Design of bandstop filters using cylindrical metallic posts

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***Abstract*—The paper presents the design, implementation and measured performance of waveguide band-reject filters based on partial height cylindrical metallic posts. The posts are inserted in a uniform waveguide in which the dominant TE_{10} is propagating. Each post provides an attenuation pole at a frequency which is adjusted mainly by its height. The offset of the post from the center of the waveguide is used to control the strength of the coupling between the waveguide mode and the post. Optimization is used to correct for dispersion effects and the fact the attenuation pole and the coupling coefficients are slightly affected by the offset and the height of the post, respectively. Measured performance of a 3rd order band-reject filter with metallic posts shows very good agreement with computed results once losses are taken into account.**

***Index Terms*— resonator filters, bandstop filters, synthesis, optimization.**

I. INTRODUCTION

Band-reject microwave filters have very useful applications in communications systems, but have received less attention compared to their bandpass counterparts. These filters are most commonly designed by placing band-reject elements along an otherwise uniform transmission line or waveguide. For a Chebychev-type response, the band-reject elements are separated by an odd multiple of the guided wavelength at the center frequency of the stopband [1]. The band-reject elements are waveguide cavities that are coupled to the main waveguide by irises [1]. Other implementations in planar technology exploit the same principle [2]. Each bandstop element produces and controls one attenuation pole. An asymmetric band-reject response can also be obtained from in-line configurations in which the separation between the band-reject elements and their respective resonant frequencies are non-uniform [3].

An alternative design is based on cross-coupled resonators in which the source-load coupling is present in order to generate the required number of attenuation poles [4], [5]. This approach is more adequate when the rejection level in the stopband is low to moderate and the fabrication process very precise. On the other hand, the resulting filters are very compact. It was recently shown that band-reject, as well as pseudo high-pass and low-pass, filters with moderate to wide bandwidths can be designed by using rectangular partial height posts in a uniform waveguide in combination with inductive irises [6]. The design is based on the model with phase shifts and non-resonating nodes presented in [3].

In this paper, we present band-reject Chebychev filters which are designed by using partial height cylindrical metallic posts in an otherwise uniform waveguide in which the dominant TE_{10} mode is propagating. The position of the attenuation pole is mainly controlled by the height of the post. The strength of the coupling between the waveguide and the post is mainly determined by the offset of the post from the center of the waveguide. Each cylindrical post is first dimensioned to produce an attenuation pole at the center of the stopband. The posts are initially separated by $3/4\lambda_g$. The assembled filter is then optimized in order to take into account dispersion effects and correlations between the characteristics of the post and its geometric parameters. A 3rd order band-reject filter is designed, fabricated and measured.

II. BAND-REJECT ELEMENT AND FILTER LAYOUT

The band-reject element used in this work is shown in Fig. 1. It consists of a cylindrical metallic post of radius *r* and height *d*. The post is offset from the center of the main waveguide by a distance *s*. The uniform rectangular waveguide is a WR90. Note that element acts as a band-reject only when the offset s is non-zero.

Fig. 2 shows the scattering parameters of a typical element with *d=6.308mm, r=1mm and s = 9.765mm*. An attenuation poles appears at 10 GHz. The band-reject nature of this response is obvious from this figure.

In order to design higher order band-reject filters with a classical Chebychev response, the required number of band-reject elements are placed in a uniform waveguide as shown in Fig. 3. The elements are separated by $3/4\lambda_g$.

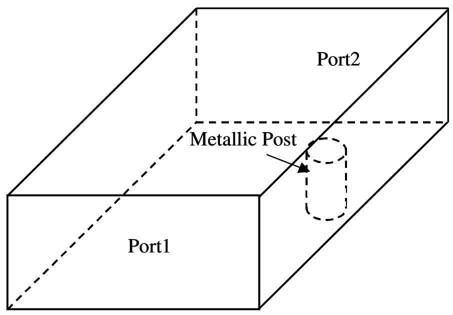

Fig. 1 Geometry of a single band-reject element using cylindrical partial-height metallic post.

