Efficient Design of Waveguide Filters Reducing Modal Interference through Cross-Shaped Slots

Sungtek Kahng

Abstract

In this paper, a new method is suggested to improve the frequency responses of dual-mode waveguide-filters that employ cross-shaped slots. In accordance with this method, regarding one cross-shaped slot between two cavities, the horizontal(vertical) mode in one cavity can be designed to influence far less the vertical(horizontal) mode in cavity. Therefore, it improves the overall performances. A 4th-order dual-mode filter is taken as an example and it validates the method.

Key words : Modal Interference, Dual-Mode Waveguide Filter, Slot Couplings.

Ⅰ. Introduction

During the last few decades, the demand on high frequency-telecommunication has been enormously increased up to broad-band service. It also has driven the rapid growth of Satellite as well as mobile communication technologies. Along with them, waveguide filters have been recognized as essential components for handling higher power, signal filtration, etc, and a number of their design techniques have been introduced and developed so far[1]~[12].

In waveguide structures, adjacent cavities of high Q factors are electromagnetically coupled through slots. The major part of designing a waveguide filter is the determination of the couplings between its resonance modes for having the specified frequency responses. The shapes and initial physical sizes of the slots for the given couplings are obtained by full-wave analysis methods such as the Mode Matching Technique[5]~[9], the Coupled Integral Equation Technique[10], the Finite Element Method and so forth[11] or by mathematical or empirical approximate formulas[13],[14].

As usual, waveguide filters are bulky, but can be smaller and lighter by adopting dual- or multiple-mode couplings[2]~[12] where cross-shaped slots are frequently used. If the horizontal(or vertical) mode in one mode undesirably interferes with the vertical(or horizontal) mode in another cavity, the overall performance of a filter can be ruined. This needs to be fixed by suppressing the unwanted disturbance for keeping the orthogonality of modes.

In this paper, a new method is proposed to suppress the undesirable modal interference occurring through the cross-shaped slot, while the required coupling relation is maintained. A 4th-order dual-mode filter is designed and the simulation results obtained before and after deciding proper slot sizes are compared for validating the proposed method.

Ⅱ. Theory

Depending on filter requirements, various kinds of coupling mechanism can be chosen. Generally, they can be expressed as the two-port network found in [2], [3] that has the following mathematical form.

$$\overline{\overline{Z}} \cdot \overline{I} = \overline{e} \tag{1}$$

where $\overline{e}^T = (1, 0, 0, \cdots, 0, 0)$ is the voltage excitation and $\overline{I}^T = (i_1, i_2, i_3, \cdots, i_{n-1}, i_n)$ the current vector.

$$\overline{\overline{Z}} = j(\tau \overline{\overline{U}} + \overline{\overline{M}}) \tag{2}$$

has self- and mutual coupling values of the n-th order network.

$$\tau = \frac{f_0}{\Delta f}\left(\frac{f}{f_0} - \frac{f_0}{f}\right) \tag{3}$$

$j = \sqrt{-1}$ and $\overline{\overline{U}}$ is the identity matrix. S-parameters for the network can be represented by the following equations, which stand for transmission and reflection coefficients.

$$S_{21} = 2\sqrt{R_{in} R_{out}}\, i_n \tag{4}$$

$$S_{11} = 1 - 2R_{in}\, i_1 \tag{5}$$

The normalized input(output) resistance $R_{in}(R_{out})$ is related to the input(output) port coupling. The elements

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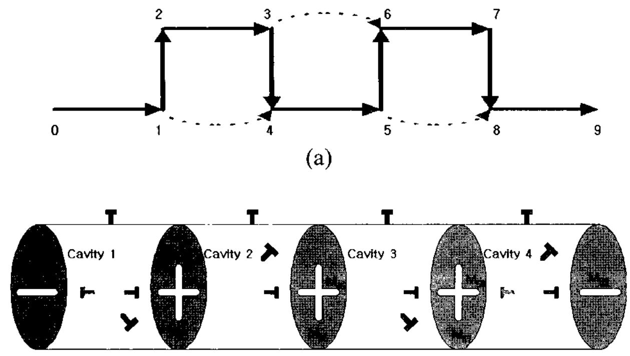


Fig. 1. (a) Signal flow of an 8th-order dual-mode filter, (b) Structure of an 8th-order dual-mode waveguide filter.

of $\overline{\overline{M}}$ or M_{pq} imply the inter-cavity couplings and $M_{pp}=0$. Also, M_{pq} can be concerned with inverter constant K_{pq} as in [7]

$$K_{pq}=M_{pq}\frac{3\pi\cdot\Delta f}{2f_o} \tag{6}$$

f_o is the center frequency and Δf is the bandwidth. If an 8th order dual-mode filter is selected, its in-line type can have the following signal flow and structure. Fig. 1(a) shows how the nodes(resonance modes) are related, and Fig. 1(b) has the circular waveguide cavities, screws, rectangular- and cross-shaped slots.

