Coupling Matrix Synthesis and Design of a Chained-Function Waveguide Filter

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***Abstract* — This paper presents, for the first time, the coupling matrix synthesis for the application of a chained-function to waveguide filters. The realization of this filter is carried out by successively adding one resonator at a time by comparing the simulated responses of each stage with those obtained using the coupling matrix synthesized from the chained-function. A sixth-order chained-function waveguide bandpass filter centered at 28 GHz with a fractional bandwidth of 2% is demonstrated. The simulated S-parameter responses and the sensitivity analysis pertaining to the manufacturing errors is included. The chained-function waveguide has the lowest percentage changes in terms of the return loss performance given the same amount of distortion as compared with those of the Chebyshev response filters. This results in a lower sensitivity rate with respect to the manufacturing errors, leading to achieving a high-performance filter implementation with a minimum tuning effort.**

Index Terms — Bandpass filter, chained-function, coupling matrix, filter synthesis, waveguide.

I. Introduction

To support the tremendous demand on mobile data traffic, researchers are motivated to explore the underutilized millimeter-wave frequency spectrum [1]. A millimeter-wave communication system has a large bandwidth, which can be exploited to provide a fast data transfer rate up to multi-gigabits-per-second [2]. Indeed, future 5G millimeter-wave communication has a clear vision, that is to accommodate the environment of Internet of Things (IoT) and provide Big-Data based platforms to billions of users deploying connected smart devices autonomously in a seamless manner [2]. With in-depth researches on the millimeter-wave technology, filters with high performance are highly demanded. A waveguide filter can offer a very high *Q* resonator factor and achieve low passband insertion loss and high suppression requirements.

Today, most of the microwave and millimeter-wave filters are designed based on the Chebyshev transfer function. This method produces the best out-of-band rejection level for a given maximum permitted level of passband equi-ripple insertion loss with a given filter order [3-4]. However, its implementation requires a low tolerance of the manufacturing error and a specific unloaded *Q* factor for each resonator. Therefore, a post-manufacturing tuning process is required. A chained-function concept can produce a variety of transfer functions based on the seed function combination to satisfy the pre-defined manufacturing limitations [5]. Through the properties of reduced sensitivity with respect to the manufacturing errors, a chained-function waveguide filter can be implemented using the additive rather than subtractive manufacturing technology, which is fast and cost-effective. This paper presents, for the first time, a chained-function waveguide filter using window-coupled inductive irises. The filter design is validated through simulated S-parameter responses using the ANSYS HFSS software without the need of global optimization.

II. Chained-Function in Waveguide

A section of waveguide is defined by its transfer matrix, which comprises a transmission line with frequency-dependent propagation constants and characteristic impedance. The inductive irises embedded in a waveguide act as an impedance inverter over a relatively broad bandwidth [6]. The physical structure of a waveguide bandpass filter can be illustrated as an equivalent circuit consisting of a bandpass resonator separated by a cascade of frequency-dependent inverters. The general transfer function of a waveguide filter can be formulated as [6]:

$$|S_{21}(j\omega)|^2 = \frac{1}{1+\varepsilon^2 \psi_N{}^2[\alpha(\frac{\lambda_g}{\lambda_{g0}})\sin(\pi\frac{\lambda_{g0}}{\lambda_g})]} \quad , \tag{1}$$

where ε is the ripple level, λ_g is the guided wavelength; $\lambda_{g0} \approx (\lambda_{g1} + \lambda_{g2})/2$ where λ_{g1} and λ_{g2} are guided wavelengths at the upper and lower band-edge frequencies, respectively, $\alpha = [\,(\lambda_{g1} / \lambda_{g0}) \sin (\pi\, \lambda_{g0} / \lambda_{g1})]^{-1}$; and ψ_N is the chained-function polynomial of *N* degree. For a chained-function filter, one can define its polynomial function as $\psi_N(\omega) \equiv G_\mu(\omega)$, where $G_\mu(\omega)$ is the product of the μ seed function $S_{ns(k)}(\omega)$ as follows [3-5].

$$G_\mu(\omega) = \prod_{k=1}^{\mu} (S_{n_{s(k)}}(\omega))^{m_{s(k)}} \quad , \tag{2}$$

where $n_{s(k)}$ is the order of the *k*th seed function and $m_{s(k)}$ is its multiplicity.

III. Design and Synthesis

The chained-function polynomial $\psi_N(\omega)$ emerges when chaining of the seed functions described in (2) is used to generate the filter coupling matrix. For a two-port network, the reflection and transmission coefficients, $S_{11}(\omega)$ and $S_{21}(\omega)$, are:

$$S_{11}(\omega)=\frac{F_N(\omega)}{E_N(\omega)} \qquad S_{21}(\omega)=\frac{P_N(\omega)}{\varepsilon E_N(\omega)}\ , \tag{3}$$

where ω is related to complex frequency variable $s = j\omega$, and $F_N(\omega)$ and $E_N(\omega)$ are the Nth degree polynomial of chained-function with complex coefficients $f_0, f_1, f_2, \ldots, f_N$ and $e_0, e_1, e_2, \ldots, e_N$, respectively [7]. Here ε is the real constant that normalizes $P_N(\omega)$ such that $|S_{21}(\omega)| \leq 1$ at any value of s. Note that the highest degree coefficient of all the polynomial functions is normalized to unity. The polynomials $E(s)$ and $F(s)$ are then used to formulate the complex-even and complex-odd polynomials, m_1 and n_1, as follows:

$$m_1+n_1=E(s)+F(s)\ . \tag{4}$$

The short-circuit admittance parameters y_{21} and y_{22} can be synthesized from (5) and (6) when N is either even or odd, respectively [7].

