# Design of a high-power harmonic waveguide filter for radar transmitter

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## ABSTRACT

*In this article, we present the research results on the designing and manufacturing method of a high-power harmonic filter applied in the X-band transmitter system. The harmonic filter utilizes Waffle-iron filters and quarter-wavelength converters on the waveguide. As a result, the loss and ripple within the passband are improved, while meeting the requirements of cutting off high-order harmonics. Based on the application of microwave theory and simulation software tools, the research team have calculated, designed and manufactured a harmonic filter that meets all the requested specifications for application in X-band transmitter systems: Loss ≤ 0,12dB@8,9-9,6GHz; Reflection coefficient ≤ -20dB@8,9-9,6GHz; Frequency selectivity ≤ -40dB@2nd harmonic, 3rd harmonic, 4th harmonic.*

**Keywords:** *Waffle-iron* filter; Harmonic filter; Lowpass filter.

## 1. INTRODUCTION

The development of radio technology increasingly demands advanced design techniques and manufacturing technology for microwave components. One of these essential components is the microwave filter. The filter plays a crucial role in this system, functioning to eliminate unwanted frequency signals while allowing desired frequency signals to pass through. Harmonic filters are among the critical components of radar systems [3]. As we can see in the block diagram of a semiconductor radar system [3], it is evident that several filters are used to perform various functions. For instance, in the receiver, a harmonic filter is placed before the low-noise amplifier to eliminate high-order harmonic components. In the transmitter, a harmonic suppression filter is positioned at the output of the power amplifier to select the required frequency and eliminate unwanted high-order harmonic components. Additionally, it must meet the requirements of low loss and high power handling capability.

Today, there are many different types of filters used for radar applications, such as SAW filters, microstrip filters, coaxial cavity filters, and waveguide filters. Microstrip filters have the advantages of small size, low cost, and ease of fabrication [1]. However, their main drawback is high insertion loss because their quality factor (Q factor) is significantly lower than that of other types. Coaxial cavity filters offer many advantages, such as low loss and compact size, but they are challenging to manufacture at high frequencies [2]. Waveguide filters have the benefits of low loss and high power handling capability; however, their size is much larger compared to other filters [3]. The Waffle-iron filter, invented by Seymour B. Cohn at the Stanford Research Institute in 1957 [9], is based on the corrugated waveguide filter design. Waffle-iron filters are used when both wide passbands with low insertion loss and wide stopbands are required. They are particularly effective at suppressing high-order harmonics [5]. Some authors have focused on the study of low-pass filter design, for example the filter of F.Teberio [10] is a Waffle-iron low-pass filter with a bandwidth of 10,7 GHz to 11,7 GHz, Insertion loss less than 0.15 dB, stopband from 17 GHz to 21 GHz.

This paper presents the research results on the design and fabrication of a harmonic filter based on the Waffle-Iron waveguide structure due to its wide passband, low loss, broad stopband, and high power handling capability. Utilizing microwave theory and software simulation tools, the paper will outline the design method for a harmonic filter for X-band radar systems.

## 2. PROBLEMS

### 2.1. Synthesis of B. Cohn's corrugated waveguide filter model

B. Cohn's method involves initially designing a corrugated waveguide filter to create the necessary stopband, replacing the guided wavelength, $\lambda_{g0}$, with the free-space wavelength, $\lambda_0$. When the horizontal slot width (forming the folds) is determined, identical vertical slots are placed to achieve TEM filtering, and $b$ (the distance between two opposite ridges in a corrugated waveguide filter) is reduced to $b''$ to compensate for the reduction in parallel capacitance at the discontinuity. The calculation of virtual impedance is based on a circuit model as shown in figure 1, where transmission lines with alternating impedances $Z_1$ and $Z_2$ represent the sections of reduced and full height (of $b''$ and $b$), with corresponding lengths $l$ and $l'$. The parallel capacitance $C_2$ compensates for the transition effect, and $C_1$ compensates for the capacitance between two adjacent folds.

