A Modified Chebyshev Bandpass Filter with Attenuation Poles in the Stopband

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***Abstract*—This paper describes a design method of a modified Chebyshev bandpass filter with attenuation poles in the stopband. The insertion of attenuation poles into resonators in the authors' bandpass-filter design is accomplished by connecting a lumped inductor or capacitor in series with a shunt-type coaxial transmission-line resonator. The inserted poles which are distributed over the stopband can be chosen such that the insertion loss of the filter has equiripple characteristic and maximum attenuation in the stopband with the given number of attenuation poles. The modified Chebyshev bandpass filter designed by this method can be effectively used in diplexer design.**

***Index Terms*—Attenuation pole, bandpass filter.**

I. Introduction

In ORDER to reduce the weight and the volume of a filter, high-dielectric ceramic coaxial resonators with added attenuation poles have been used in bandpass-filter designs [1]–[3]. However, these filters have been designed by connecting a capacitor in series with a short-circuited coaxial transmission line or a resonator. Thus, it is only possible to insert attenuation poles into the lower stopband.

Another way of inserting attenuation poles into a stopband is to design the filter as elliptic or pseudoelliptic. The elliptic or pseudoelliptic filter is defined as having its finite frequency-attenuation poles distributed freely throughout the stopband or at a single frequency just outside the edge of the passband. However, both of these filters are quite difficult to construct and tune [4].

In this paper, the authors propose a modified Chebyshev bandpass-filter design method by inserting attenuation poles into the lower or upper stopband and distributing them throughout the stopband in order to reduce the number of shunt-type transmission-line resonators and to give maximum attenuation characteristic in the desired stopband [5], [6]. This was essentially approached by connecting a lumped inductor or capacitor in series with a resonator instead of a capacitor, as in [1]–[3]. The reduction in resonators comes from the steep transition at the desired stopband due to the attenuation poles introduced. The maximum attenuation comes from pseudoelliptic filter characteristic due to the attenuation poles distributed to have equiripples in the stopband [7].

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This paper describes in detail the design procedures of modified Chebyshev bandpass filters with an equiripple transmission characteristic in the lower stopband, upper stopband, and both stopbands, respectively. Emphasis is placed on inserting and distributing attenuation poles in the stopband to result in pseudoelliptic filter characteristics. In Section II, a resonator structure having an attenuation pole is described. In Section III, a detailed design theory of a modified Chebyshev bandpass filter with attenuation poles in the stopband is given. Lastly, in Section IV, design examples and simulation results are presented.

II. Resonator Structure Having Attenuation Poles

To design a Chebyshev bandpass filter using only shunt-type resonators and admittance inverters, a determination of basic factors such as resonant frequency, bandwidth, susceptance slope parameter of the resonator, and the element values of lowpass prototype filters are necessary [8]. If the desire is to locate attenuation poles in the stopband, an inductor or a capacitor should be connected in series with a shunt-type resonator. However, the introduction of an additional element to the resonator for the purpose of locating attenuation poles changes the susceptance slope parameter of the resonator. This effect must be taken into account in order to design a modified Chebyshev bandpass filter.

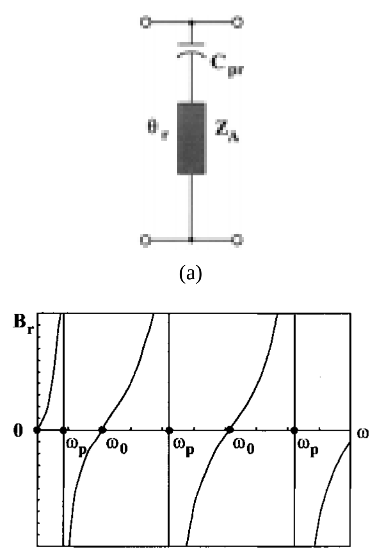
A. Resonator Structure with Attenuation Poles in the Lower Stopband

To locate an attenuation pole in the lower stopband, a capacitor might be connected in series with a shunt-type coaxial resonator as shown in Fig. 1(a). The susceptance characteristic of this type of resonator structure is shown in Fig. 1(b). The resonator structure can be used to construct a bandpass filter with attenuation poles in the lower stopband because the series resonant frequency ω_p, which is the pole frequency, is lower than the parallel resonant frequency ω_0. This structure is named RLP which stands for <u>R</u>esonator structure with <u>L</u>ower stopband attenuation <u>P</u>ole.