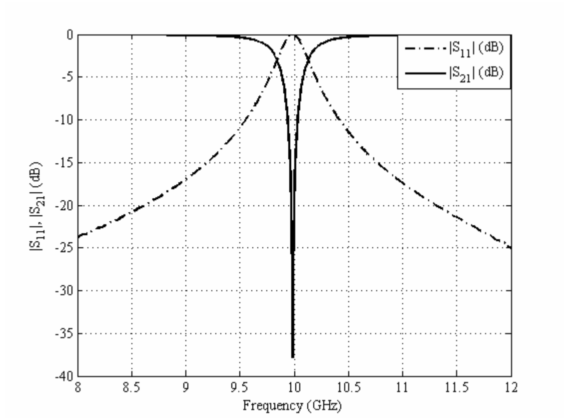

Fig. 2 EM simulated response of a single band-reject element

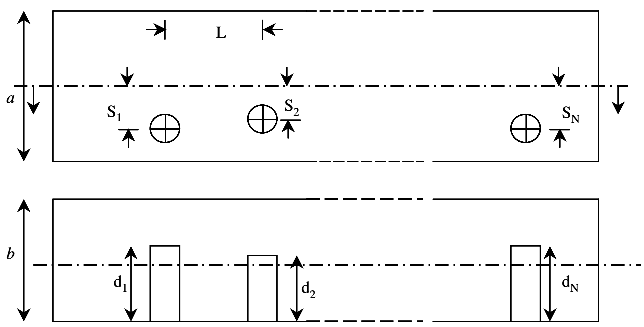

Fig. 3 Geometry of the bandstop waveguide filter with cylindrical partial height posts.

III. PARAMETERS OF EQUIVALENT CIRCUIT

Prior to commencing the dimensioning of the partial height posts and determining their positions, the parameters of the equivalent circuit are computed. The equivalent circuit consists of ideal, frequency independent inverters and band-reject elements that generate attenuation poles at the center of the stopband. The values of the elements of the circuit can be calculated by following [1].

Each partial height post is represented by a shunt series *LC* resonator that resonates at the center of the stopband, ω_0. The slope parameter of the i_{th} band-reject element is given by [1]

$$x_i = \omega_o L_i = \frac{1}{\omega_o C_i} = \frac{1}{g_i FBW} \tag{1}$$

Here, g_i is the i^{th} element of the low-pass prototype and FBW is the fractional bandwidth. For a 3rd order filter with a fractional bandwidth of 5%, we have $x_1=x_3=23.4357$ and $x_2=18.1176$. Naturally, with the assumption that the inverters are constant with frequency, the equivalent circuit can be designed to reproduce an ideal Chebychev response. In reality, the inverters do depend on frequency. It is important to correct for this frequency dependence at the equivalent circuit level before starting the actual implementation of the design.

IV. EFFECT OF DISPERSION AND FREQUENCY DEPENDENCE

In the above equivalent circuit and its associated response, the invertors were assumed ideal. This assumption is valid only over a narrow frequency range around the center of the stopband. The model will not correctly predict the return loss outside the stopband. For the case of rectangular waveguides the frequency dependence of the invertors is known analytically. The response of the circuit is recalculated taking the invertors as waveguides with length $3\lambda_g/4$ at the center frequency. The phase shift provided by each inverter can be written as

$$\phi(f) = \sqrt{\left(\frac{2\pi f}{C}\right)^2 - \left(\frac{\pi}{a}\right)^2}\, L \tag{2}$$

where *L* is the length of the waveguide section. The physical length of each inverter is adjusted until an optimum return loss in the passband is reached. The resulting values are found to be close to $3\lambda_{go}/4$. These corrections are first made on the equivalent circuit alone by using the slope parameters and the physical lengths of the uniform waveguide sections are optimization variables.

Fig.4 shows the response of the equivalent circuit of a 3rd order Chebychev filter with a stopband centered at 10 GHz with ideal invertors as well as frequency dependant ones. It is obvious that both responses agree well in the stopband but yield different return loss characteristics in the passbands. When the ideal, frequency-independent inverters are used, the return loss has a minimum of 20 dB in the passband as shown by the dotted line in Fig. 4. If the slope parameters are maintained at their ideal values as given by the low-pass prototype, but the frequency dependence of the invertors is taken into consideration, the return loss is degraded as shown by the solid lines. When both the slope parameters and the lengths of the uniform sections are adjusted, the minimum return loss in the passband is better than 20 dB within 1 GHz on either side of the stopband as shown by the dash-dotted lines. The new values of the slope parameters are $x_1=x_3=32$ and $x_2=18$.