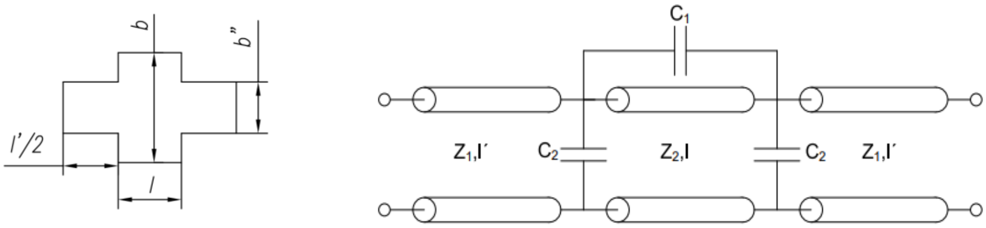


***Figure 1.*** *Cohn's corrugated waveguide filter model.*

The synthesis method does not directly involve the circuit model but instead uses the design charts published in [4], which provide dimensions for each specific stopband frequency. The synthesis process (based on the equations and diagrams in [5]) is carried out as follows:

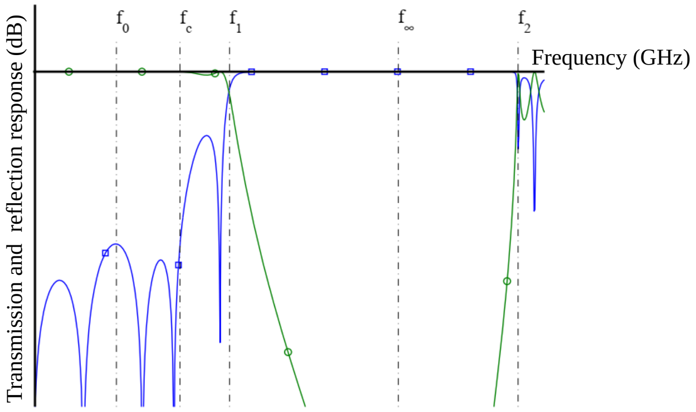


***Figure 2.*** *Definition of frequencies $f_0$, $f_c$, $f_1$, $f_\infty$ and $f_2$ for Waffle-iron filters.*

1. Select the upper cutoff frequency, $f_c$, and the upper stopband frequency, $f_2$.
2. Select the frequencies $f_1$ and $f_\infty$ based on the rule of thumb: $f_1 > 1{,}43f_c$ and $f_\infty \approx 0{,}8f_2$.
3. Select $b'$ and $l/b$ values.
4. Using the selected values in Step 3, as well as $\lambda_1/\lambda_\infty$, to determine $b_0/\lambda_1$ and $b/\lambda_1$ from figure 7.04-5 [5]. Then, calculate $b_0$, $b$, and $l$. Repeat Steps 2 through 4 until the appropriate values of $b$ and $l$ are found.
5. Use figure 7.04-6 [5] to calculate $G$ parameter, and use equation (1) to find $l'$. Repeat Steps 2 through 5 until a value $l'$ is found, that can satisfy the following equation:

$$tan\frac{\pi l'}{\lambda_g} = \pi\delta\frac{b}{\lambda_{g1}}\left[G - \frac{2}{\pi}ln\frac{1}{\delta} + 0{,}215\right] \qquad (1)$$

6. Use equation (2) to calculate the height of the main guiding bar, $b_T$, to optimize the Waffle-iron filter, and use equation (3) to calculate the peak distances *b''*. Repeat step 2 to 6 until a value of *b''* is found, that can satisfy equation (3).

$$b_T = \frac{b}{b_0}\sqrt{1 - \left(\frac{\lambda_{g1}}{\lambda_g}\right)^2} \qquad (2)$$

$$\frac{b''}{b'} = \frac{l'}{l+l'} + \frac{2}{\pi}\frac{l}{(l+l')}\left[tan^{-1}\left(\frac{b''}{b'}\frac{b'}{l}\right) + \frac{ln\sqrt{1+(lb'/b'b'')}}{\frac{l\,b'}{b'b''}}\right] \qquad (3)$$

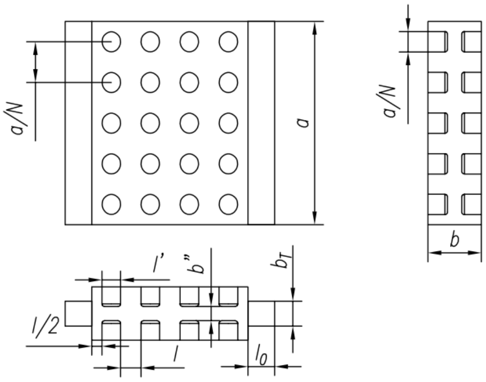


*Figure 3. Waffle-iron filter's model and dimensions.*

### 2.2. Calculate the Matching Elements in the waveguides

The proposed structure involves a transition in the waveguide height from $b_0$ to $b_2$ as shown in figure 4. To avoid reflection from the direct transistion, the authors use a quarter-wavelength section between these two parts. The height $b_1$ of this section is calculated using the following equation:

