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Compact Band-Pass and Band-Reject Microwave Filters Using Partial H-Plane Waveguide and Dielectric Layers

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Abstract— **In this paper, microwave filters were designed using dielectric layers, which were transversely located inside a partial H-plane waveguide. The proposed structure can be used to design microwave filters with arbitrary frequency response including band-pass or band-reject filters. Its longitude was reduced by about 31% compared with conventional partial H-plane band-pass filters. Since the cross-section of partial H-plane waveguide, in a determined frequency range, is one quarter of the conventional waveguide, then the proposed filter has the cross-section of one quarter compared with the counterpart E-plane waveguide filter. Besides compactness, it is easy to fabricate, cheap, mass producible, mechanically stable, and capable of sustaining high microwave power and has very good adjustment to any arbitrary ideal filter. The proposed partial H-plane band-pass filter and its performance in terms of compactness and adjustment to any arbitrary ideal filter were verified by designing and simulating three filters.**

Keywords-Partial H-plane waveguide; Partial H-plane filter; Band-pass E-plane filter; Compact microwave filter; Band-pass microwave filter.

I. INTRODUCTION

Microwave filters have wide applications in microwave and communication systems. Some kinds of these filters include micro-strip filters [1, 2], substrate integrated waveguides (SIWs) [3], dielectric resonator (DR) filters [4, 5], waveguide filters filled with dielectric layers [6, 7], and waveguide filters filled with dielectric and magnetic layers [8] which are multi-layer longitudinally inhomogeneous waveguide (LIW) [9, 10]. Now, restriction in terms of size and weight of microwave components is a momentous consideration. In fact, in many applications, the total size of filter is reduced. There are always the challenges of size reduction and many methods have been proposed for compact microwave components. Since many microwave filters contain transmission line sections, some efforts have been made to reduce the length of transmission lines such as using DGS [11], fractal line [12], stepped stubs [13], and non-uniform transmission line [14]. Cut off frequency has an inverse relation to the dimension of waveguide so that increasing cut off frequency leads to size reduction [15]. Thus, some changes should be made to design a filter with suitable size, which works at lower frequency. Three types of band-pass filters using a new type of compact waveguide, namely partial H-plane waveguide, have been presented [16]. It has been shown that the cross-section of partial H-plane waveguide is one quarter of that of the conventional rectangular waveguide [17].

In this paper, using partial H-plane waveguide, in which several dielectric layers are inserted, a new type of compact band-pass microwave filter was proposed. The proposed structure did not employ inductive elements such as diaphragm, rods, irises, and posts; so, it was easy to fabricate. Besides, because of using partial H-plane waveguide in the proposed filter, its cross-section was one quarter of that of the conventional one, while their frequency responses were the same. Another trait of the introduced filter was replacing λ/2 waveguide sections as resonators with dielectric layers, which made it possible to considerably reduce the total length of the filter. Thus, the proposed filter had both advantages including reduced cross-sectional size and longitudinal length. To design the proposed filter, permittivity and thickness of dielectric layers had to be obtained. Performance of the proposed filter was verified using some theoretical and simulation examples.

II. Analysis of the Proposed Filter

Fig. 1 shows the partial H-plane waveguide. Partial H-plane waveguide is a conventional rectangular waveguide in which a partial metal vane is inserted in the H-plane. The cross-section of partial H-plane waveguide has one quarter cross-section of the conventional waveguide, while the dispersion characteristics of the first two dominant modes are the same [17]. Fig. 2 demonstrates the proposed dielectric filled partial H-plane filter which was made of K dielectric layers that were transversely inserted in a partial H-plane waveguide. Partial H-plane cross-sections were a and b and the vane width and thickness of partial H-plane vane were assumed to be d and zero, respectively. The relative electric permittivity and thickness of dielectric layers were $\varepsilon_{r,k}$ and d_k, respectively, for k=1, 2, …, K. The proposed structure did not vary in the transverse direction; thus, only dominant TE_{10} mode was propagated in the positive z-direction. The frequency domain analysis of multi-layer longitudinal inhomogeneous waveguides can be used to analyze the proposed structure. Based on this method, the chain parameter matrix of total structure can be written as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{k=1}^{K} \mathbf{T}_k \tag{1}$$

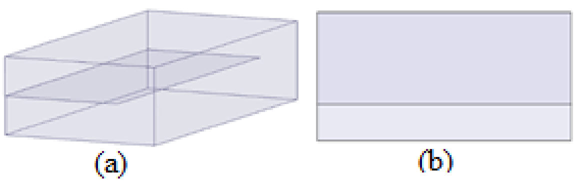

Fig.1. Partial H-plane waveguide. (a) Side view. (b) Top view.