When a waveguide filter is designed, a rectangular slot is used for coupling between modes(of transverse electric fields) in different cavities, which are polarized in a parallel or anti-parallel manner. In a dual-mode circular waveguide filter, in each cavity there appears a pair of degenerate modes(or polarizations) that can be coupled by the screw in between. Assumed that two adjacent cavities are coupled through a cross-shaped slot, two pairs of modes along the two cavities shown in Fig. 2.

Roughly, a cross-shaped slot can be thought of as being composed of a vertical slot(or vertical arm) and a horizontal one(or horizontal arm). Accordingly, the vertical arm is used for the coupling of horizontal modes, and the horizontal arm couples vertical modes. Like this, as far as the slot-coupling mechanisms of the vertical and horizontal modes are independent each of the couplings is independently determined with the shape and sizes of its corresponding slot.

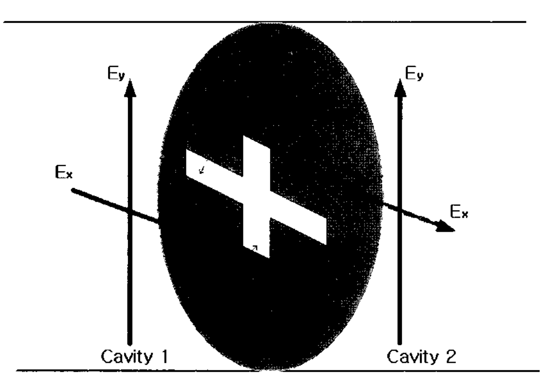


Fig. 2. Coupling through a cross-shaped slot.

As the frequency increases the higher-order modes can be ignored no longer. They start to reactively disturb independence between the aforementioned couplings. It can be verified by full-wave analysis results that no elements of the generalized scattering matrix are zero or no equivalent-circuit parameters are purely imaginary for the slot-discontinuity. If a slot is either vertical or horizontal one, almost only the dominant modes should be considered. However, if the cross-shaped slot has to be used, the vertical(or horizontal) mode in cavity 1 influences the horizontal(or vertical) mode in cavity 2, though its horizontal and vertical arms have been separately used for obtaining the initial sizes. Particularly, when slot-width increases and becomes closer to slot-length not only the dominant component of the electric field but also the other components get to transmit through it in the cross-section of a circular cavity. Given the sizes which have been separately obtained as those of rectangular arms, each coupling value will change, after they are combined into the cross-shape.

Seeing how the electric field distributes in a circular cavity, with reference to the polarization of the excitation field, except for the line along 0° or 90°, neither of two orthogonal components vanishes. For instance, the two electric field components, say, E_x and E_y have the same amount of intensity at 45°. Regardless of its shape, a slot occupies a finite area including the center of a transverse plane where both E_x and E_y exist. If the y-direction size(width)of the slot for E_x-coupling is increased it enables more E_y to transmit from one cavity to the other. As to the E_y-coupling, its width affects it in the same way.

There may be a variety of ways in obtaining the initial sizes of the rectangular slots such as vertical and horizontal arms, once all the needed coupling values are computed for the specified frequency responses. One of them is that the coupling values of modes p and q are converted into magnetic polarizabilities $P_{M,\text{int},pq}$.

$$P_{M,\,\text{int},\,pq}=\frac{l_c^3(3R_c^2)}{\lambda_0^2}\frac{\Delta f}{f_o}M_{pq} \tag{7}$$

R_c, l_c and λ_o denote the cavity radius, the cavity length and the waveguide wavelength at the center frequency, respectively. And then, $P_{M,\mathrm{int},pq}$ or P_{in} is taken as goal values and the sizes are searched using the following approximate formula[14].

$$P_{in}(L_s)=P_m'(L_s)10^{-\alpha}/\left[1-\left(\frac{\lambda_1}{\lambda_o}\right)^2\right] \tag{8}$$

where

$$P_m'(L_s)=L_s^3\left[0.187+0.052\left(\frac{W_s}{L_s}\right)\left(1-\frac{W_s}{L_s}\right)\right]/ \\ /\left[In\left(1+2.12\frac{L_s}{W_s}\right)\right],$$

