Zolotarev Bandpass Filters

H. Clark Bell, *Fellow, IEEE*

***Abstract*—Zolotarev rational functions may be used in certain bandpass filter applications for which two narrower passbands are required. Coupled-resonator low-pass prototypes for narrow bandpass filters based on even- and odd-degree Zolotarev functions are synthesized using a transformed variable. Compared to other filters, those with Zolotarev responses have sharper skirt selectivity, resulting in lower passband distortion.**

***Index Terms*—Bandpass filters, Chebyshev filters, circuit synthesis, elliptic filters, passive filters, resonator filters.**

I. Introduction

A DOUBLE-PASSBAND RF or microwave filter requirement is usually satisfied with two bandpass filters, diplexed at both ends. In instances where rejection between the passbands is not required, a more efficient use of resonators and a simpler structure may be obtained with a single coupled-resonator filter based on a Zolotarev low-pass prototype of either even or odd degree. The conventional Chebyshev *LC* low-pass filter has an equiripple passband, in the normalized frequency domain, defined by $0 \leq \omega \leq 1$. The Zolotarev low-pass filter is similar, except that the equiripple passband is defined by $0 < a \leq \omega \leq 1$, as for a conventional *LC* bandpass filter. Even and odd-degree Zolotarev low-pass filter responses are illustrated in Fig. 1, for degree six and seven filters with 26-dB minimum return loss and $a = 0.75$.

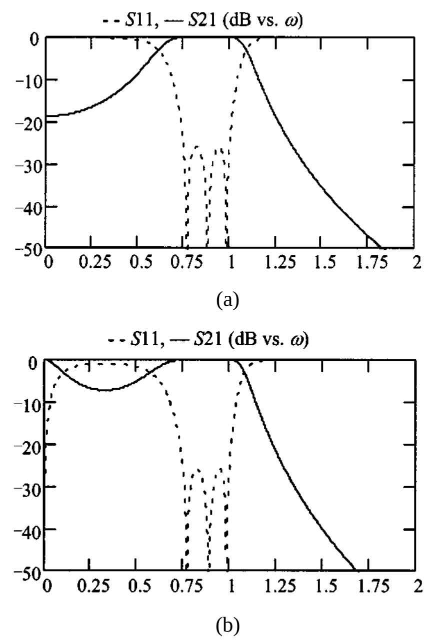


Fig. 1. Zolotarev low-pass responses. (a) Degree six. (b) Degree seven.

Zolotarev rational function approximations for even-degree low-pass filters were introduced by Szentirmai [1] and Matthaei [2] and for odd-degree low-pass filters by Levy [3]; Horton extended the odd-degree Zolotarev approximation to responses with finite-frequency transmission zeros (loss poles) [4]. Even-degree approximation was achieved by mapping a Chebyshev response, while odd-degree Zolotarev approximation required specialized computational techniques using Jacobi's eta function. The even-degree Zolotarev low-pass filter has a mismatch at zero frequency and is realizable as an impedance-transforming *LC* ladder network with unequal terminations. The odd-degree Zolotarev low-pass filter has a single reflection zero (loss zero) at zero frequency and a large ripple between zero frequency and the lower passband corner and is realizable in *LC* ladder form with equal terminations.

In this paper, classical Chebyshev rational function approximation in a transformed variable is extended to include Zolotarev responses, thus simplifying the design procedure. The resulting amplitude response can be easily converted to that of a narrow bandpass filter and used to realize a coupled-resonator low-pass prototype network. Comparisons with other types of filter responses demonstrate that, for double passband requirements and a fixed number of resonators, the Zolotarev filter response has greater stopband skirt selectivity. The improved selectivity may be used to achieve lower passband signal distortion (less variation of loss and delay) in critical applications.

II. Transformed Variable Synthesis

The conventional *LC* bandpass transformed frequency variable is given by [5]

$$z^2 = \frac{\omega^2 - 1}{\omega^2 - a^2}, \qquad \mathrm{Re}(z) \geq 0 \tag{1}$$

which maps the filter passband onto the entire imaginary z axis and the upper stopband ($1 < \omega$) into $0 < z \leq 1$ and the lower stopband ($\omega < a$) into $1/a < z$ on the positive z axis. For $a = 0$, use of (1) results in a low-pass response. The Zolotarev response, having nonzero a, has no lower stopband (except incidentally resulting from the large ripple below the passband) and will still be considered a low-pass response, later to be transformed into a bandpass response with a double passband.