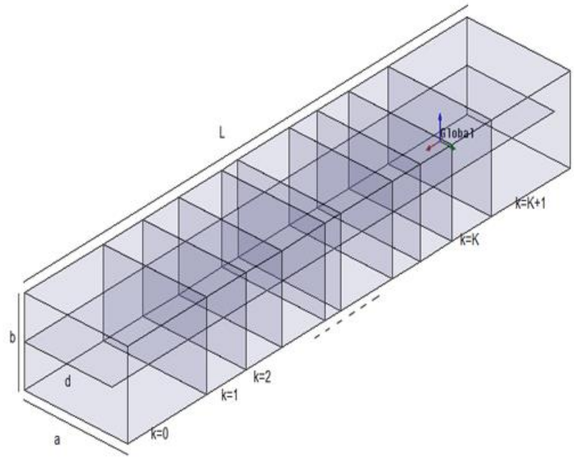

Fig. 2. The proposed dielectric filled partial H-plane filter.

where $\mathbf{T}_k$ is chain parameter of the k-th dielectric layer and can be written as follows:

$$\mathbf{T}_k = \begin{bmatrix} \cos(\beta_k d_k) & jZ_k \sin(\beta_k d_k) \\ j\sin(\beta_k d_k)/Z_k & \cos(\beta_k d_k) \end{bmatrix}. \tag{2}$$

In (2), β_k and Z_k are propagation coefficient constants and characteristic impedance, respectively, as follows:

$$\beta_k = k_0 \sqrt{\varepsilon_{r,k} - (f_c/f)^2}. \tag{3}$$

$$Z_k = \eta_0 \Big/ \sqrt{\varepsilon_{r,k} - (f_c/f)^2}. \tag{4}$$

where $k_0 = 2\pi f/c$ is the wave number of electromagnetic wave and $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ is the intrinsic impedance of wave both in free space. For finding scattering parameters, conversion of T-parameter into S-parameter can be used:

$$S_{11} = \frac{AZ_0 + B - CZ_0^2 - DZ_0}{AZ_0 + B + CZ_0^2 + DZ_0}. \tag{5}$$

$$S_{12} = S_{21} = \frac{2Z_0}{AZ_0 + B + CZ_0^2 + DZ_0}. \tag{6}$$

$$S_{22} = \frac{-AZ_0 + B - CZ_0^2 + DZ_0}{AZ_0 + B + CZ_0^2 + DZ_0}. \tag{7}$$

where Z_0 is the characteristic impedance of partial H-plane waveguide at the center frequency given by:

$$Z_0 = \eta_0 \Big/ \sqrt{1 - (f_c/f)^2}. \tag{8}$$

III. Design Procedure

To design the proposed filter, values of the relative permittivity of dielectric layers and their thicknesses had to be obtained so that a predefined frequency characteristic could be achieved in a frequency domain. The designed method was based on the optimization of a suitable fitness function along with limiting conditions for easy fabrication or implementation consideration. On the other hand, the amplitude of S_{21} parameter of the proposed structure was adjusted to the transfer function of arbitrary desired filter in a frequency range. That frequency range was indicated by some frequency samples with equal distance. So, the following fitness function can be defined for M discrete frequencies $f_1, f_2, \ldots, f_M$ all in the frequency domain:

$$fitness = \sqrt{\frac{1}{M}\sum_{m=1}^{M}\left\| s_{21}(f_m) \right| - \left| H(f_m) \right\|^2}. \quad (9)$$

In (9), $\left|s_{21}(f_m)\right|$ is the absolute value of the proposed scattering parameter and $|H(f_m)|$ is the absolute value of any desired transfer function both at frequency f_m. Here, the fitness function is defined based on the mean square error, by which the amplitude of desired ideal filter is related to the amplitude of S_{21} parameter of the proposed structure; so, optimum values including dielectric layer lengths and their relative electric permittivity will be obtained.

The number of dielectric layers inserted in the partial H-plane waveguide was arbitrarily chosen; if the precision of transfer function of the designed filter were not acceptable, the number of layers must be increased.

Moreover, some restrictions could be dispensed on dielectric lengths and their permittivity for easy fabrication and implementation considerations. These constrained conditions are as follows:

$$d_k \geq d_{\min} \quad (10)$$

$$1 \leq \varepsilon_{r,k} \leq \varepsilon_{r,\max} \quad (11)$$

for k=1,2, … K.