From the equivalent circuit of this RLP structure, the susceptance can be expressed as

$$B_r = \frac{\omega C_{pr}}{1 - \omega C_{pr} Z_A \tan\theta_r} \tag{1}$$

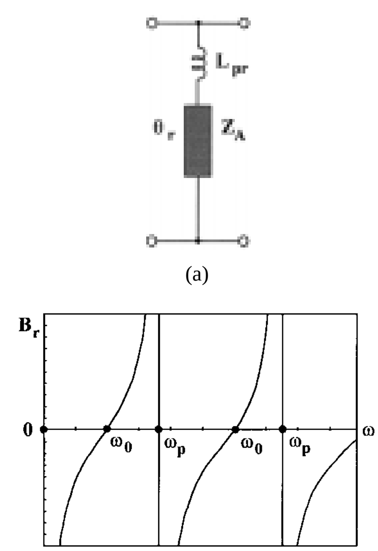
where Z_A is the characteristic impedance of the coaxial transmission-line resonator and θ_r is the electrical length of the rth resonator. As the susceptance must be infinite at the



(a)

(b)

Fig. 1. (a) The equivalent circuit of the resonator structure with attenuation poles in the lower stopband (RLP structure). (b) The susceptance characteristic of (a).



(a)

(b)

Fig. 2. (a) The equivalent circuit of the resonator structure with attenuation poles in the upper stopband (RUP structure). (b) The susceptance characteristic of (a).

attenuation pole frequency, one obtains from (1)

$$\omega_p = \frac{1}{C_{pr} Z_A \tan\theta_p} \quad \text{and} \quad \infty \tag{2}$$

where θ_p is the electrical length of a resonator at the attenuation pole frequency. Also, since the susceptance must be zero at the resonant frequency, one obtains

$$\omega_0 = 0 \quad \text{and} \quad \omega\left(\theta_r = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \cdots\right). \tag{3}$$

B. Resonator Structure with Attenuation Poles in the Upper Stopband

To locate an attenuation pole in the upper stopband, an inductor as opposed to a capacitor might be connected in series with a shunt-type coaxial resonator as shown in Fig. 2(a). The susceptance characteristic of the resonant structure is shown in Fig. 2(b). In this case, the series resonant frequency ω_p is higher than the parallel resonant frequency ω_0. Therefore, this type of resonator structure can be used to construct a bandpass filter with attenuation poles in the upper stopband. This structure is named RUP, which stands for *R*esonator structure with *U*pper stopband attenuation *P*ole.

From the equivalent circuit of this RUP structure, the susceptance can be expressed as

$$B_r = \frac{-1}{\omega L_{pr} + Z_A \tan\theta_r}. \tag{4}$$

Since the susceptance must be infinite at the attenuation pole frequency, one obtains from (4)

$$\omega_p = 0 \quad \text{and} \quad \frac{-Z_A \tan\theta_p}{L_{pr}} \tag{5}$$

where θ_p is the electrical length of a resonator at attenuation pole frequency. Also, since the susceptance must be zero at the resonant frequency, one obtains

$$\omega_0 = \omega\left(\theta_r = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \cdots\right) \quad \text{and} \quad \infty. \tag{6}$$

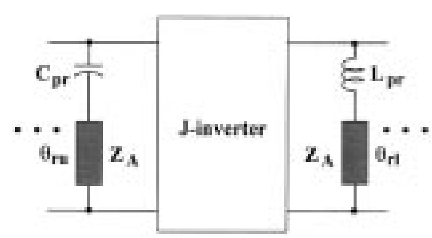


Fig. 3. The equivalent circuit of the resonator structure with attenuation poles in both stopbands (RBP structure).

C. Resonator Structure with Attenuation Poles in Both Stopbands

To locate attenuation poles in both stopbands, RLP and RUP structures might be connected in parallel with an admittance inverter as shown in Fig. 3. This type of circuit structure can be used to construct a bandpass filter with attenuation poles in both stopbands. This structure is named RBP which stands for *R*esonator structure with *B*oth stopbands attenuation *P*ole.