$$y_{21}(s)=\frac{P(s)}{\varepsilon m_1} \qquad y_{22}(s)=\frac{n_1}{m_1}\ . \tag{5}$$

$$y_{21}(s)=\frac{P(s)}{\varepsilon n_1} \qquad y_{22}(s)=\frac{m_1}{n_1}\ . \tag{6}$$

Using partial fractions:

$$y_{21}(s)=j\sum_{k=1}^{N}\frac{T_{Nk}T_{1k}}{\omega-\lambda_k} \qquad y_{22}(s)=j\sum_{k=1}^{N}\frac{T_{Nk}^{\ 2}}{\omega-\lambda_k}\ , \tag{7}$$

where λ_k is the eigenvalue pole, T_{1k} and T_{Nk} are the first and last rows of the orthogonal matrix, T. The orthogonal rows can be constructed using the Gram-Schmidt orthogonalization procedure. Finally, the coupling matrix is formed. A similarity transformation and annihilation of matrix elements [7] is carried out, and the final coupling matrix, M is

$$M=\begin{bmatrix} 0 & 0.01765 & 0 & 0 & 0 & 0 \\ 0.01765 & 0 & 0.01219 & 0 & 0 & 0 \\ 0 & 0.01219 & 0 & 0.01112 & 0 & 0 \\ 0 & 0 & 0.01112 & 0 & 0.01219 & 0 \\ 0 & 0 & 0 & 0.01219 & 0 & 0.01765 \\ 0 & 0 & 0 & 0 & 0.01765 & 0 \end{bmatrix}$$

$$Q_{e1}=Q_{e6}=42.88 \tag{8}$$

Using the coupling coefficients in (8), the approximate initial dimensions of all resonators and irises can be calculated, as explained in [7-8].

IV. Prototype Design

A sixth-order chained-function polynomial $\psi_N(\omega) = 8\omega^6 - 10\omega^4 + 3\omega^2$ with the seed function of order (1, 2, 3) is implemented in a waveguide filter WR-34 with a cut-off frequency of 17.357 GHz. It is designed to operate at 28 GHz with a return loss of 21.14 dB and a fractional bandwidth of 2%. Figure 1(a) shows the 3D layout of the designed chained-function waveguide filter with its design values. The thickness, t of all irises is 2.359 mm. Instead of performing global optimization on the entire structure, the simulation of this filter can be carried out by tuning the dimensions of only one resonator and its connecting irises towards a desired response. The procedure is then repeated by adding one successive resonator at one time [9]. Tables I and II list the iris dimensions and resonator lengths of the chained-function waveguide filter tuned at each successive step, respectively. Figure 1(b) plots the simulated and theoretical responses of this bandpass filter centered at 28 GHz with 2% bandwidth and return loss of 19.59 dB and 21.14 dB, respectively. Both results depict a good agreement. Group delay responses shown in Figure 1(c) indicate a smaller ripple level than that of the theoretical response. As a result, the group delay distortion near the cut-off frequency in the simulated response is lower; therefore, the signals remain in the cut-off frequencies in a shorter period. This explains the lower selectivity of the simulated responses, as compared with those from the theoretical results.

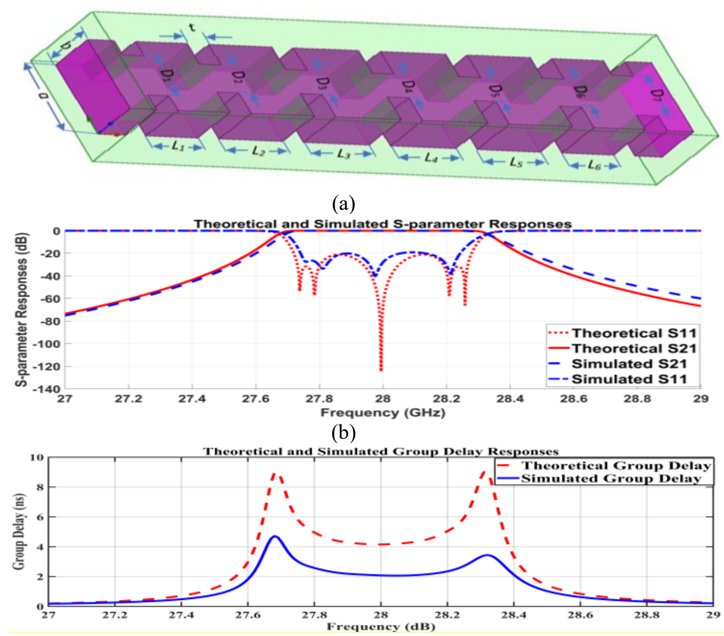


Fig. 1. (a) 3D model (b) S-parameter responses (c) Group delay responses.