IV. EXAMPLE AND RESULTS

Example I: In this section and in the first example, a third-order Chebyshev band-pass filter with the center frequency of 5 GHz, fractional bandwidth (FBW) of 5%, and equal ripples of 0.01dB in passband using partial H-plane waveguide was designed. Cross-sectional dimensions of this partial H-plane waveguide were a=23.8 mm and b=12 mm and width of the metal vane was d=20.2 mm. Also, the thickness of metal vane was assumed to be zero. The number of dielectric layers inserted in the partial H-plane waveguide was K= 15. In [17], the cutoff frequency of $f_c = 3.35GHz$ for the dominant mode was calculated by both analytic and numerical methods, which was equivalent to the dominant cut-off frequency of the conventional waveguide with the dimension of a=47.55 mm and b=22.15 mm. Then, the value of characteristic impedance was Z_0=485.9 (ohm). Thus, it is obvious that this kind of filter possessed the cross-section of one quarter compared to the counterpart E-plane waveguide filter.

Optimization constrained conditions were set so that dielectric layer thicknesses were greater than or equal to d_{min}=0.4 mm and maximum relative electric permittivity was $\varepsilon_{r,\max} = 13$. The frequency range of optimization was 4.5-5.5 GHz, $f_1 = 4.5$ GHz, and $f_M = 5.5$ GHz and the number of equally spaced frequency samples was M=51. Table I shows optimum relative permittivity and thickness of dielectric layers which were obtained using optimization process. Fig. 3 illustrates the optimum relative permittivity of dielectric layers. Also, Fig. 4 demonstrates optimum thickness values of dielectric layers.

Fig. 5 compares the transmission response of the band-pass filter designed with MATLAB and simulated by HFSS and that of the ideal one. It is obvious that there was an excellent agreement between three curves in the frequency range.

It can be deduced from the optimum values of Table I that the proposed filter had the length of L=100 mm; its length can be compared with that of three compact partial H-plane waveguide filters, as presented in [18]; thus, it can be concluded that this filter was 31% shorter than the most compact one among those filters.

TABLE I. Optimum parameter of example I of the proposed filter.

Part No	**0, 16**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
L (mm)	20	3.8	14.2	6.4	7	4.1	10.3	4.64
$\boldsymbol{\varepsilon_r}$	1	11	13	1	13	1	13	1

Part No	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
L (mm)	7.0	5.6	8.95	0.72	9.51	5.7	5.5	6.52
$\boldsymbol{\varepsilon_r}$	13	1	13	1.02	13	1	13	4.74

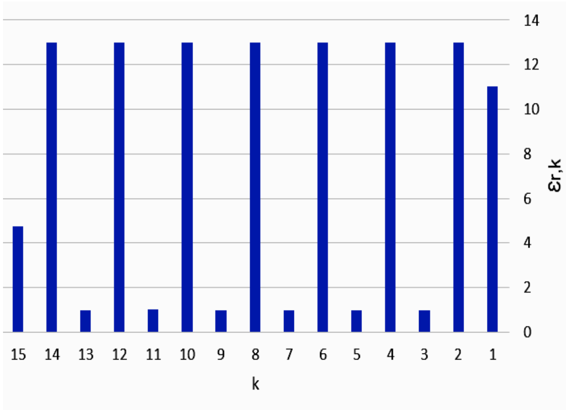

Fig. 3. Optimum relative permittivity of dielectric layers for example I.

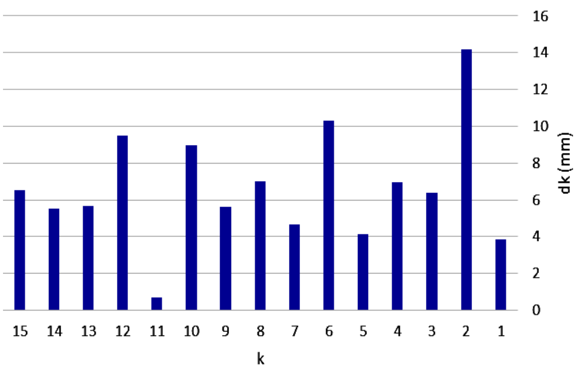

Fig. 4. Optimum thickness values of dielectric layers for example I.

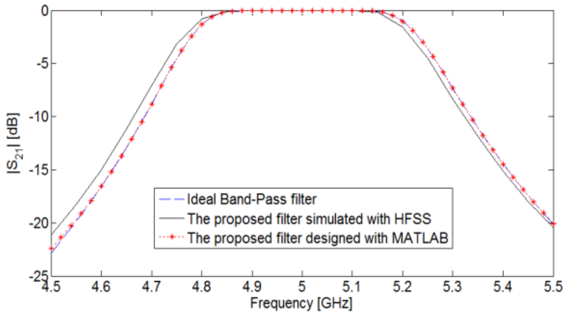

Fig. 5. Transmission response of band-pass filter of example I designed with MATLAB and simulated by HFSS and that of the ideal one versus frequency.

