H-Plane Sectoral Filtering Horn Antenna in PCB Substrates Using Via Fences at Millimetre-Wave

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Abstract— **The design procedures and electrical performances of filtering antenna consisting of simply cascaded or embedded bandpass filter into H-plane sectoral horn antenna are investigated in this paper. The waveguide type filter and H-plane sectoral horn antenna have been replaced with considerably size-reduced PCB substrate-type filter and antenna using via fences. The simulation results have been obtained from the commercially available software, CST MWS based on FDTD algorithm.**

I. INTRODUCTION

Nowadays the frequency band reaches saturation in terms of frequency reuse with the help of the remarkable advancement of wireless communication systems. In a near future, the use of millimetre frequency band will be widely spread in many wireless communication systems for high speed data rate, light-weight hardware, and a low-cost fabrication.

Since the compact and cost-reduced devices have a relative importance in the front-end module, many researchers have studied for the low-loss transmission or transition, intelligent integration of several components and smart packaging technology.

In this paper, the combined integration of bandpass filter and horn antenna at millimetre-wave is suggested through the down-scaling conversion process from conventional waveguide(WR-22) structure to PCB embedded structure.

Generally, BPF which is located in front of antenna is acting as a discriminating device of in-band wanted signal and out-band unwanted signal. Many researchers have studied the combination of filter and antenna in waveguide to improve the electrical performances[8]-[9]. This paper deals with an implementation method on PCB substrate of filtering antenna in waveguide type. In addition to that, the down-scaled PCB integrated filter is inserted and embedded into the H-plane sectoral horn antenna to accomplish the size reduction of entire combined filtering antenna.

At that time, the electrical performances of filtering antenna still have excellent skirt characteristics at cut-off frequency and show that since the circular posts of the embedded filter into horn antenna make an influence on the direction of the fundamental mode, the radiation patterns are different according to the filtering antenna type.

II. DESIGN PROCEDURE

A. Design of Waveguide Filter Using Circular Post

Before the filter-design using dielectric materials, waveguide-type filter is introduced for design guidelines. The conventional waveguide BPF with circular posts along the symmetric axis, as shown in Fig. 1(a), is designed by showing an equivalent circuit (in Fig. 1(b)) and circuit parameters to meet system requirements. The equivalent circuit shown in Fig. 1(b) is composed of inductance and capacitance[1]-[2] and it represents Chebychev 3-rd order prototype with unknown impedances of divided 4 parts.

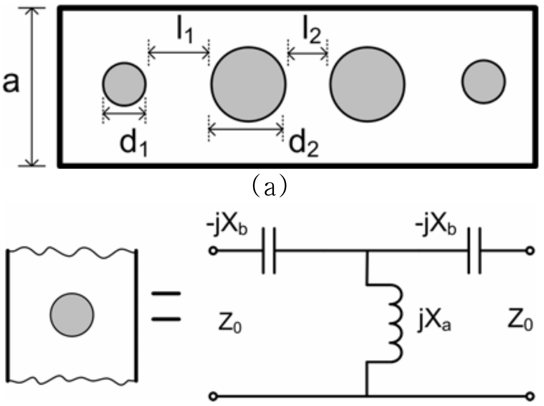


Fig. 1. (a) Parameters for circular inductive post waveguide filter. (b) Typical equivalent circuit for circular post in rectangular waveguide.

The radius and relative distance of posts can be estimated from the solved impedances at each stage and Fig. 2. At first, we defined the centre frequency and cut-off frequency as f_0, f_1 and f_2, respectively, resulting in the following notations[1].

$$w = \frac{f_2 - f_1}{f_0} \tag{1}$$

$$w_\lambda = \left(\frac{\lambda_g}{\lambda_0}\right)^2 \bullet w \tag{2}$$

Substituting Eq. (1), (2) and prototype parameters of Chebyshev filter into Eq. (3) and (4), the impedance inverters, K_{ij} at each stage can be evaluated as follows[1].

$$\frac{K_{01}}{Z_0} = \frac{K_{34}}{Z_0} = \sqrt{\frac{\pi}{2}\frac{w_\lambda}{g_0 g_1 w_1^{'}}} \tag{3}$$

$$\frac{K_{12}}{Z_0} = \frac{K_{23}}{Z_0} = \frac{\pi w_\lambda}{2w_1'} \frac{1}{\sqrt{g_1 g_2}} \tag{4}$$

The final impedances at each stage for filter design can be solved from impedance inverters, K as follows[1].

$$\frac{X_{j,j+1}}{Z_0} = \frac{\frac{K_{j,j+1}}{Z_0}}{1-\left(\frac{K_{j,j+1}}{Z_0}\right)^2} \tag{5}$$

Thus, the radius of circular posts can be determined from impedances parameters using Eq. (5) and Fig. 2 estimating circuit parameters.