TABLE III
SENSITIVITY ANALYSIS

Category	Return Loss (dB)			Percentage Change (%) Return Loss	
	Theoretical	10%	-10%	10%	-10%
6th Order Chained-Function	21.14	18.92	16.73	10.50	20.86
6th Order Chebyshev	21.14	15.83	14.56	25.12	31.13
5th Order Chebyshev	21.14	17.48	14.94	17.31	29.33

TABLE I

IRIS DIMENSIONS IN EACH SUCCESSIVE STEP

Steps	Iris Dimensions (mm)						
	D_1	D_2	D_3	D_4	D_5	D_6	D_7
1	4.87	3.45	-	-	-	-	-
2	4.87	3.47	3.08	-	-	-	-
3	4.87	3.49	3.16	3.02	-	-	-
4	4.87	3.49	3.16	3.08	3.16	-	-
5	4.87	3.48	3.13	3.08	3.13	3.48	
6	4.85	3.46	3.13	3.083	3.13	3.46	4.85

TABLE II

RESONATOR LENGTH IN EACH SUCCESSIVE STEP

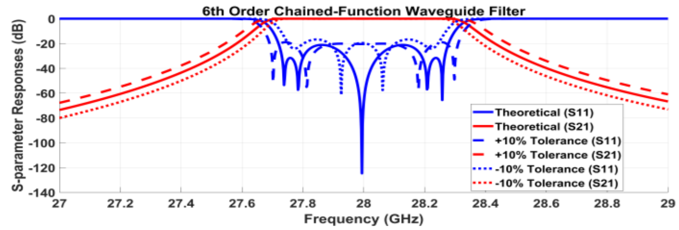
Steps	Resonator Length (mm)					
	L_1	L_2	L_3	L_4	L_5	L_6
1	4.91	-	-	-	-	-
2	4.95	5.85	-	-	-	-
3	4.95	5.86	5.98	-	-	-
4	4.92	5.86	6.00	6.00	-	-
5	4.90	5.86	6.02	6.02	5.86	-
6	4.895	5.835	5.975	5.975	5.835	4.895

V. SENSITIVITY TO MANUFACTURING ERRORS

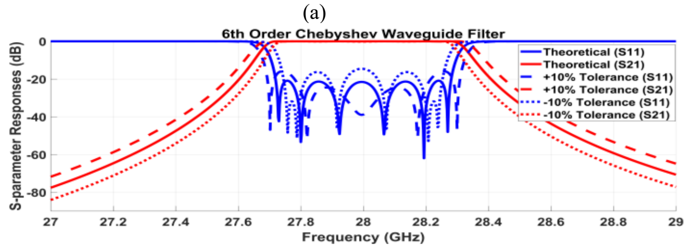
It can be shown that to obtain a similar out-of-band rejection of the N-th order Chebyshev response filter, the ($N+1$)-th order of chained-function filter is required [5]. Therefore, a sixth-order chained function waveguide filter is compared with a fifth-order conventional Chebyshev response waveguide filter. To determine the effect of the filter order and its sensitivity towards the manufacturing errors, a sixth-order Chebyshev response filter is also included in the comparison study. The sensitivity analysis is conducted by applying a ±10% tolerance to the coupling matrices and compared the return loss performances with those of the theoretical models. The worst-case passband return loss level is pre-defined at 21.14 dB before distortion for both Chebyshev and chained response filters. Table III and Figure 2 show the sensitivity analysis of the three filters. It can be noticed in Table 3 that the chained function has the lowest percentage changes in terms of the return loss performance given the same amount of distortion. Therefore, a filter can be implemented with the minimum tuning effort.

VI. CONCLUSION

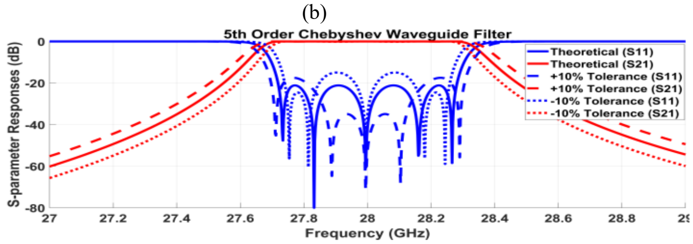
A sixth-order chained-function waveguide filter has been successfully designed and developed using window-coupled inductive irises. The design and synthesis of the chained-function filter in a waveguide using the coupling matrix synthesis method has been formulated. The theoretical and simulation results are in good agreement. Given the same amount of distortion, the sensitivity analysis indicates that the implementation of the chained-function concept in a waveguide results in the lowest percentage changes. Therefore, the waveguide filter can be manufactured using the fast and cost-effective additive manufacturing technology. This filter is currently being manufactured; and the measured performance will be presented upon completion of the necessary experiments.



(a)



(b)



(c)

Fig. 2. The effects of tolerance towards the S-parameter responses for the chained and Chebyshev response filters.

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