III. Design Theory of a Modified Chebyshev Bandpass Filter with Attenuation Poles in the Stopband

Attenuation poles might be inserted into all resonators of a bandpass filter. The attenuation poles which are distributed over the stopband can be chosen such that the transmission characteristic of the filter in the stopband where the poles are located is equiripple. This equiripple transmission characteristic gives the maximum attenuation in the stopband with the given number of attenuation poles. The frequencies of these attenuation poles can be found by iterative calculations to give equiripple stopband transmission characteristics. This

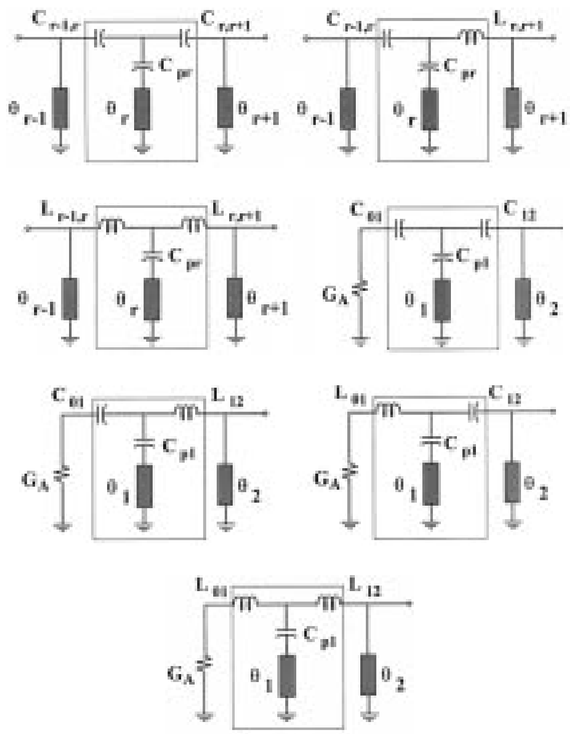


Fig. 4. The equivalent circuits with RLP and the adjacent admittance inverters.

distribution of attenuation poles allows one not only to reduce the number of required resonators in the filter, but also to provide the equiripple transmission characteristic in the stopband.

A. Bandpass Filter with Attenuation Poles in the Lower Stopband

If all resonators are replaced in the generalized bandpass-filter circuit using admittance inverters described in [8] with RLP structures, it is then possible to design a bandpass filter with attenuation poles in the lower stopband. The equivalent circuits with RLP and the adjacent admittance inverters can be divided into seven categories as shown in Fig. 4, according to the type of inverters and the locations of RLP. As an interstage resonator structure of a bandpass filter, one can choose either RLP-1 or RLP-2. RLP-4, RLP-5, or RLP-6 can be used for the first or last resonator structures. However, from the results of various design simulations, the structures of RLP-3 and RLP-7 turn out to be inadequate for the filter-design purpose.

The susceptance slope parameters of these resonators with series capacitors depend on the attenuation pole frequency and the adjacent admittance inverters. To illustrate this, one arbitrarily chooses the structure RLP-2 and redraws the equivalent circuit as shown in Fig. 5. Then, the susceptance of this resonator structure can be expressed as

$$B_r = \frac{\omega C_{pr}}{1 - \omega C_{pr} Z_A \tan\theta_r} + \left(\omega C_{r-1,r} - \frac{1}{\omega L_{r,r+1}}\right). \quad (7)$$

Since the susceptance must be infinite at the attenuation pole frequency, the value of the series capacitor can be obtained

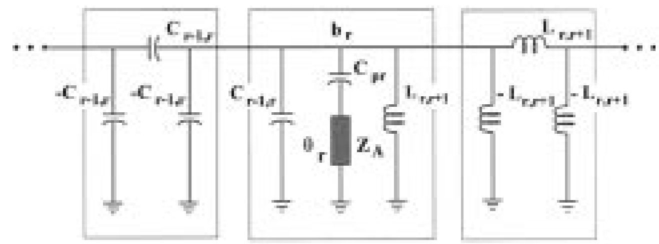


Fig. 5. The equivalent circuit of RLP-2.

from (7) as

$$C_{pr} = \frac{1}{\omega_p Z_A \tan\theta_p}. \quad (8)$$

Since the susceptance must be zero at the resonant frequency, the electrical length θ_r of the resonator can also be obtained from (7) as

$$\theta_r = \tan^{-1}\left[\frac{1}{Z_A}\left(\frac{1}{\omega_0 C_{pr}} + \frac{1}{\omega_0 C_{r-1,r} - \frac{1}{\omega_0 L_{r,r+1}}}\right)\right]. \quad (9)$$

