted to meet good impedance matching and radiation property. The working frequencies are centered at 5.5GHz, in the passband of the proposed filtering waveguide.

Fig. 9 illustrates the reflection coefficient of the proposed antenna. In the working band of 5.3-5.7GHz, well matched impedance is obtained with $|S_{11}|<-10dB$. While in the stopband of 7.9-8.7GHz, the nearby 0-dB S_{11} performance means an almost total reflection so to reject the interference signal in this band.

Fig. 10 gives the simulated broadside gain of the proposed antenna versus frequency. As seen, the gain is about 12.2dBi in the working band while below -29dBi over the stopband, corresponding to a suppression level of 41dB. Compared with the stopband (8.1-8.9GHz) of the filtering waveguide, the stopband (7.9-8.7GHz) of the filtering antenna shifts to low frequency a little, and the suppression here is also weaker than that of the filtering

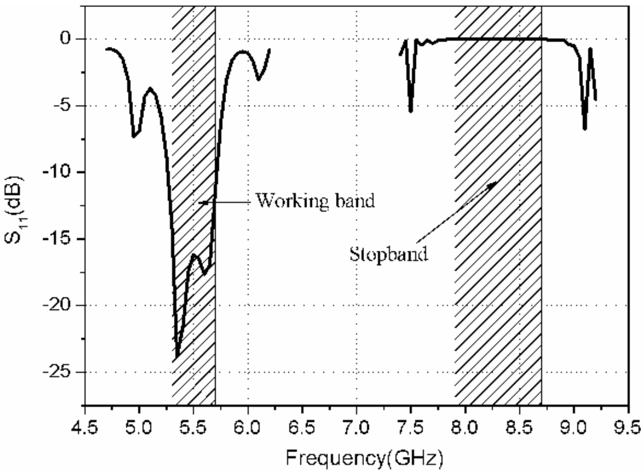


Fig. 9. Simulated reflection coefficient of the proposed filtering antenna..

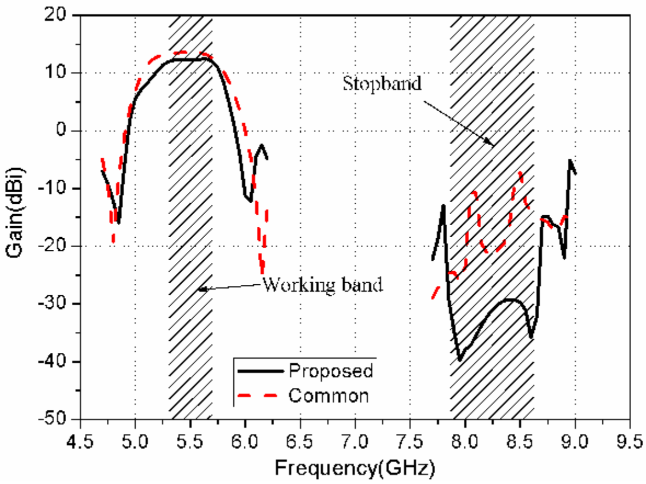
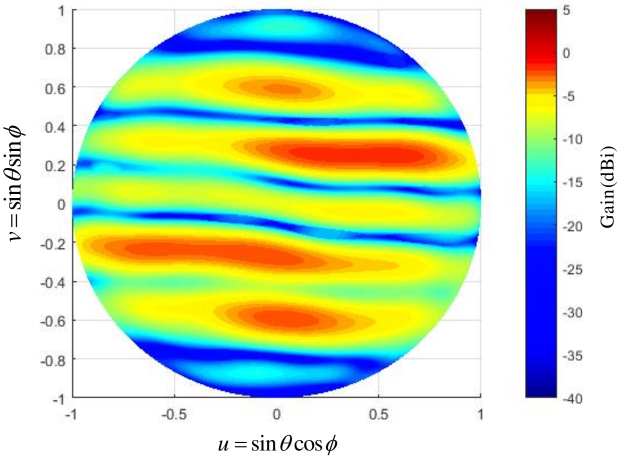