The starting point for the approximation step of synthesis is formation of the polynomial

$$E + zF = \prod_{i=1}^{n} (m_i + z) \tag{2}$$

Manuscript received April 2, 2001; revised August 24, 2001.

The author is with HF Plus, Chatsworth, CA 91311 USA (e-mail: h.c.bell@ieee.org).

Publisher Item Identifier S 0018-9480(01)10457-6.

where n is the filter degree, the m_i are the loss poles transformed by (1) and E and F are even polynomials in z. Finite nonzero loss poles transform to identical pairs on the real z axis (for each real or imaginary s-plane pair), or to two positive-real conjugate pairs (for each complex s-plane quadruplet). As a result, $E+zF$ is strictly Hurwitz, and the roots of E and zF are interlaced along the imaginary z axis (the filter passband). For stopband (positive z axis) loss estimates, a further frequency transformation may be made to $\gamma = \ln z$, and $\gamma_i = \ln m_i$.

Although "Chebyshev" or "Zolotarev" typically refer to filters having all loss poles at infinite frequency, in this paper they will refer to rational function filter responses having arbitrary distributions of loss poles, and the names will distinguish the passband behaviors.

A. Even-Degree Approximation

An even-degree Zolotarev-passband response can be obtained by a straightforward bilinear mapping of a Chebyshev-passband response, where the lower passband corner at $\omega^2 = 0$ is mapped to $\omega^2 = a^2$, and the upper passband corner at $\omega^2 = 1$, and $\omega^2 \to \infty$, are mapped to their same values [1]–[3] as follows:

$$\omega_{\text{zolo}}^2 = \left(1 - a^2\right) \omega_{\text{cheb}}^2 + a^2. \tag{3}$$

The reverse mapping

$$\omega_{\text{cheb}}^2 = \frac{\omega_{\text{zolo}}^2 - a^2}{1 - a^2} \tag{4}$$

is useful in mapping a stopband corner frequency for use in a degree equation relating the filter selectivity to the degree n, the minimum passband return loss, and the minimum stopband loss [6].

The same results can also be obtained with the transformed variable using (1), (2), and the classical Chebyshev rational function [5]

$$\left.\begin{aligned} |K|^2 &= \frac{k^2 E^2}{E^2 - z^2 F^2} \\ k &= \frac{1}{\sqrt{10^{RL/10} - 1}} \end{aligned}\right\}. \tag{5}$$

The characteristic function is $K = S11/S21$, where $S11$ and $S21$ are the reflection and transmission coefficients, respectively, and RL is the minimum passband return loss. The rational function (5) may be used for any general distribution of loss poles; the frequency transformation (1) guarantees that $|K|^2$ oscillates between zero and k^2 with the maximum possible number of ripples and is, therefore, a Chebyshev (optimum equiripple) rational function.

Further examination of the Chebyshev rational function will be helpful in subsequently deriving an odd-degree Zolotarev rational function in a transformed variable. The oscillating passband behavior of $|K|^2$ is also observable by expanding (5) into

$$|K|^2 = \frac{k^2}{4} \left[\sqrt{\frac{E + zF}{E - zF}} + \sqrt{\frac{E - zF}{E + zF}} \right]^2 \tag{6}$$

which, on the imaginary z axis (the filter passband), is

$$\left.\begin{aligned} |K|_{z=jy}^2 &= k^2 \cos^2 \theta \\ \theta &= \arg(E + zF)|_{z=jy} \\ &= \sum_{i=1}^{n} \arg(m_i + jy) \end{aligned}\right\}. \tag{7}$$

As y increases along the entire imaginary z axis (the filter passband), each of the angles $\arg(m_i + jy)$ increases from $-\pi/2$ to $+\pi/2$; the limits of θ are, therefore, $-n\pi/2$ and $+n\pi/2$, and $\cos(\theta) = 0$ at n different passband frequencies.