The susceptance slope parameter b_r is also obtained from (7) as

$$\begin{aligned} b_r &= \frac{\omega_0}{2}\frac{dB_r}{d\omega}\bigg|_{\omega=\omega_0} \\ &= \frac{1}{2}\bigg[\omega_0 C_{pr}\frac{1+\omega_0 C_{pr} Z_A \theta_r \sec^2\theta_r}{(1-\omega_0 C_{pr} Z_A \tan\theta_r)^2} \\ &\qquad + \omega_0 C_{r-1,r} + \frac{1}{\omega_0 L_{r,r+1}}\bigg] \end{aligned} \quad (10)$$

where

$$C_{r-1,r} = \frac{J_{r-1,r}}{\omega_0} = \frac{w}{\omega_0}\sqrt{\frac{b_{r-1}b_r}{g_{r-1}g_r}} \quad (11)$$

$$L_{r,r+1} = \frac{1}{\omega_0 J_{r,r+1}} = \frac{1}{w\omega_0}\sqrt{\frac{g_r g_{r+1}}{b_r b_{r+1}}}. \quad (12)$$

g_r-parameters are element values of the lowpass prototype filter and w is the fractional bandwidth.

If (8)–(12) are solved simultaneously, one can get all circuit values necessary in the filter design.

B. Bandpass Filter with Attenuation Poles in the Upper Stopband

If all the resonators are replaced in the generalized bandpass-filter circuit using admittance inverters described in [8] with RUP structures, it is possible to design a bandpass filter with attenuation poles in the upper stopband. The equivalent circuits with RUP and the adjacent admittance inverters can be divided into seven categories, as shown in Fig. 6, according to the type of inverters and the locations of RUP. As an interstage resonator structure of a bandpass filter, one can choose either RUP-1 or RUP-2, while RUP-4, RUP-5, or RUP-6 can be used for the first or last resonator structures. However, from the results of various design simulations, the

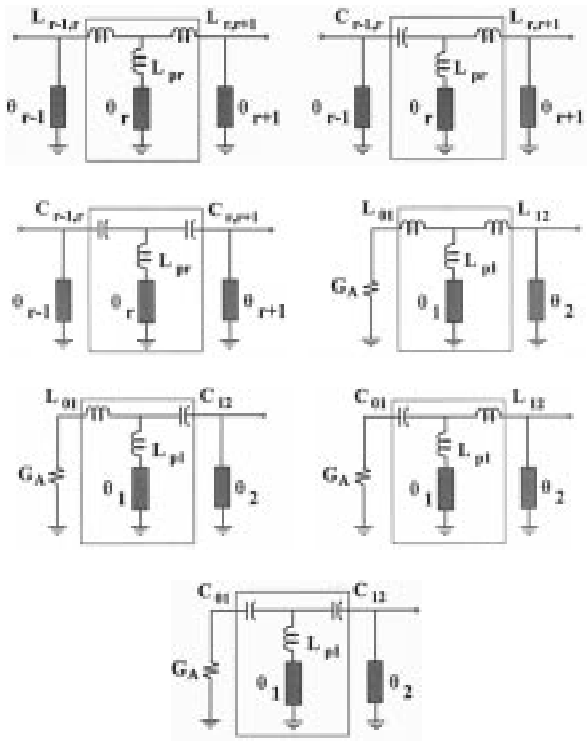


Fig. 6. The equivalent circuits with RUP and the adjacent admittance inverters.

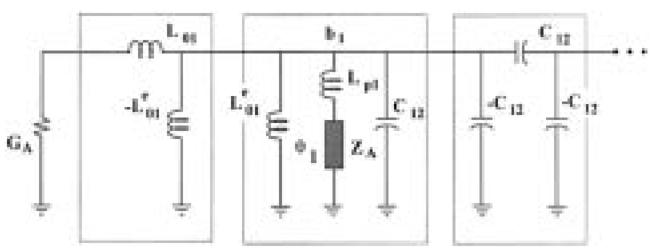


Fig. 7. The equivalent circuit of RUP-5.

structures of RUP-3 and RUP-7 also turn out to be inadequate for the filter-design purpose.