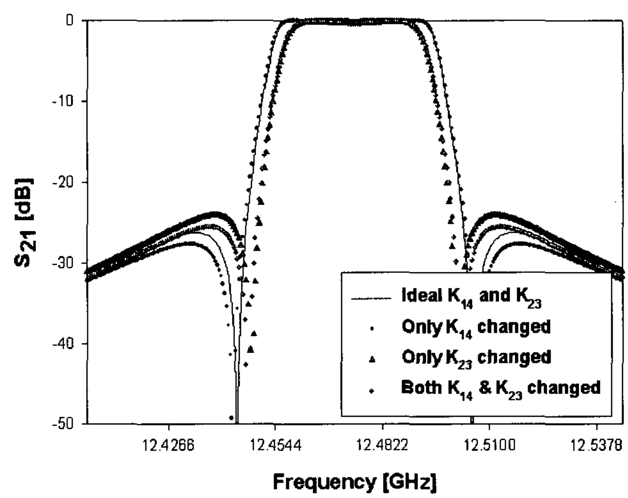
$$\alpha=\frac{8.19t_s}{\lambda_1}\sqrt{1-\left(\frac{\lambda_1}{\lambda_o}\right)^2}$$

L_s, W_s, t_s and λ_l denote the slot length, width, thickness and slot resonance length, respectively. Equation (8) implies that different sets of the slot width and length can produce one result. For one coupling, if the slot width is smaller, the slot length should be larger. At this point, the following method is proposed. First, a cross-shaped slot is decomposed into the vertical and horizontal arms and their initial sizes are independently evaluated using Equation (8) for their own couplings. Second, a full-wave analysis method is employed to observe possible change of the couplings, when the two arms are combined into the cross-shaped discontinuity. Third, it is checked how much the change in couplings varies the overall performance. Fourth, if it does not satisfy the specification, returning to step 1, taking into account feasibility, the new width and length will be sought. Then, the slot will be narrower and longer to suppress the undesirable modal interference.

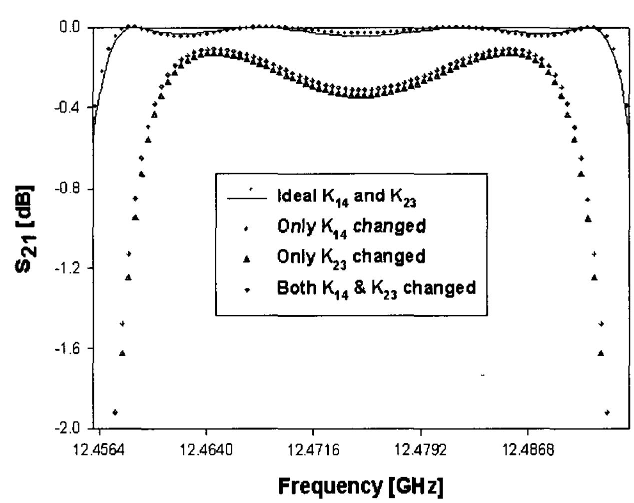
Ⅲ. Numerical Experiments and Results

In the process of designing a dual-mode waveguide filter that will show 12.475 GHz as center frequency, 0.25 dB as ripple, a 35 MHz wide pass-band, attenuation less than −25 dB at 12.44 GHz and 12.51 GHz, the fourth-order one turns out to be proper. If a symmetric structure is assumed circuit parameters $R_{in}=R_{out}$ (Input/output impedance), $K_{12}=K_{34}$, K_{14}, and K_{23} are solved as the coupling values(or inverter constants) K_{ij} between the i-th and j-th modes. Particularly, K_{14} and K_{23} are of interest, for these are related to the horizontal and vertical arms of the cruciform slot, respectively. Through computation, K_{14} and K_{23} are ideally −0.003093 and 0.010020, in order. They are obtained as long as the slot-coupling mechanisms of the vertical and horizontal modes are independent. For physical realization, with 1.2 mm as the common width for the two couplings, by way of Equation (8) and extra calculation, the initial lengths are sought as 4.045 mm for K_{14} and 5.920 mm for K_{23}. Pertinently adjusting these initial sizes for the rectangular arms, the cruciform slot is formed in a circular-cavity structure of 11.5 mm as its radius and TE_{mnp} with $m=n=1$ and $p=3$ as its resonance mode. Performing a full-wave analysis on this cruciform slot in the cavities with the help of the Agilent HFSS, K_{14} changes to −0.002851 and K_{23} to 0.008280. Fig.'s 3 present the influence of the changed couplings on the overall transfer performance, denoted as S_{21}.