In the stopband of the filter, where $|K|^2 \gg 1$, the loss α in decibels may be estimated using (6), with the additional transformation $\gamma = \ln z$, by [5]

$$\alpha \approx -RL - 6.02 + 4.34 \sum_{i=1}^{n} \ln \coth \left| \frac{\gamma - \gamma_i}{2} \right| \tag{8}$$

with negligible error for values of RL and α which are greater than 15 dB each. Equation (8) is used to approximate a stopband specification by iteratively adjusting the loss poles.

B. Odd-Degree Approximation

The method used to form the Chebyshev rational function (5) does not apply to an odd-degree Zolotarev rational function because a loss zero is required at $z = 1/a$ ($\omega = 0$), which is outside the passband. However, the approximating function can be formed as the product of two rational functions: one which is equiripple in the passband with $n - 1$ loss zeros, and another which is nearly constant across the passband and contains the loss zero at $z = 1/a$. This procedure is similar to that for the doubly-terminated asymmetric parametric *LC* bandpass filter [5]; the Zolotarev rational function filter is treated as an asymmetric parametric bandpass filter with no loss poles below the passband and with the real-axis loss zero fixed (rather than a free parameter) at zero frequency. The odd-degree filter must have an odd number of loss poles at $\omega \to \infty$ ($z = 1$).

Consider the following product of two rational functions:

$$\left.\begin{aligned} |K|_{z=jy}^2 &= G \cdot k^2 \cos^2 \theta \\ \theta &= \arg\left[(-c + z)\left(E + zF\right)\right]_{z=jy} \\ &= \arg(-c + jy) + \sum_{i=1}^{n} \arg(m_i + jy) \end{aligned}\right\}. \tag{9}$$

$G(z^2)$ is an even rational function which has no zeros or poles on $z^2 \leq 0$ (the filter passband), and the positive constant c corresponds to a hypothetical (nonphysical) loss pole at $z = -c$ [5]. On $z = jy$, with increasing y, $\arg(-c + jy)$ *decreases* from $-\pi/2$ to $+\pi/2$ with the result that the limits of θ are $-(n-1)\pi/2$ and $+(n-1)\pi/2$, and $\cos(\theta) = 0$ at the required $n - 1$ different passband frequencies.

Analytic continuation of the equiripple rational function $\cos^2(\theta)$ in (9) yields

$$\begin{aligned} |K|^2 &= G \frac{k^2}{4} \left[\sqrt{\frac{-c + z}{-c - z} \frac{E + zF}{E - zF}} + \sqrt{\frac{-c - z}{-c + z} \frac{E - zF}{E + zF}} \right]^2 \\ &= G \frac{k^2 \left(-cE + z^2 F\right)^2}{\left(c^2 - z^2\right)\left(E^2 - z^2 F^2\right)}. \end{aligned} \tag{10}$$

The polynomial $-cE + z^2F = \mathrm{Ev}[(-c + z)(E + zF)]$, which has $(n-1)/2$ conjugate pairs of imaginary (passband) roots, must also have a pair of real roots in a factor $(-b^2 + z^2)$. The square of that factor, as well as the divisor $(c^2 - z^2)$, which contains the hypothetical loss pole, are to be cancelled by $G(z^2)$; hence,

$$G(z^2) = \frac{(1/a^2 - z^2)(c^2 - z^2)}{(b^2 - z^2)^2}. \tag{11}$$

Choosing $c = b^2 a, G(z^2) = 1$ and $|K|^2 = k^2$ at the passband edges ($z^2 = 0$ and $z^2 \to \infty$).

After canceling common factors in the two rational functions, the resulting Zolotarev rational function is

$$|K|^2 = \frac{k^2(1/a^2 - z^2)U^2}{E^2 - z^2F^2}$$
$$U(z^2) = \frac{cE - z^2F}{b^2 - z^2}. \tag{12}$$

The one positive root of $cE - z^2F$ at $z^2 = b^2$ is factored out to form the polynomial $U(z^2)$, whose remaining roots are in $z^2 < 0$ (the passband). The positive constant b is calculated by [5]

$$b = \frac{1}{a}\left.\frac{zF}{E}\right|_{z=b} = \frac{1}{a}\,\frac{\prod_{i=1}^{n}(m_i + b) - \prod_{i=1}^{n}(m_i - b)}{\prod_{i=1}^{n}(m_i + b) + \prod_{i=1}^{n}(m_i - b)}. \tag{13}$$

Equation (13) is solved iteratively, starting with $b = 1/a$ until b no longer changes value. Note that $b \cdot a = c/b > 1$ because the factors $(m_i - b)$ are negative and n is odd.