The susceptance slope parameters of these resonators with series inductors depend on the attenuation pole frequency and the adjacent inverters. To illustrate this, arbitrarily choose the structure RUP-5 and redraw the equivalent circuit as shown in Fig. 7. Then the susceptance of this resonator structure can be expressed as

$$B_1 = \frac{-1}{\omega L_{p1} + Z_A \tan\theta_1} - \frac{1}{\omega L_{01}^e} + \omega C_{12}. \qquad (13)$$

Since the susceptance must be infinite at the attenuation pole frequency, the value of the series inductor can be obtained from (13) as

$$L_{p1} = \frac{-Z_A \tan\theta_p}{\omega_p}. \qquad (14)$$

Also, since the susceptance must be zero at the resonant frequency, the electrical length of the resonator can be obtained from (13) as

$$\theta_1 = \tan^{-1}\left[\frac{1}{Z_A}\left(\frac{1}{\frac{-1}{\omega_0 L_{01}^e} + \omega_0 C_{12}} - \omega_0 L_{p1}\right)\right] \qquad (15)$$

where

$$L_{01}^e = \frac{Z_A}{\omega_0 \tan\left|\frac{\phi_1}{2}\right|} \qquad (16)$$

$$\left|\frac{\phi_1}{2}\right| = \tan^{-1}\left[\sqrt{\frac{\left(\omega_0 L_{01}^e G_A\right)^{-2} - 1}{1 - \left(\frac{\omega_0 L_{01}^e}{Z_A}\right)^2}}\right] \qquad (17)$$

$$C_{12} = \frac{w}{\omega_0}\sqrt{\frac{b_1 b_2}{g_1 g_2}}. \qquad (18)$$

The coupling inductor L_{01} can be obtained from the following equations:

$$L_{01} = \frac{Z_A + Z_0}{\omega_0 \tan\left|\frac{\phi_1}{2} + \frac{\phi_0}{2}\right|} \qquad (19)$$

$$\left|\frac{\phi_0}{2}\right| = \tan^{-1}\left[\sqrt{\frac{\left(\frac{Z_A}{\omega_0 L_{01}^e}\right)^2 - 1}{1 - \left(G_A \omega_0 L_{01}^e\right)^2}}\right]. \qquad (20)$$

The susceptance slope parameter is given from the definition as

$$b_1 = \frac{1}{2}\left[\frac{1}{\omega_0 L_{01}^e} + \omega_0 C_{12} + \frac{\omega_0 L_{p1} + Z_A \theta_1 \sec^2\theta_1}{(\omega_0 L_{p1} + Z_A \tan\theta_1)^2}\right]. \qquad (21)$$

As in the case of a bandpass filter with attenuation poles in the lower stopband, one can get all circuit values necessary in the filter design by solving (13)–(21) simultaneously.

C. Bandpass Filter with Attenuation Poles in Both Stopbands

If all resonators are replaced in the generalized bandpass-filter circuit using admittance inverters described in [8] with RBP structures, one can design a bandpass filter with attenuation poles in both stopbands. There are only four possible structures, as shown in Fig. 8, if one attenuation pole is inserted in each stopband. If two attenuation poles are inserted in each stopband, there are twelve possible structures, as shown in Fig. 9. For the structure RBP-I–4, (22)–(37) can be derived following the same procedure mentioned in Section III-A and III-B. Again, (22)–(37) can be solved simultaneously to get all circuit values necessary in the filter design as

$$L_{p1} = \frac{-Z_A \tan\theta_{p1}}{\omega_{p1}} \qquad (22)$$

$$\theta_1 = \tan^{-1}\left[\frac{1}{Z_A}\left(\frac{1}{\frac{-1}{\omega_0 L_{01}^e} + \omega_0 C_{12}} - \omega_0 L_{p1}\right)\right] \qquad (23)$$

$$b_1 = \frac{1}{2}\left[\frac{1}{\omega_0 L_{01}^e} + \omega_0 C_{12} + \frac{\omega_0 L_{p1} + Z_A \theta_1 \sec^2\theta_1}{(\omega_0 L_{p1} + Z_A \tan\theta_1)^2}\right] \qquad (24)$$

where

$$\left|\frac{\phi_0}{2}\right| = \tan^{-1}\left[\sqrt{\frac{\left(\frac{Z_A}{\omega_0 L_{01}^2}\right)^2 - 1}{1 - \left(G_A \omega_0 L_{01}^e\right)^2}}\right] \qquad (25)$$

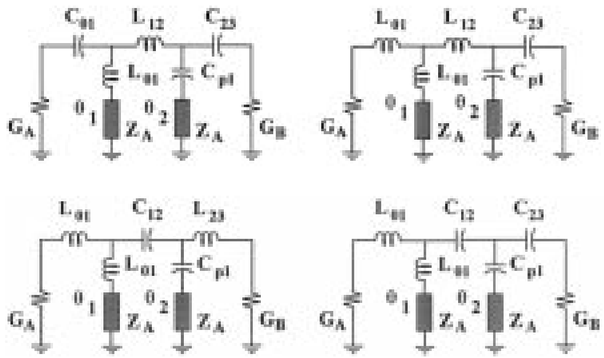


Fig. 8. The equivalent circuits of the four possible bandpass filters with one attenuation pole in each stopband (RBP-I).