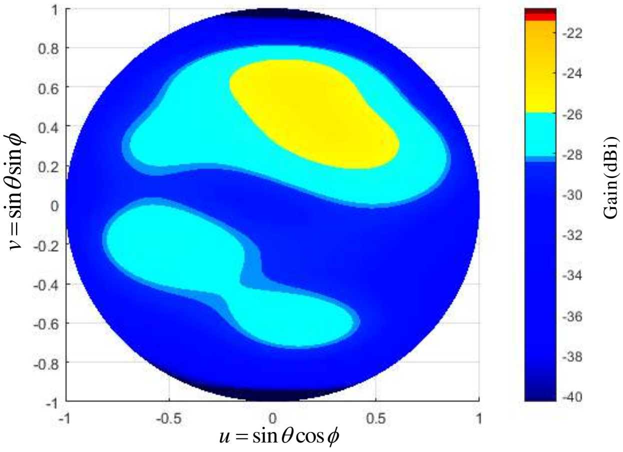
Fig. 10. Simulated broadside gain responses of the proposed filtering antenna and a common waveguide slot antenna.

waveguide (more than 60dB as shown in Fig. 6). This may be because that the close of the waveguide cavity is destructed in some degree due to the introduction of radiating slots.

As a comparison, the gain response of a common waveguide slot antenna is also shown in Fig. 10. The common antenna has the same working band and number of radiating slots as the proposed one does. As illustrated, the gain of the common antenna is about 13.3dBi in the working band, 1.1dB higher than that of the proposed one, this is because the common antenna has longer waveguide wavelength, i.e. a larger aperture (about 1.3 times). While in the stopband, the gain level of the common antenna flucuates around -15dBi, which is average 14dB higher than -29dBi of the proposed antenna. And there are two peaks of -10.7dBi and



(a)

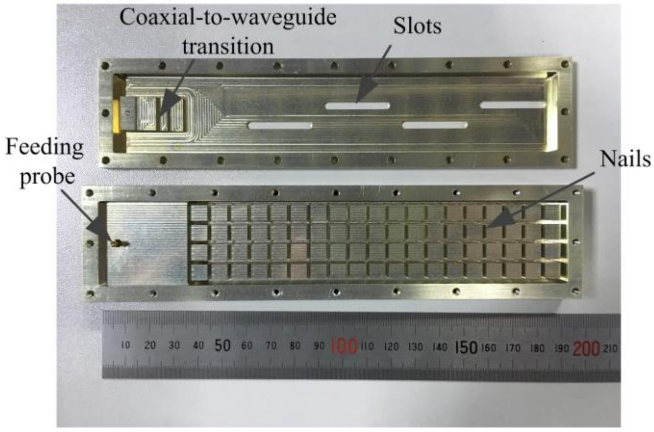


(b)

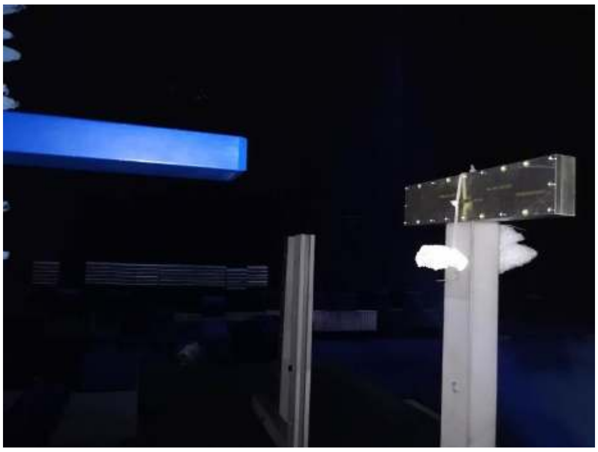
Fig. 11. Gain patterns at 8.5GHz for (a) the common waveguide slot antenna and (b) the proposed filtering antenna.

-7.2dBi, at 8.1GHz and 8.5 GHz, respectively, at which the interference signals can come in more easily.