The rational function solution (12) is not exactly equiripple; $G(z^2)$ determines how much $|K|^2$ will depart from an equiripple passband response. Examining (11), the extremum of G inside the passband is at $z^2 = -b^2$

$$G(-b^2) = \left(\frac{c/b + b/c}{2}\right)^2 > 1. \tag{14}$$

Ordinarily c/b will be nearly unity. The deviation from a true equiripple response will be maximum in the vicinity of $z^2 = -b^2$, but for practical cases the deviation is imperceptible in the loss responses. For example, in the degree seven Zolotarev response of Fig. 1(b), the deviation from equiripple is less than 10^{-10} dB in the return loss, which is computationally negligible.

In estimating the odd-degree stopband loss, the contribution of the loss zero at $z = 1/a$ is taken into account in (8) by including the negative term

$$-4.34 \ln \coth \left|\frac{\gamma + \ln c}{2}\right| < 0. \tag{15}$$

C. Realization

Following either filter approximation step above, the realization step of synthesis may be performed to obtain a low-pass *LC* ladder [5] or other appropriate structure.

For bandpass applications, either the even- or odd-degree Zolotarev response can be remapped to a narrow-bandpass response and realized as a coupled-resonator prototype [7] for the design of a filters using a wide variety of practical structures [8], [9]. As in the Chebyshev case, a Zolotarev coupled-resonator filter of even or odd degree can be structurally symmetric with equal terminations.

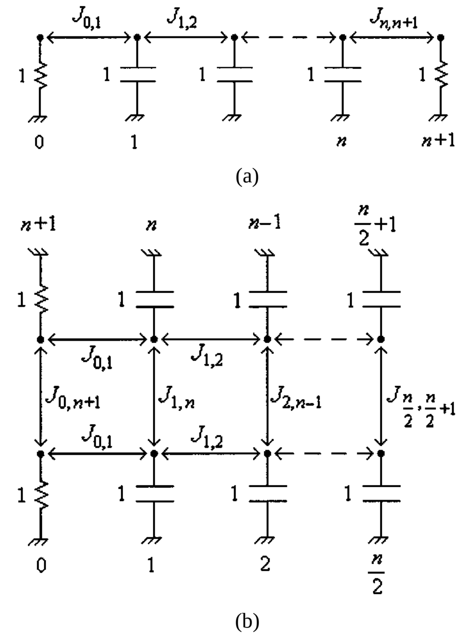


Fig. 2. Normalized coupled-resonator low-pass prototypes. (a) All-pole. (b) General stopband, even degree.

III. Coupled Resonator Prototypes

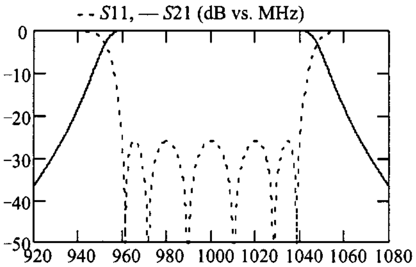
Following are comparisons of lossless Chebyshev and Zolotarev narrow-bandpass prototype filters of degree six and seven. The normalized coupled-resonator low-pass prototypes for these examples are shown in Fig. 2. The filter whose low-pass prototype has all of its loss poles at infinite frequency, commonly referred to as an “all-pole” filter, has a prototype network as shown in Fig. 2(a). The more general filter of even degree with loss poles at finite frequencies can be realized in the form shown in Fig. 2(b). The filter terminations and n resonators are represented by unit-valued resistors and capacitors, respectively, and ideal admittance inverters of characteristic admittance $J_{i,\,i+1}$ represent the couplings. The filters are structurally symmetric, so that $J_{n,\,n+1} = J_{0,1}$, etc.