Example II: In this section and in the second example, the same filter as in example I with new restriction on the maximum value of relative electric permittivity of dielectric layers was designed. Here, it was assumed that $\varepsilon_{r,\max} = 10$ and all other specifications were the same as the former example. Table II shows optimum relative permittivity and thickness of dielectric layers of example II. Fig. 6 illustrates the optimum relative permittivity of dielectric layers. Also, Fig. 7 demonstrates optimum thickness values of dielectric layers.

Fig. 8 compares the transmission response of the band-pass filter designed with MATLAB and simulated by HFSS and that of the ideal one.

The length of the filter was L=100 mm. It is obvious that, with a limitation on maximum dielectric permittivity, the agreement between the desired and optimum curves was degraded. Also, as the number of dielectric layers, K, increased, the adjustment precision increased.

TABLE II. Optimum parameter for the proposed filter in example II.

Part NO	**0, 15**	**1**	**2**	**3**	**4**	**5**	**6**
L (mm)	20	20.3	3.96	7.83	6.08	8.18	2.79
$\boldsymbol{\varepsilon_r}$	1	10	2.94	10	1	10	4.64

Part NO	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
L (mm)	11.5	5.06	7.84	5.22	9.9	0.59	7.4	3.34
$\boldsymbol{\varepsilon_r}$	10	1.48	10	1.29	10	3.53	10	8.3

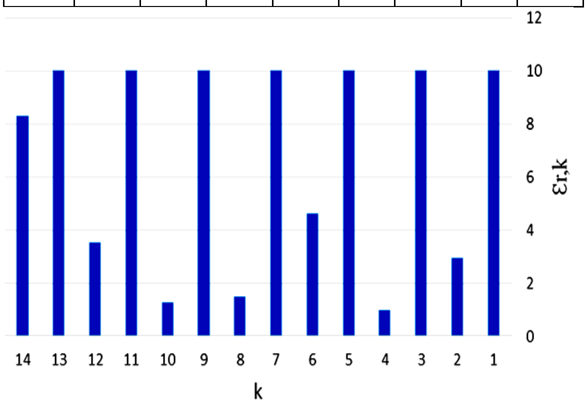

Fig. 6. The optimum relative permittivity of dielectric layers for example II.

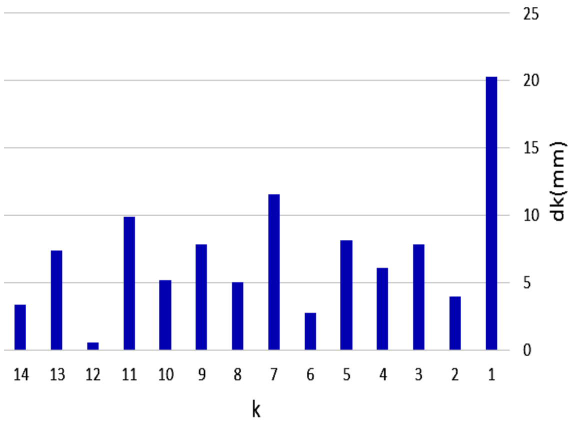

Fig. 7. Optimum thickness values of dielectric layers for example II.

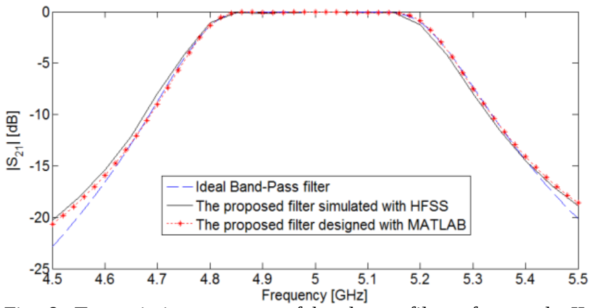

Fig. 8. Transmission response of band-pass filter of example II designed with MATLAB and simulated by HFSS and that of the ideal one versus frequency.

Example III: In this section and in the third example, a third-order Chebyshev band-reject filter with the center frequency of 5 GHz, fractional bandwidth (FBW) of 10% and equal ripples of 1 dB was designed in passband using partial H-plane waveguide. Here, the length of filter was L=150mm. Also, it was assumed that $\varepsilon_{r,\max} = 15$ and all other specifications of the structure were the same as the former example. The number of dielectric layers inserted in the partial H-plane waveguide was K= 17.