$$\left|\frac{\phi_1}{2}\right| = \tan^{-1}\left[\sqrt{\frac{\left(\omega_0 L^e_{01} G_A\right)^{-2} - 1}{1 - \left(\frac{\omega_0 L^e_{01}}{Z_A}\right)^2}}\right] \tag{26}$$

$$L_{01} = \frac{Z_A + Z_0}{\omega_0 \tan\left|\frac{\phi_0}{2} + \frac{\phi_1}{2}\right|} \tag{27}$$

$$L^e_{01} = \frac{Z_A}{\omega_0 \tan\left|\frac{\phi_1}{2}\right|} \tag{28}$$

$$C_{12} = \frac{w}{\omega_0}\sqrt{\frac{b_1 b_2}{g_1 g_2}} \tag{29}$$

$$C_{p2} = \frac{1}{\omega_{p2} Z_A \tan\theta_{p2}}. \tag{30}$$

$$\theta_2 = \tan^{-1}\left[\frac{1}{Z_A}\left(\frac{1}{\omega_0 C_{p2}} + \frac{1}{\omega_0 C_{12} + \omega_0 C^e_{23}}\right)\right] \tag{31}$$

$$b_2 = \frac{1}{2}\left[\omega_0 C_{p2}\frac{1 + \omega_0 C_{p2} Z_A \theta_2 \sec^2\theta_2}{(1 - \omega_0 C_{p2} Z_A \tan\theta_2)^2} + \omega_0 C_{12} + \omega_0 C^e_{23}\right] \tag{32}$$

where

$$\left|\frac{\phi_3}{2}\right| = \tan^{-1}\left[\sqrt{\frac{\left(\omega_0 C^e_{23} Z_A\right)^2 - 1}{1 - \left(\frac{G_B}{\omega_0 C^e_{23}}\right)^2}}\right] \tag{33}$$

$$\left|\frac{\phi_2}{2}\right| = \tan^{-1}\left[\sqrt{\frac{\left(\frac{\omega_0 C^e_{23}}{G_B}\right)^2 - 1}{1 - 1/\left(Z_A \omega_0 C^e_{23}\right)^2}}\right] \tag{34}$$

$$C_{12} = \frac{w}{\omega_0}\sqrt{\frac{b_1 b_2}{g_1 g_2}} \tag{35}$$

$$C_{23} = \frac{\tan\left|\frac{\phi_2}{2} + \frac{\phi_3}{2}\right|}{\omega_0 (Z_A + Z_0)} \tag{36}$$

$$C^e_{23} = \frac{\tan\left|\frac{\phi_2}{2}\right|}{\omega_0 Z_A}. \tag{37}$$

IV. Design Examples and Simulation Results

Bandpass filters were designed by basically following the procedures described in the previous section with a Chebyshev passband ripple of 0.1 dB. The characteristic impedance of coaxial transmission-line resonators of $(Z_r, S_n)T_i O_4$ with a dielectric constant 38 [9] used in these filter designs is 7.46 Ω, and the source and load conductances are 0.02 mho, respectively. The designed filters are simulated with Hewlett-Packard MDS software.

The resonators in these filter designs might be made of shunt-type rectangular or circular coaxial ceramic transmission lines. Both the capacitors and inductors might be realized on a dielectric or ceramic substrate as interdigital capacitors and spiral-line or single-loop inductors.

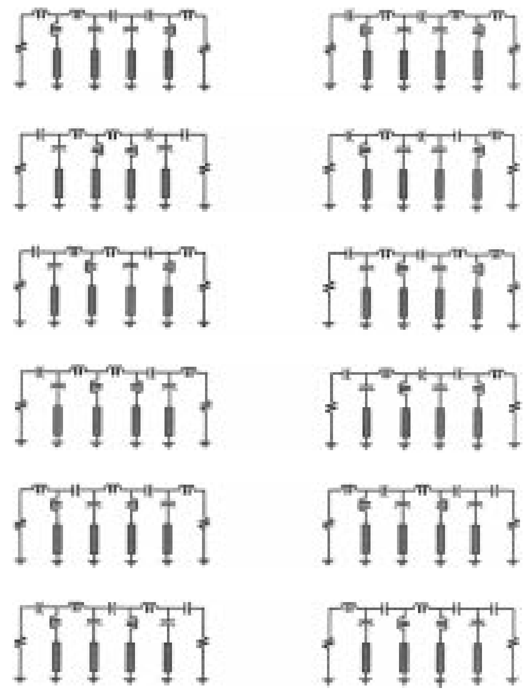


Fig. 9. The equivalent circuits of the twelve possible bandpass filters with two attenuation poles in each stopband (RBP-II).