$$b_1 = \sqrt{b_0 \times b_2} \qquad (4)$$

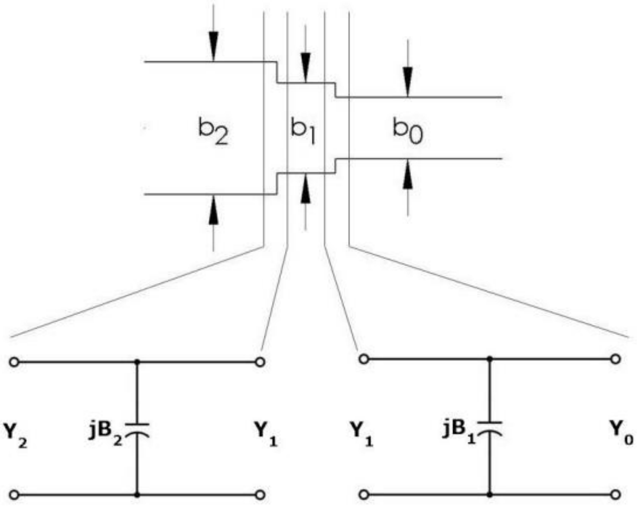


*Figure 4. Equivalent cirucit of the waveguide transistion region.*

In [6], mathematical equations have been provided to calculate the inductance due to the step discontinuities. Figure 4 shows the side view of the symmetrical step transitions along the axis in the proposed design and the corresponding equivalent circuits.

The impedance of an air-filled waveguide with a width of $a$ and a height of $b$ is given by the formula:

$$Z = \sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{b}{a}\right]\left[\frac{\lambda_g}{\lambda_0}\right] \tag{5}$$

where,

$\mu_0$ is the permeability in vacuum,

$\varepsilon_0$ is the vacuum permittivity,

$\lambda_g = \left(\sqrt{\lambda^{-2} - (2a)^{-2}}\right)^{-1}$ is the effective wavelength inside the waveguide,

$\lambda_0 = c/f$ is the wavelength in free space.

From [1] we receive:

$$\frac{Y_1}{Y_0} = \frac{b_0}{b_1} = \alpha_1 = 1 - \delta_1 \tag{6}$$

Here, $\delta_1 << 1$, so:

$$\frac{B_1}{Y_1} = \frac{2b_1}{\lambda_g}\left[\frac{\delta_1}{2}\right]^2\left[\frac{2ln\left(2/\delta_1\right)}{1-\delta_1} + 1 + \frac{17}{16}\left[\frac{b_1}{\lambda_g}\right]^2\right] \tag{7}$$

To compensate for these inductive values, the positions of the width transistions must be shifted towards the source, and the length of the matching element is reduced from the original value of $\lambda_g/4$ [7]. The new length of the matching element is:

$$l\_match = (\lambda_g/4) + x_0 - x_1 \tag{8}$$

where:

$$x_0 = \frac{\emptyset_0 \lambda_g}{720}$$

$$\emptyset_0 = tan^{-1}\left(\frac{B_0/Y_1}{Y_0/Y_1 - 1}\right) + tan^{-1}\left(\frac{B_0/Y_1}{Y_0/Y_1 + 1}\right)$$

$$x_1 = \frac{\emptyset_1 \lambda_g}{720}$$

$$\emptyset_1 = tan^{-1}\left(\frac{B_1/Y_2}{Y_1/Y_2 - 1}\right) + tan^{-1}\left(\frac{B_1/Y_2}{Y_1/2 + 1}\right) + 2tan^{-1}\left(\frac{B_0/Y_1}{Y_0/Y_1 + 1}\right)$$

### 2.3. Design method for Harmonic Filter on waveguides

Based on the synthesis theory of Cohn's corrugated waveguide filter and the calculation of matching elements in the waveguide transmission line, the authors have proposed a method for calculating and designing a harmonic filter using Waffle-iron filters, including the following steps:

- Based on the required parameters of the filter to be designed, specifically from the stopband requirements and the selectivity within the stopband, calculate the number of filters and the requirements for the Waffle-iron filter. The wider the stopband required, the more Waffle-iron filters need to be used in series. The structure of the Waffle-iron filter depends on the selectivity requirements within the stopband;

- From the requirements for the Waffle-iron filter, calculate the design parameters as outlined in section 2.2;

- Calculate the matching elements from the Waffle-iron filter to the standard waveguide as described in section 2.3. The number of quarter-wavelength elements depends on the passband requirements and the reflection coefficient within the passband;

- To optimize high power handling capability, the authors have proposed rounding the corners of the elements in the Waffle-iron filter. This is because the simulations showed that the electric field strengths is greatest at the edges of the elements in the Waffle-iron filter.