It should be noticed that the maxmum gain is usually not in the broadside direction when the frequency is far way from the working frequency. And the interference signal may come from any direction. So it is necessary to examine the whole gain pattern, not only the broadside gain. As an example, the gain patterns at 8.5GHz are shown in Fig. 11 for both the common and proposed waveguide slot antennas. The patterns are in the U-V coordinate system. As observed, the maxmun gain is indeed not at the broadside direction (i.e. at the center of the circle). For the common case, the maxmum gain is -1.4dBi, while it is -24.8dBi for our case (notice that the scales are different). Taking the 12.2dBi gain in the working band into account, a strong suppression more than 35dB is obtained for the proposed antenna. As a



(a)



(b)

Fig.12. Photographs of the proposed filtering antenna. (a) Inner view; (b) 3-D view in the anechoic chamber

comparison, the suppression is only at the level of 15dB for the common one. The properties of gain patterns at other frequencies in the stopband is similar with that we mentioned just above, due to the limit of the extent, they are not shown in this paper.

IV. EXPERIMENTAL RESULTS

To verify the design method and the predicted performance of the proposed filtering antenna, the prototype antenna was fabricated and tested. The antenna is firstly fabricated into two parts: a cover and a cavity. As shown in Fig. 12, the cover is consisted of coaxial-to-waveguide transition and radiation slots, while the cavity includes the feeding probe and nails. Then the antenna is assembled by fixing the cover on the top of the cavity with screws.

The measured reflection coefficient of the proposed antenna is plotted in Fig. 13, and the simulated result is

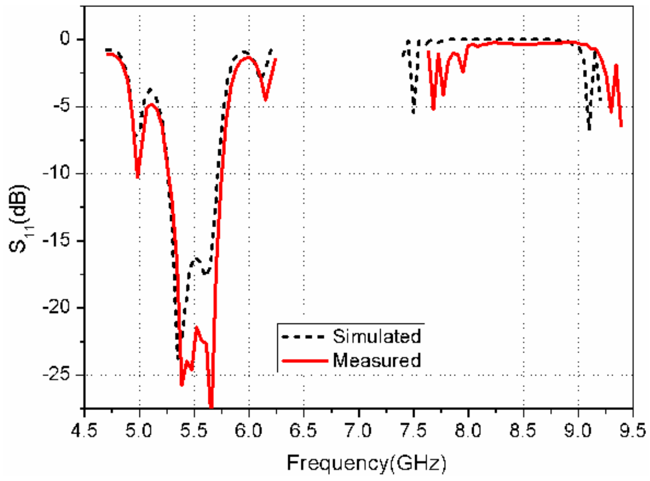


Fig.13. Simulated and measured reflection coefficients for the filtering antenna.

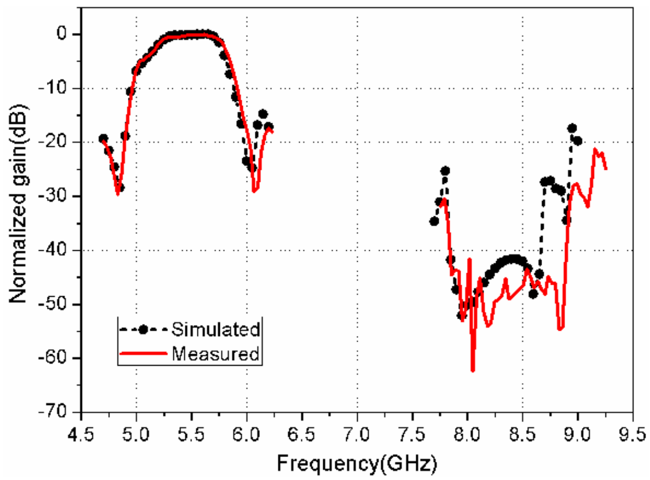
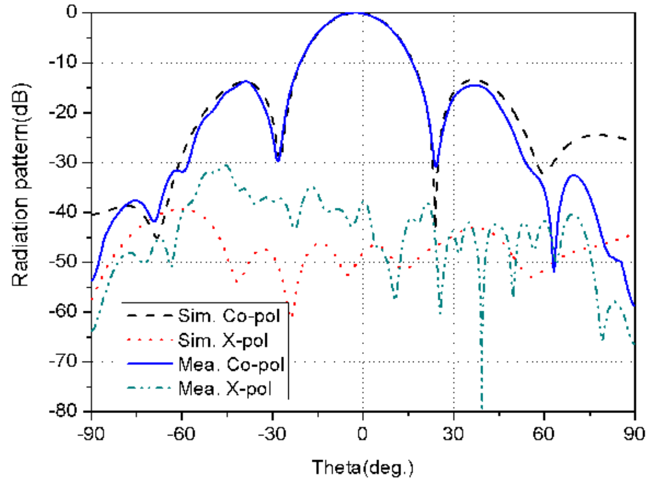