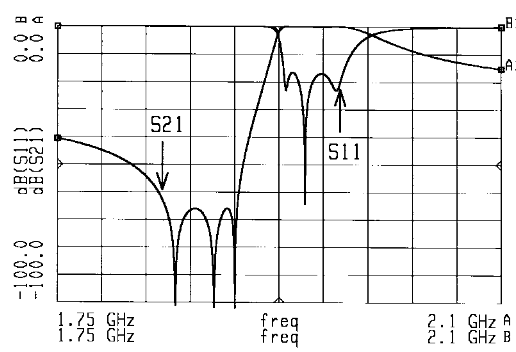


Fig. 10. The simulated transmission and reflection characteristics of a modified third-order Chebyshev bandpass filter with three attenuation poles in the lower stopband.

A. Design of a Modified Chebyshev Bandpass Filter with Attenuation Poles in the Lower Stopband

Fig. 10 shows the simulated responses of the designed third-order bandpass filter with three attenuation poles in the lower stopband (from 1850 to 1890 MHz). This modified Chebyshev bandpass filter has been designed at the center frequency of 1950 MHz with a fractional bandwidth of 0.0205.

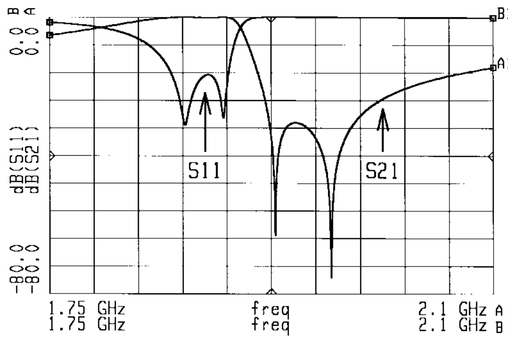


Fig. 11. The simulated transmission and reflection characteristics of a modified second-order Chebyshev bandpass filter with two attenuation poles in the upper stopband.

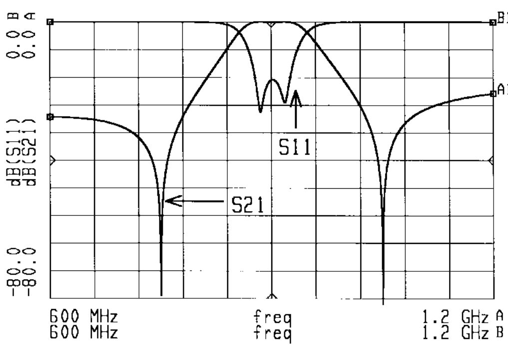


Fig. 12. The simulated transmission and reflection characteristics of a modified second-order Chebyshev bandpass filter with one attenuation pole in each stopband.

The pseudoelliptic transmission characteristic, which has a passband ripple of 0.1 dB and about 70-dB equiripple attenuation response in the lower stopband, was achieved in the simulation.

B. Design of Bandpass Filter with Two Attenuation Poles in the Upper Stopband

Fig. 11 shows the simulated responses of the designed second-order bandpass filter with two attenuation poles in the upper-stopband edge frequencies of 1930 and 1970 MHz, respectively. This modified Chebyshev bandpass filter has been designed at the center frequency of 1870 MHz with a fractional bandwidth of 0.0214. An attenuation level of more than 40 dB in the upper stopband was achieved in the simulation, and one gets the passband ripple of 0.1 dB and attenuation poles at the two edge frequencies in the upper stopband.

C. Design of Bandpass Filter with One Attenuation Pole in Each Stopband

Fig. 12 shows the simulated responses of the designed second-order bandpass filter with one attenuation pole in each stopband, respectively. This modified Chebyshev bandpass filter has been designed at the center frequency of 900 MHz with a fractional bandwidth of 0.0556.