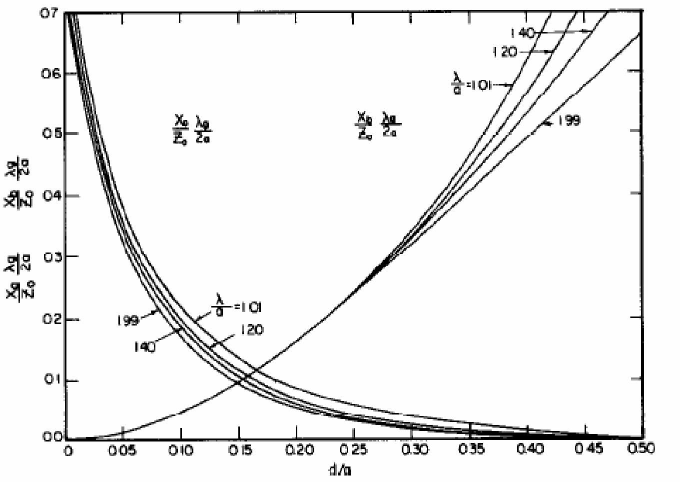


Fig. 2. Parameters for single circular post in rectangular waveguide[1].

Finally, the relative distance between two nearest posts can be determined from Eq. (6) and (7) listed in [1]

$$\theta_j = \pi - \frac{1}{2}\left[\tan^{-1}\left(\frac{2X_{j-1,j}}{Z_0}\right) + \tan^{-1}\left(\frac{2X_{j,j+1}}{Z_0}\right)\right] \tag{6}$$

$$l_1 = l_3 = \frac{\theta_1 \lambda_g}{2\pi}, l_2 = \frac{\theta_2 \lambda_g}{2\pi} \tag{7}$$

Based on the design process listed above, the 3-rd order Chebyshev BPF operating at millimetre wave with center frequency, $f_0 = 41.5$ GHz and fractional bandwidth(FBW), $FBW = 2.5\%$, is designed using the conventional waveguide WR-22. The values of design parameters are listed in Table1. It is necessary to tune finely parameters for satisfying the requirements and compensating the coupling effects between the nearest circular posts and effects caused by the negligence of capacitive component in equivalent circuit.

TABLE 1. GEOMETRICAL PARAMETERS OF THE WAVEGUIDE FILTER : Q-BAND WR-22 ($a \times b = 5.7 \times 2.8$ unit:mm)

Parameter	l_1	l_2	d_1	d_2
Computed	4.3	4.53	0.313	0.678
Optimized	4.5	5.07	0.222	0.592

B. Down-Scaling Process of Waveguide Filters into PCB

In order to implement the waveguide filter on PCB substrate (which is also called "SIW(Substrate Integrated Waveguide)"), the effects of the chosen dielectric material on the entire structure must be considered with the implementing method of side wall into PCB substrate[3].

$$\lambda_g = \frac{2\pi}{\beta} = \frac{2\pi}{\sqrt{k^2 - k_c^2}} \tag{8}$$

Eq. (8) indicates that k is very larger than k_c in millimetre wave for the fundamental mode. Hence the Eq.(8) can be rewritten as follows.

$$\lambda_g = \frac{2\pi}{k} = \frac{1}{\sqrt{\varepsilon_r}} \frac{2\pi}{k_0} \tag{9}$$

Thus, Eq. (7) and Fig. 2 lead to the relationship between the distance and impedance at each stage.

$$d = c_2 \frac{X_{01}}{Z_0} \frac{\lambda_g}{2c_1} \quad \text{where } c_1, c_2 = const. \tag{10}$$