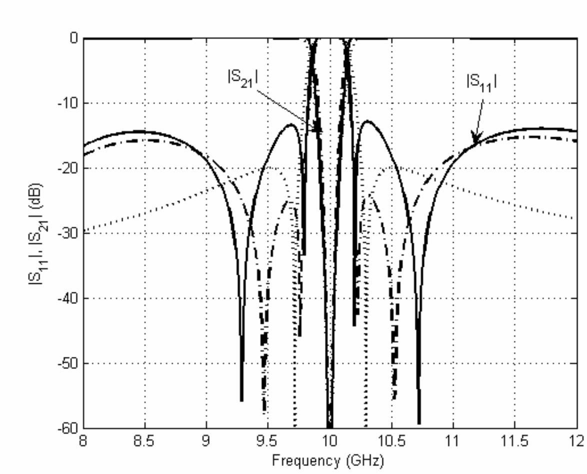

Fig. 4 Bandstop filter circuit response. Dotted line: using ideal invertors, solid line: considering frequency dependence and using the ideal values for slope parameters, dash-dotted line: using modified slope parameters.

V. Initial design

The bandstop filter realization suggested in this work was realized by cascading partial height cylindrical metallic posts along a uniform WR90 waveguide. A relationship between the physical dimensions of the posts and the equivalent circuit parameters is required to design the filter. The resonant frequency of the posts is mainly controlled by the post height whereas its inductance, or slope parameter, is more influenced by the position of the posts.

To demonstrate the performance of the developed configuration, a bandstop filter with f_o=*10 GHz, FBW=5%,* ε*=0.1005,* was designed, optimized and fabricated. The proposed filter was simulated using Microwave Studio from *CST*^{TM}.

The first design step is to extract the circuit parameters from the EM simulated response of a single post. It was shown in [6] that the slope parameters can be extracted from the simulated S parameters using:

$$\frac{x}{Z_o} = \frac{f_o}{2\Delta f_{3dB}} \tag{3}$$

where f_o is the center frequency and Δf_{3dB} is the 3dB bandwidth. The most popular way of design is producing design curves by varying the geometrical parameters (the height and position of the posts). This will determine the dependence of the slope parameters and resonant frequency on the geometrical parameters. Fig. 5 shows the design curves for posts of 2 mm diameter. The initial design was based on these curves such that: $s_1=0.445a$, $s_2=0.43a$, $d_1=0.65b$, and $d_2=0.62b$ ($a=22.10mm$ and $b=10.443mm$).

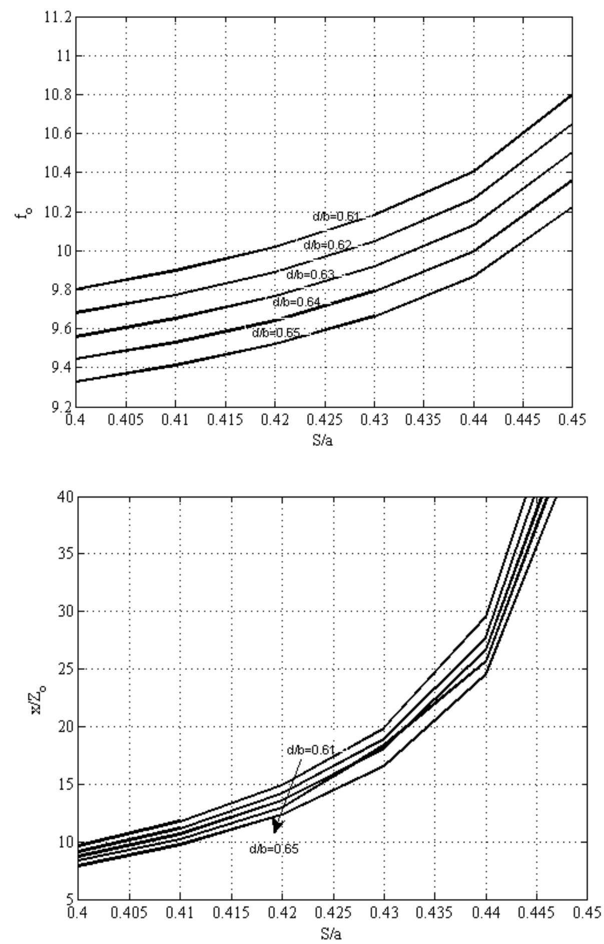

Fig. 5 Design curves for bandstop filter with cylindrical posts of 2 mm diameter.