The optimization simulation process is carried out using CST Studio Suite software.

## 3. DESIGN, MANUFACTURING AND RESULTS

### 3.1. The design requirements for the harmonic filter

The requirements for the filter to be designed are as follows:

Passband : 8,9 ÷ 9,6 GHz;
Passband insertion loss : ≤ 0,2 dB;
Passband reflection coefficient : ≤ - 20 dB;
Stopband : 17 ÷ 40 GHz;
Attenuation stopband : ≤ -40 dB.

### 3.2. Calculation and optimization simulation

Based on the filter's stopband criteria, the authors decide to use two Waffle-iron filters. The first Waffle-iron filter has 5 rows and 4 columns, with frequencies $f_1$=12,5 GHz and $f_\infty$ = 24 GHz. The second Waffle-iron filter also has 5 rows and 4 columns, with frequencies $f_1$=19 GHz and $f_\infty$ = 38 GHz. The dimensional parameters of the Waffle-iron filters were calculated using B. Cohn' corrugated waveguide filter synthesis method as described in section 2.1. After calculating the dimension parameter $b_T$ , the impedance matching elements were calculated to match the standard WR90 waveguide (22,86 x 10,16 mm). To ensure the passband reflection coefficient requirements are met, two quarter-wavelength sections were used, with these dimensions calculated based on the formulas in section 2.2.

The calculated results were input into CST Studio Suite software for optimization simulation of the filter's characteristics. In the simulation model, the authors used an elliptical cylindrical model with rounded tops to enhance power handling capability. During the simulation, mechanical parameters $b_T$, $bm_1$, $bm_2$, $lm$ were optimally adjusted to achieve the best results. Table 1 presents the mechanical parameters of the filter after optimization. The 3D model and the optimized filter characteristics are shown in figure 5.

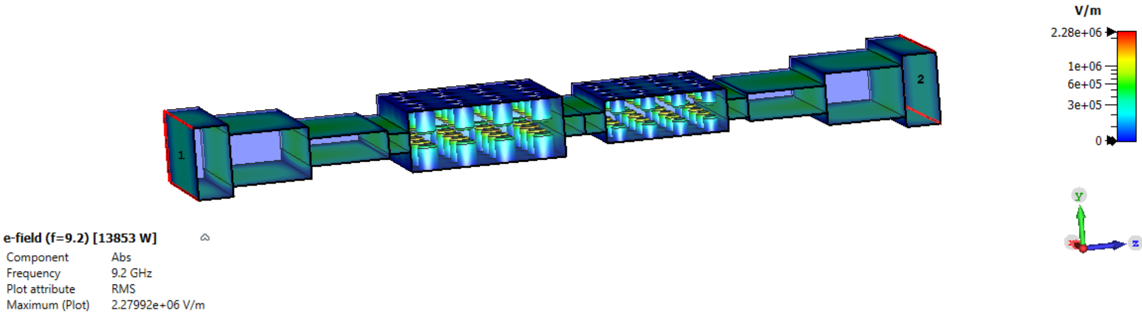
***Table 1.*** *Parameter value after optimaztion simulation of the filter.*

| *Waffle-iron I (5x4)* | | | *Waffle-iron II (5x4)* | | | *Waveguide transition* | | |
|---|---|---|---|---|---|---|---|---|
| *No* | *Parameter* | *Value* | *No* | *Parameter* | *Value* | *No* | *Parameter* | *Value* |
| 1 | $l'$ (mm) | 2,85 | 1 | $l'$ (mm) | 2,1 | 1 | b (mm) | 10,16 |
| 2 | l (mm) | 2,7 | 2 | l (mm) | 2,3 | 2 | a (mm) | 22,86 |
| 3 | $b_T$ (mm) | 2,8 | 3 | $b_T$ (mm) | 2,8 | 3 | $b_0$ (mm) | 2,8 |
| 4 | $b''$ (mm) | 1,65 | 4 | $b''$ (mm) | 1,6 | 4 | $bm_1$ (mm) | 3,9 |
| 5 | b (mm) | 8,5 | 5 | b (mm) | 6 | 5 | $bm_2$ (mm) | 7,3 |
| 6 | $l_0$ (mm) | 3,0 | 6 | $l_0$ (mm) | 3,0 | 6 | lm (mm) | 11,3 |