D. Application to Diplexer Design [6]

Fig. 13 shows the equivalent circuit of the diplexer constructed by a modified third-order Chebyshev bandpass filter with three attenuation poles in the lower stopband and a modified second-order Chebyshev bandpass filter with two attenuation poles in the upper stopband. The transmitting filter is composed of two quarter-wavelength resonators (R1, R2), two coupling capacitors (C2, C3), two coupling inductors (L1, L4), and one series inductor (Ls1), while the receiving filter has three quarter-wavelength resonators (R3–R5), six coupling capacitors (C7–C12) and one series capacitor (Cs1). The capacitor C5 and the inductor L6 are used in order to construct a branch circuit which connects both filters to the common antenna port. The input impedance of each filter, seen by the other filter at the antenna port, should be infinite at its own center frequency so as to remove interference from the other filter. The capacitor C5 and inductor L6 provide this function. The values of the equivalent circuit elements of the diplexer are shown in Table I.

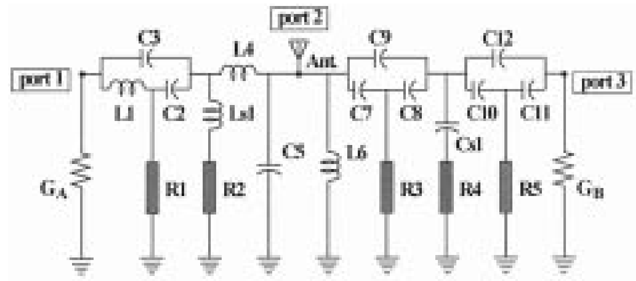


Fig. 13. The equivalent circuit of the diplexer.

TABLE I
VALUES OF THE EQUIVALENT CIRCUIT ELEMENTS OF THE DIPLEXER

component	element value	component	element value
R1(electrical length)	91.04 deg.	C2	0.28 pF
R2(electrical length)	91.3 deg.	C3	0.39 pF
R3(electrical length)	85.3 deg.	C5	0.92 pF
R4(electrical length)	86.0 deg.	C7	0.52 pF
R5(electrical length)	86.3 deg.	C8	0.37 pF
L1	11.8 nH	C9	0.21 pF
L4	9.18 nH	C10	0.25 pF
L6	6.0 nH	C11	0.64 pF
Ls1	5.82 nH	C12	0.5 pF
		Cs1	1.42 pF

Every resonator in the equivalent circuit of the diplexer shown in Fig. 13 has an attenuation pole which causes a series resonance. The attenuation poles related to R1 and R2 resonators are located in the upper stopband, and these poles result from C3, Ls1, respectively. The attenuation poles related to R3, R4, and R5 resonators are located in the lower stopband, and these poles result from C9, Cs1, and C12, respectively. The capacitors C3, C9, and C12 can be obtained after $Y-\Delta$ conversion.

Fig. 14 shows the simulated responses of the diplexer in Fig. 13. The receiving bandpass filter of the diplexer shows good isolation at the transmitting band as required. This type of diplexer can be used in a communication system where the

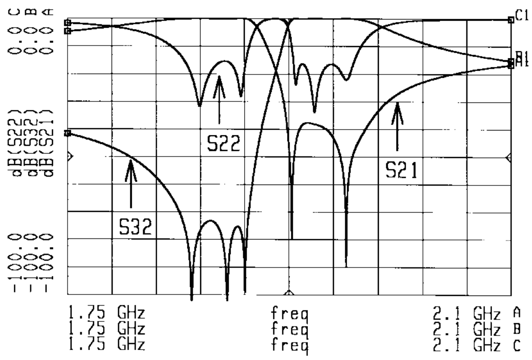


Fig. 14. The simulated transmission characteristics of the diplexer.

center frequency of the receiving band is higher than that of the transmitting band.

V. Conclusion

A systematic design procedure for modified Chebyshev bandpass filters with attenuation poles in the stopband has been developed successfully to fulfill the requirement for reducing the filter volume and providing maximum stopband attenuation. The procedures given here lead to filters with good passband- and stopband-performance characteristics and, in general, are quite simple to apply. These modified Chebyshev bandpass filters might have potential applications in diplexer design where one of the lower or upper stopbands can have more attenuation than the other.

As mentioned before, the advantages of utilizing modified Chebyshev bandpass filters is the reduction in the number of resonators and also to have maximum attenuation in the stopband. The main disadvantage expected is the difficulty in practically realizing the lumped elements at microwave frequencies.

Lastly, it is speculated that the design procedure for modified Chebyshev bandpass filters with attenuation poles in the stopband might be extended to designing modified Chebyshev bandstop filters.

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