$$l \,\&\, d \propto \lambda_g \propto \frac{1}{\sqrt{\varepsilon_r}} \tag{11}$$

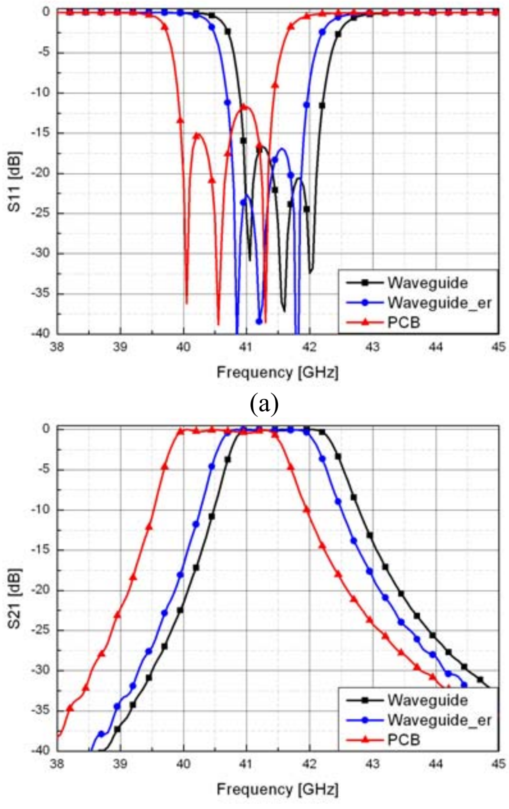
It is consequently observed that the length, l and the distance, d are inversely proportional to the square root of the relative dielectric constant. This means that when the conventional waveguide filter is converted into PCB substrate, the design parameter values of waveguide filter can be remarkably reduced except the vertical z-axis.

Next, the sidewall of the conventional waveguide is replaced with via holes of equal or unequal distance in array to meet the electric wall boundary conditions.

In order to reduce the leaky energy through via holes, it is recommended that the nearest distance of via holes should be less than two times via diameter and the diameter of via should be less than one tenth of wavelength of maximum frequency within in-band signals [4].

Fig. 3(a) and (b) shows the electrical performances of the conventional air-filled waveguide filter(WR-22), size-reduced dielectric-filled waveguide filter with vertical sidewall and PCB integrated waveguide filter with via holes by employing relative dielectric constant, $\varepsilon_r = 2.2$ and thickness, $h = 3.175$ mm and using commercially available software based on FDTD algorithm. They depict a good agreement among three waveguide filters.

The entire volume of the conventional waveguide filter, $5.7 \times 2.8 \times 19 = 303.24$ mm^3 has been considerably reduced to $3.843 \times 3.175 \times 12.8 = 156.18$ mm^3 .



(b)

Fig. 3. Simulated S-parameters of bandpass filter(BPF) (a) S11 (b) S21

C. *Design of Horn Antenna using Waveguide*

From the properly chosen aperture size (A) to meet antenna specifications, the other parameters for H-plane sectoral horn antenna are determined such that side lobe can be minimized and the directivity can be maximized [5].

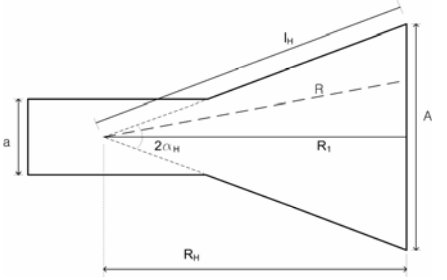


Fig. 4. Parameters for H-plane sectoral horn antenna, H-plane

$$A = \sqrt{3\lambda R_1} \tag{12}$$

$$l_H^2 = R_1^2 + \left(\frac{A}{2}\right)^2 \tag{13}$$

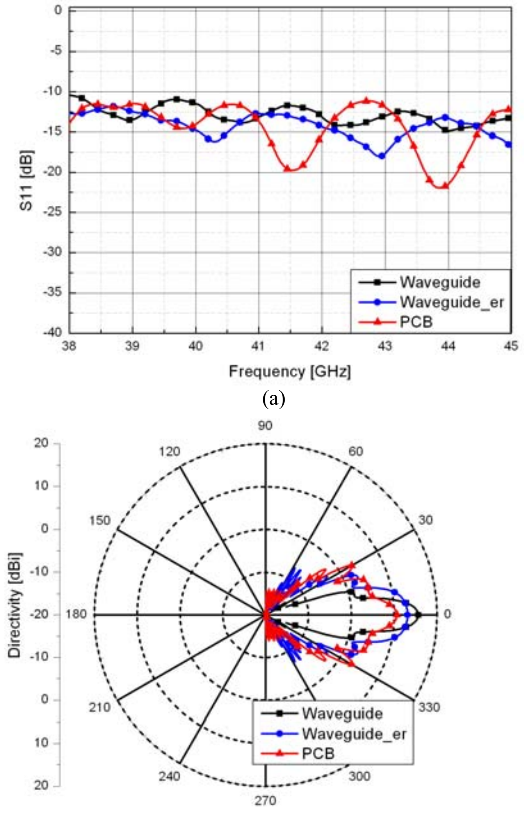
$$\alpha_H = \tan^{-1}\left(\frac{A}{2R_1}\right) \tag{14}$$

$$R_H = (A-a)\sqrt{\left(\frac{l_H}{A}\right)^2 - \frac{1}{4}} \tag{15}$$

Simulated result of waveguide-typed H-plane sectoral horn antenna is shown in Fig. 5. It indicates that the very low side lobe level and high directivity can be obtained from waveguide-typed horn antenna[6]-[7].