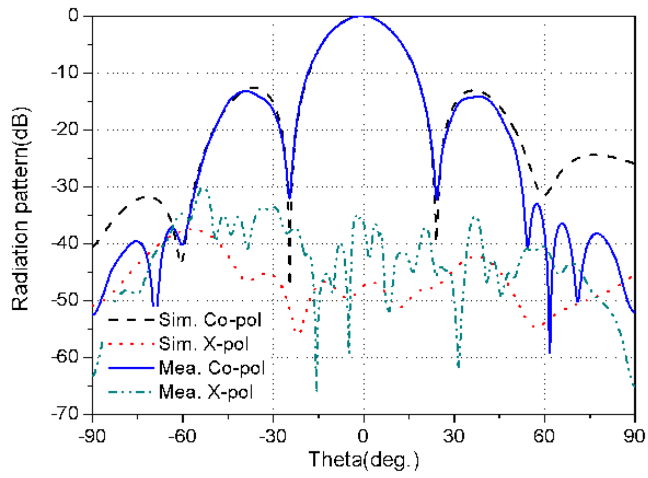
Fig.14. Simulated and measured normalized gain for the filtering antenna.

also given out as a comparison. As observed, the measured result shows good agreement with the simulated one, especially in the working band. While in the stopband, the measured result differs a little from the simulated one, it shifts to higher frequency. The small discrepancy may be attributed to the fabrication tolerances of the height of nails since the location of the stopband is sensitive to the height.

Fig. 14 shows the simulated and measured broadside gain responses of the proposed antenna versus frequency. They show a good agreement with each other. Comparing the gain levels in the working band and stopband, the suppression to the interference signal is calculated to be more than 40dB. Considering the interference signal may be not in the broadside direction, it is still reasonable that a suppression around 35dB can be achieved, as analyzed in part C, section III. The



(a)



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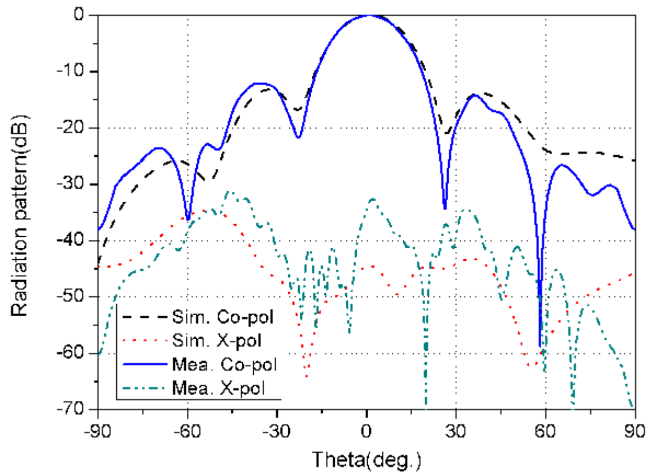

(c)

Fig.15. Simulated and measured H-plane radiation patterns for the filtering antenna. (a) 5.3GHz; (b) 5.5GHz; (c) 5.7GHz.

simulated and measured H-plane radiation patterns in the working band are given in Fig. 15. We see that the measured results are very close to the simulated ones. And they are classic patterns of one-dimension four-element linear array, verifying the good radiation properties of the filtering antenna.

V. CONCLUSION

A waveguide slot filtering antenna has been reported in this work. The design principle and process have been explained. This kind of filtering antenna consists of a common waveguide slot antenna and a metamaterial surface embedded into the bottom of the waveguide cavity. The surface is in the form of bed of nails, it works as a PEC in the working band while a PMC in the interference band. A prototype was fabricated and tested, the measured results shows good agreements with the simulated ones, and a suppression of 35dB to the interference signal shows its excellent filtering property. The proposed antenna can be expanded to larger array and its metal structure makes itself very suitable for practical application.

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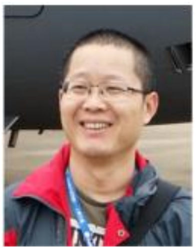

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