VI. Optimization

The first step is to optimize the length of the invertors to improve the return loss in the passband of the filter. This can be realized by using the lengths of the uniform waveguide sections as optimization variables and minimizing the following cost function

$$K = \sum_{\omega_i} \left| \frac{20\log(|S_{11}\_target|)}{20\log(|S_{11}(\omega_i)|)} \right|^2 \tag{4}$$

Here, ω_i is a frequency in the passband and S_{11} is the calculated return loss from the equivalent circuit taking the dispersion and frequency dependence into account. Frequencies in the stopband are not used because these are not affected by the lengths of the waveguide sections. The initial values of the lengths are all set to $3\lambda_g/4$. For the 3rd order filter, the optimum length was found to be 29.96 mm. This is slightly larger than $3\lambda_{go}/4$. The rest of the optimization exploits the space-mapping technique [7]. Both the resonant frequencies and slope parameters were used as optimization variables. Fig. 6 shows the initial filter design along with the optimized one. The optimization process converges in one iteration using linear approximation. Simulation results show that the filter produces around 50 dB of attenuation in the stopband and a minimum return loss of 16.16 dB in the passbands which extend 2 GHz on either side of the stopband.

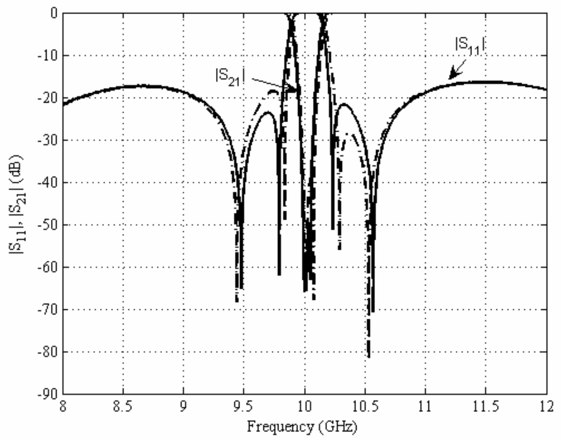

Fig. 6 Optimization progress of bandstop filter. Dashed lines: initial response, solid lines: iteration 1

VII. EXPERIMENTAL VALIDATION

The housing of the designed filter was fabricated from two aluminum blocks. The brass posts were fabricated separately and forced into place. Fig. 7 shows a picture of the fabricated filter.

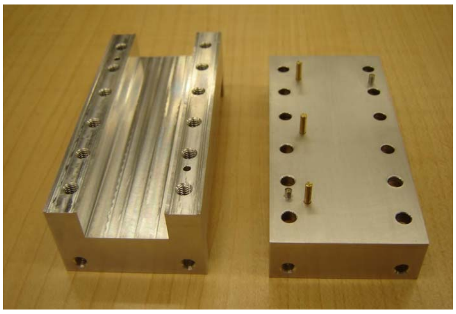

Fig. 7 Photograph of the fabricated third order bandstop filter.

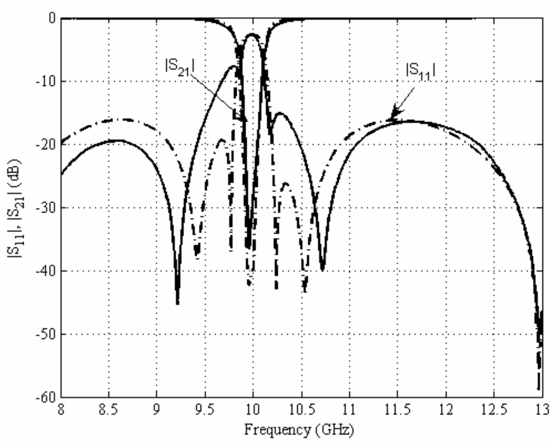

Fig. 8 Response of the fabricated filter. Solid lines: measured data and dashed lines: EM simulation

Fig. 8 shows the measured results for the fabricated filter along with those obtained from Microwave Studio where losses were taken into consideration. The posts were assumed to have a conductivity of $\sigma=0.5e6$ S/m. The simulated attenuation in the stopband shows very good agreement with measurement. The filter shows a rejection of 36.5 dB in the stopband and a return loss better than 16.5 dB over most of the passband. The difference between the simulated and measured response on the left side of the passband is attributed to manufacturing tolerances.

VIII. CONCLUSION

Partial height cylindrical metallic posts placed in-line inside an otherwise uniform rectangular waveguide are used to design band-reject filters. The posts are separated by an odd multiple of $\lambda_g/4$. The filter was designed by first taking into account the frequency dependence of the inverters at the equivalent circuit level. The filter is then optimized by exploiting the space-mapping technique. A 3rd order filter was designed, fabricated and measured. Good agreement is achieved between the measured and simulated results when metallic loss is taken into account in the simulation. The rather low Q-factor of the metallic (brass) posts can be improved by using high-Q dielectric posts of high dielectric constants.

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