Frequency range of optimization was 4-6 GHz and the number of equally spaced frequency samples was M=67.

Table III shows optimum relative permittivity and thickness of dielectric layers of example III. Fig. 9 illustrates the optimum relative permittivity of dielectric layers. Also, Fig. 10 represents optimum thickness values of dielectric layers.

Fig. 11 compares the transmission response of the band-reject filter designed with MATLAB and simulated by HFSS and that of the ideal one. As demonstrates, there was about 3 dB ripple in the passband of transmission response, which was negligible in some applications and had a sort of good stopband.

TABLE III. Optimum parameter for the proposed filter in example III.

Part No	0, 18	1	2	3	4	5
L(mm)	20	9.5	2.2	9.95	4.19	10. 27
ε_r	1	15	1	15	1	15

Part No	6	7	8	9	10	11
L(mm)	1.03	18. 54	3.72	8.96	17. 2	2.83
ε_r	2.39	15	1	15	2.99	1

Part No	12	13	14	15	16	17
L(mm)	2.84	20.3	9.02	4.22	8.92	16.29
ε_r	15	2.95	15	1	15	8.03

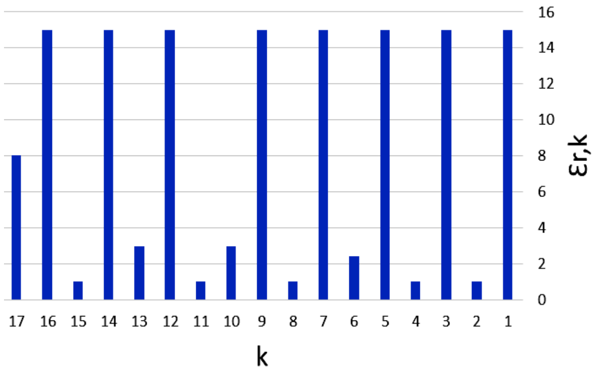

Fig. 9. The optimum relative permittivity of dielectric layers for example III.

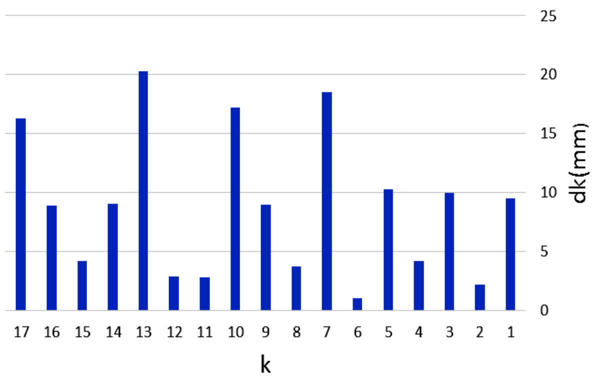

Fig. 10. Optimum thickness values of dielectric layers for example III.

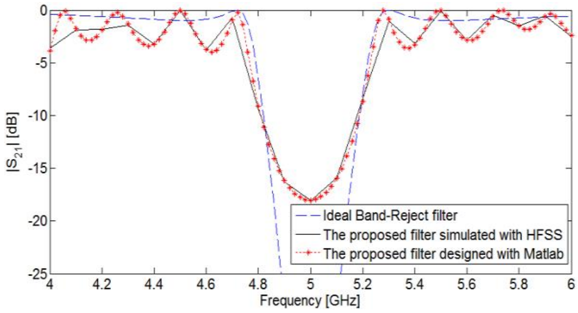

Fig. 11. Transmission response of band-reject filter of example III designed with MATLAB and simulated by HFSS and that of the ideal one versus frequency.

V. CONCLUSION

In this article, a new kind of compact microwave filter was proposed. The proposed compact filter was made of some dielectric layers which were transversely inserted in a partial H-plane waveguide. Because of using partial H-plane waveguide, this filter had one quarter cross-section compared with the conventional waveguide filter for the same frequency response. Moreover, it had considerably shortened total longitudinal length compared with that of the existing partial H-plane waveguide filters. Some other advantages of the proposed filter included its easy fabrication since there was no requirement on the inductive elements in its structure, high mechanical stability, ability of being used in high microwave power, and ability of designing a arbitrary kind of filters. Also, it was possible to arbitrarily close frequency response of the proposed filter to that of the desired one by increasing the number of dielectric layers. Usefulness and performance of the proposed structure were confirmed and verified by designing and simulating some filters.

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