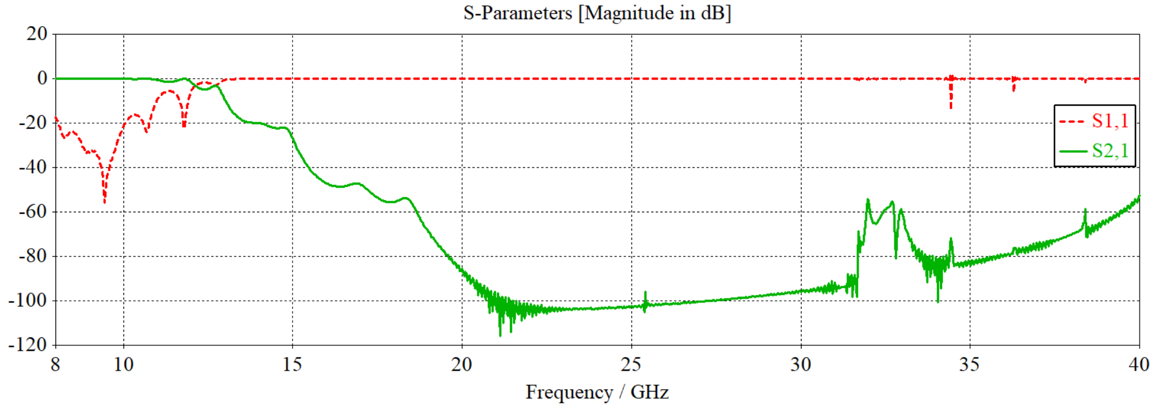
From the simulation results, we can see that all parameters meet the technical requirements of the filter. The electric field simulation results show that, with an input power of 1 W at a frequency of 9,2 GHz, the maximum electric field strengths is 19373,9 V/m. Therefore the filter has a power handling capacity at 9,2 GHz, calculated by formula (9), up to 13,85 kW. From the electric field simulation results in table 2, we can see that the filter model with rounded corners significantly improves power handling capability.

$$P_{max} = \left(\frac{E_b}{E_{max}}\right)^2 P_{in} \tag{9}$$

where, $E_b$ is the breakdown electric field strength in air, which has a value of 22,8 kV/cm RMS (or 30 kV/cm peak [5]).



*a) 3D model and electric field simulation results of the harmonic filter.*



*b) Harmonic filter's response*

**Hình 5.** *3D model and simulation results of the harmonic filter.*

**Table 2.** *Comparing the power handling capability of the harmonic filter.*

| *No* | *Parameter* | *Hamonic filter without rounded corners* | | | *Harmonic filter with rounded corners r = 0,3 mm* | | |
|---|---|---|---|---|---|---|---|
| 1 | *Frequency (GHz)* | *9,1* | *9,2* | *9,3* | *9,1* | *9,2* | *9,3* |
| 2 | *Input power (W),* $P_{in}$ | *1* | *1* | *1* | *1* | *1* | *1* |
| 3 | *Maximum electric field strengths (V/m RMS),* $E_{max}$ | *34348,9* | *34600,7* | *34728,2* | *19286,9* | *19373,9* | *19434,7* |
| 4 | *Maximum power handling (W),* $P_{max}$ | *4405,99* | *4342,10* | *4310,28* | *13974,8* | *13853,8* | *13763,7* |

### 3.3. Manufacturing and testing results

After the simulation, parameters were evaluated and found to meet the requirements, the authors generated technical drawings and used CNC machines to fabricate the filter from aluminum, with the interior of the waveguide plated with silver. The fabricated harmonic filter is shown in figure 6.

From the measurement results of the fabricated filter parameters, shown in figure 7, it can be seen that:

- Insertion loss in the frequency range of 8,9 to 9,6 GHz is: < 0,12 dB;
- Reflection in the frequency range of 8,9 to 9,6 GHz is: < -25 dB;
- The measured parameters are consistent with the simulation results in the frequency range of 8 GHz to 12 GHz.