D. *Horn Antenna using PCB Substrate*

The PCB substrate integrated horn antenna can be designed in a similar way like a conversion process of waveguide filter in section II-B. The employed material is the same as that of filter design. In addition to that, size-reduction has been achieved from $5857.51\ \text{mm}^3$ to $1941.18\ \text{mm}^3$.



(b)

Fig. 5. Simulated results of horn antenna only (a) Return losses (b) Radiation pattern

III. FILTERING ANTENNA

Independently designed components (Filter/Antenna) having independent electrical functions are integrated into a single module. Due to the complexity of the effects according to the lengths between filter and antenna, the final optimized structure has been obtained from Full EM Simulation.

A. *Simply connected filtering antenna*

This configuration is a simple combination of independently matched filter and antenna as shown in Fig. 6. The used radii of via holes are 0.3mm and 0.8mm, respectively, and the distance between the nearest via holes is set to be 0.5mm to prevent leaky wave from guiding structure through side walls. The thickness of the employed substrate is assumed to be 3.175 mm.

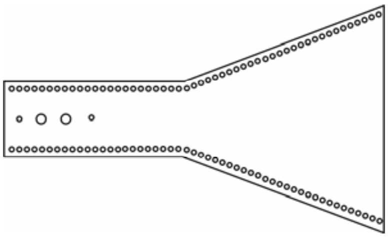


Fig. 6. Antenna configuration of simply connected filtering antenna

B. *Embedded Filtering Antenna*

As another suggested structure, consider the embedded filtering antenna shown in Fig. 7. In Fig. 7, the circular post inserted filter is embedded into H-plane sectoral horn antenna to reduce the total size of integrated module keeping the electrical performances. The return loss and radiation patterns according to two filtering antenna are listed in Fig. 8.

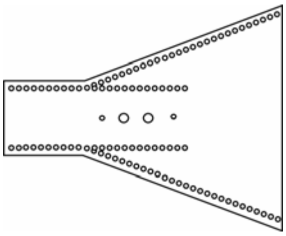
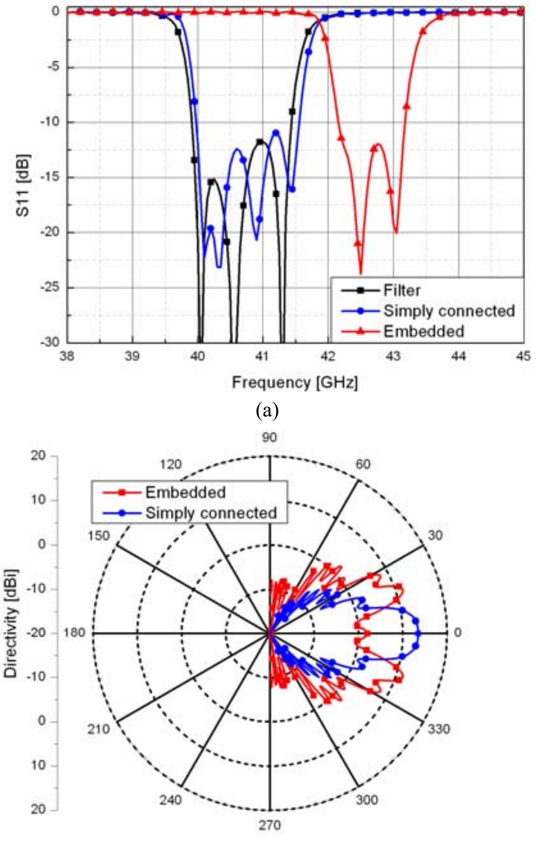


Fig. 7. Antenna configuration of embedded filtering antenna



(a)

(b)

Fig. 8. Return losses and radiation patterns according to filtering antenna types (a) Return losses (b) Radiation patterns

IV. CONCLUSIONS

A novel structure of bandpass filter embedded or inserted into H-plane sectoral horn antenna, which is called filtering antenna, is suggested and designed with design procedure and down-scaling process. The optimized values of design parameters have been obtained by using commercially available software. Especially, the advantage of reducing the size and keeping the electrical performances of each components of embedded filtering antenna rather than simply connected filtering antenna has been verified.

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