As in Fig. 3, the change of cross coupling K_{14} influences the frequency responses little, but the reduced K_{23} deteriorates the passband performance very much, reducing the bandwidth and the number of in-band zeros, and so on. Rectangular slot-based sizes have been directly used for the cruciform geometry and the forward coupling K_{23} is interfered a lot.



(a)



(b)

Fig. 3. (a) S_{21}'s for different coupling values, (b) Pass-band insertion losses for different coupling values.

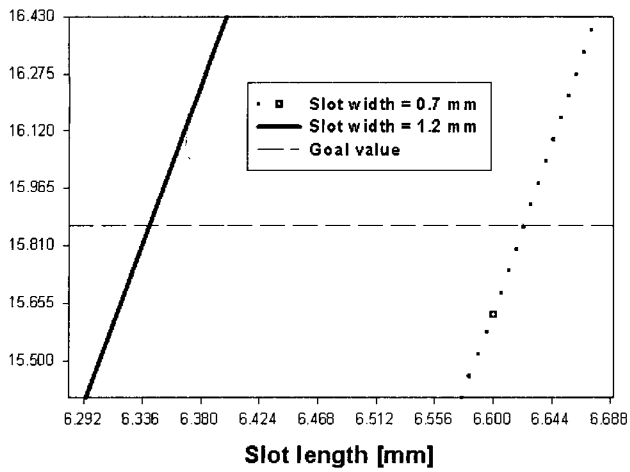


Fig. 4. Two sets of the width and length for $P_{M,\mathrm{int},pq}$.

For the unnecessary interference to be suppressed more, the narrower and longer rectangular arms should be considered. Simultaneously, they must result in the ideal values of K_{14} and K_{23}, when forming the cruciform slot. In Fig. 4, two sets of the approximate slot width and length are given for the same magnetic polarizability.

When the former width 1.2 mm is replaced by 0.7mm(still physically realizable) the slot becomes longer as seen in Fig. 2. Therefore, correcting the approximate lengths to precise ones, the slot lengths become 4.390 mm for the horizontal arm and 6.580 mm for the vertical arm. They are put into the HFSS work and K_{14} and K_{23} are evaluated as −0.003041 and 0.010012. This improves the overall performances as in Fig. 5.

It represents that through the narrower and longer arms of the cruciform slot, the horizontal(vertical) mode in cavity 1 hardly disturbs the vertical(horizontal) mode in cavity 2.

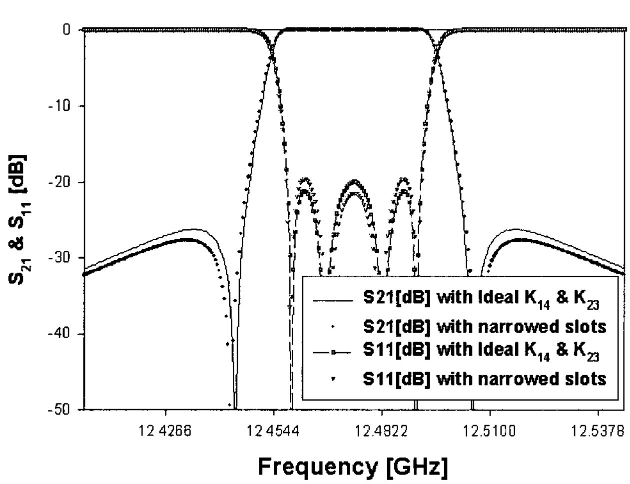


Fig. 5. Improved frequency responses.

Ⅳ. Conclusion

When a cross-shaped slot, which is decomposed to vertical and horizontal arms, is adopted for two sets of mode couplings, the field couplings corresponding to the orthogonal arms undesirably interfere such that the frequency responses of a waveguide filter are deteriorated. A method is proposed to reduce the undesirable modal interference, examining the level of deviation from the wanted coupling through the full-wave analysis, and for better performance, decreasing the slot width but increasing the slot length for a given coupling value, while keeping physical realizability. Its effect has been observed with an example of 4 order dual-mode filter and proves that the suggested method can enhance the design result.

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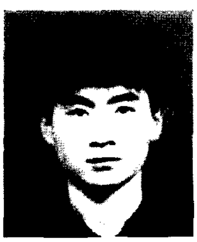

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