***Figure 6.*** *The fabricated harmonic filter.*

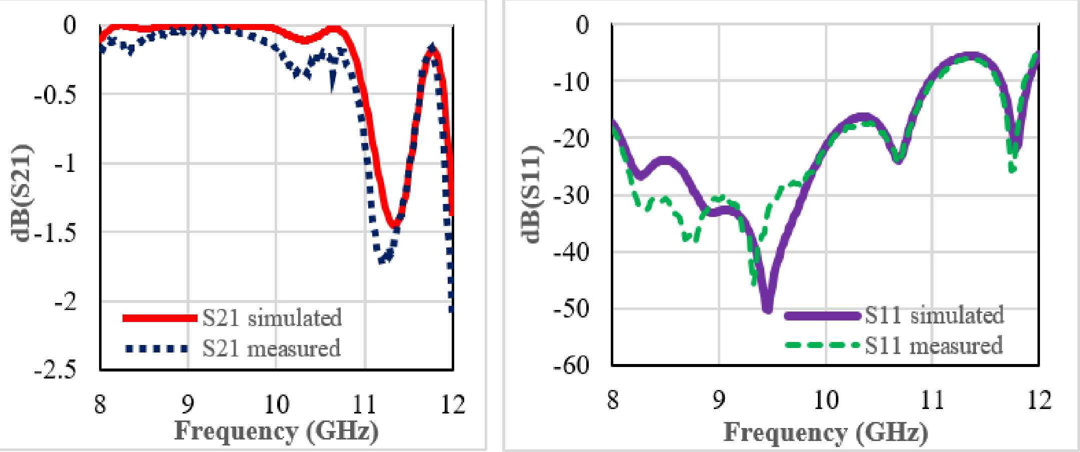


***Figure 7.*** *Simulation results and measurement results of the filter response.*

The simulation and measurement results of the designed harmonic filter are compared with some other filters in table 3. It clearly shows the advantages of the designed harmonic filter such as: wide stopband, low loss and high maximum power handling capability.

***Table 3.*** *Comparing the parameters of filters.*

| **No** | **Parameter** | **Unit** | **Zalotarev Low-Pass Filter [10]** | **Waffle-Iron Low-Pass Filter [9]** | **Harmonic Filter of this paper** |
|---|---|---|---|---|---|
| 1 | Passband | GHz | 9 ÷ 12,6 | 10,7 ÷ 11,7 | 8,9 ÷ 9,6 |
| 2 | Maximum insertion loss in passband | dB | 0,3 | 0,15 | 0,12 |
| 3 | Minimum return loss in passband | dB | 18 | 20 | 25 |
| 4 | Stopband | GHz | 14 ÷ 24 | 17 ÷ 21 | 17 ÷ 40 |
| 5 | Minimum attenuatin in stopband | dB | 40 | 60 | 50 |
| 6 | Maximum power handling | kW | - | - | 13,763 |

## 4. CONCLUSIONS

The paper presents the calculation and design method for a harmonic filter using Waffle-iron filters and quarter-wavelength converters on a waveguide. The simulation and fabrication results show that the filter parameters fully meet the requirements for low loss, high power and are applicable in X-band radar transmitter systems. These research and experimental results provide a foundation for extending the research to design and fabricate harmonic filters on waveguides for different frequency bands.

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## TÓM TẮT

### Thiết kế bộ lọc triệt hài công suất cao trên ống dẫn sóng sử dụng cho hệ thống phát đài ra đa

*Bài báo trình bày kết quả nghiên cứu phương pháp thiết kế, chế tạo bộ lọc triệt hài công suất cao ứng dụng trong hệ thống phát của đài ra đa băng X. Bộ lọc triệt hài sử dụng các bộ lọc Waffle-iron và chuyển đổi một phần tư bước sóng trên ống dẫn sóng. Do vậy, tổn hao và độ mấp mô trong dải thông của bộ lọc được cải thiện, đồng thời, đáp ứng được yêu cầu cắt được các hài bậc cao. Trên cơ sở ứng dụng lý thuyết siêu cao tần và các công cụ phần mềm tính toán mô phỏng, nhóm tác giả đã tính toán thiết kế chế tạo bộ lọc triệt hài đạt chỉ tiêu kỹ thuật ứng dụng trong hệ thống phát ra đa băng X: Tổn hao ≤ 0,12dB@8,9-9,6GHz; Hệ số phản xạ ≤ -20dB@8,9-9,6GHz; Độ chọn lọc tần số ≤ -40dB@hài bậc 2, hài bậc 3, hài bậc 4.*

**Từ khoá:** Bộ lọc *Waffle-iron*; Bộ lọc triệt hài; Bộ lọc thông thấp.