A. Degree Six, All-Pole Filters

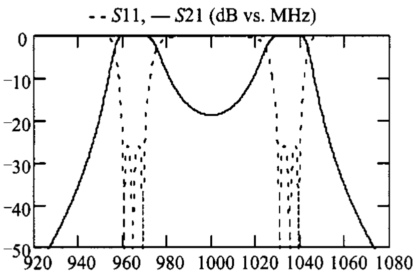
For a six-resonator narrow-bandpass Chebyshev filter (i.e., an all-pole Chebyshev-passband filter) centered at 1000 MHz, with an 80-MHz-wide equiripple passband and 26-dB maximum return loss, theoretical reflection and transmission responses are shown in Fig. 3(a). The couplings in the prototype network, shown in Fig. 2(a), which may be calculated from standard formulas, are

$$J_{0,1} = J_{6,7} = 1.1238 \quad J_{1,2} = J_{5,6} = 0.9619$$
$$J_{2,3} = J_{4,5} = 0.6564 \quad J_{3,4} = 0.6184.$$

Responses for a six-resonator all-pole Zolotarev-passband filter with the equiripple passbands only in the outer 10-MHz segments of the 80-MHz band (corresponding to $a = 0.75$ in



(a)



(b)

Fig. 3. All-pole, $n = 6$ responses. (a) Chebyshev passband. (b) Zolotarev passband.

the normalized low-pass prototype) are shown in Fig. 3(b). The corresponding couplings are

$$J_{0,1} = J_{6,7} = 0.6300 \quad J_{1,2} = J_{5,6} = 0.8984$$
$$J_{2,3} = J_{4,5} = 0.3129 \quad J_{3,4} = 0.8314.$$

Although the Chebyshev filter may be adequate for a typical bandpass filter requirement, it is inefficient when only the outer 10 MHz at each end of the 80-MHz band is actually needed to pass signals, and the Zolotarev filter shows higher stopband rejection. The even-degree Zolotarev filter also provides a small amount of rejection at the center frequency, which could be useful in some applications.

Fig. 4(a) shows a normalized prototype network for a commensurate-line high-pass filter based on the six-resonator Zolotarev-passband coupled-resonator prototype above. The commensurate frequency is 1000 MHz, and Fig. 4(b) shows the theoretical responses. This prototype is in a form which can be used to realize a TEM interdigital bandpass filter.

B. Degree Seven, All-Pole Filters

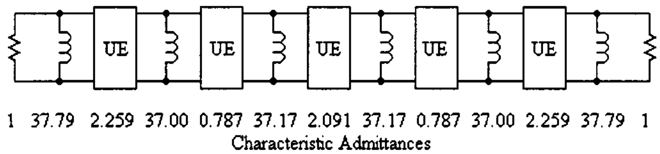
Seven-resonator all-pole Chebyshev-passband filter responses for the same center frequency and equiripple bandwidth are shown in Fig. 5(a), with couplings given by

$$J_{0,1} = J_{7,8} = 1.1129 \quad J_{1,2} = J_{6,7} = 0.9417$$
$$J_{2,3} = J_{5,6} = 0.6382 \quad J_{3,4} = J_{4,5} = 0.5900.$$

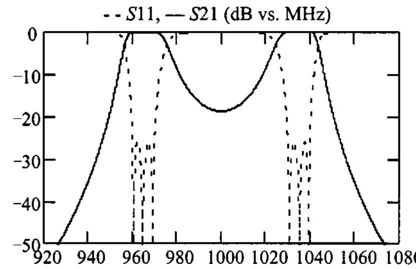
Seven-resonator all-pole Zolotarev-passband responses, equiripple only over the outer 10-MHz segments, are shown in Fig. 5(b). The coupling elements are

$$J_{0,1} = J_{7,8} = 0.6762 \quad J_{1,2} = J_{6,7} = 0.8533$$
$$J_{2,3} = J_{5,6} = 0.4294 \quad J_{3,4} = J_{4,5} = 0.6097.$$

Again the Zolotarev filter shows higher stopband rejection than the Chebyshev filter. In the odd-degree Zolotarev filter, a

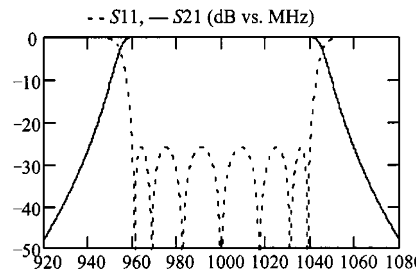


(a)

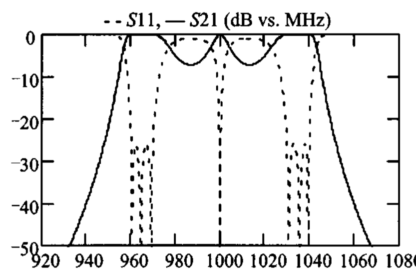


(b)

Fig. 4. Commensurate-line Zolotarev filter, $n = 6$. (a) Normalized prototype. (b) Responses.



(a)



(b)

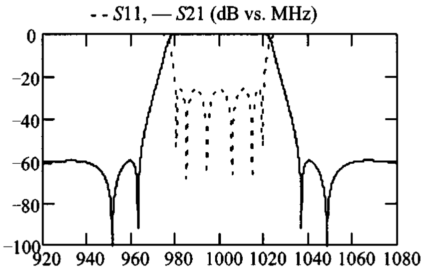
Fig. 5. All-pole, $n = 7$ responses. (a) Chebyshev passband. (b) Zolotarev passband.

narrow passband occurs at center frequency, which could be of use if, for example, a pilot tone must be passed by the filter.

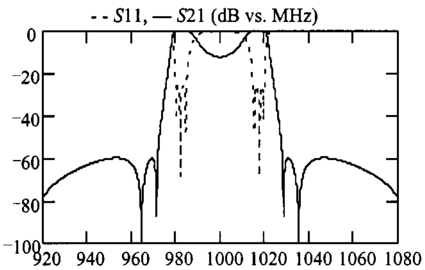
C. Degree Six, Equal-Minima-Stopband Filters

Theoretical reflection and transmission responses of a six-resonator narrow-bandpass elliptic-function filter (i.e., an equal-minima- stopband, Chebyshev-passband filter) centered at 1000 MHz, with a 40-MHz-wide equripple passband, 26-dB maximum return loss, and 60-dB minimum stopband loss, are shown in Fig. 6(a). The couplings in the prototype network, Fig. 2(b), are

$$J_{0,1} = J_{6,7} = 1.1152 \quad J_{0,7} = -0.0005$$
$$J_{1,2} = J_{5,6} = 0.9456 \quad J_{1,} = 0.0188$$
$$J_{2,3} = J_{4,5} = 0.6264 \quad J_{2,5} = -0.1496$$
$$J_{3,4} = 0.7216.$$



(a)



(b)

Fig. 6. Equal-minima stopband (elliptic-function), $n = 6$ responses. (a) Chebyshev passband. (b) Zolotarev passband.

Responses for a six-resonator equal-minima-stopband, Zolotarev-passband filter with the equiripple passbands only in the outer 5-MHz segments of the 40-MHz band (also corresponding to $a = 0.75$ in the normalized low-pass prototype) are shown in Fig. 6(b). The corresponding couplings are

$$J_{0,1} = J_{6,7} = 0.6404 \quad J_{0,7} = -0.0005$$
$$J_{1,2} = J_{5,6} = 0.8815 \quad J_{1,6} = 0.0256$$
$$J_{2,3} = J_{4,5} = 0.3154 \quad J_{2,5} = -0.1237$$
$$J_{3,4} = 0.8795.$$

As expected, the Zolotarev-passband filter has steeper skirt rejection than the Chebyshev-passband filter; the 60-dB bandwidths are 56.2 and 71.8 MHz, respectively.

IV. Delay Performance

With stopband loss and passband return-loss specifications that include margins, additional performance margin is usually put into widening the passband in order to reduce signal distortion. Passband delay is very useful in comparing narrow-bandpass coupled-resonator filter designs, since it not only indicates signal distortion resulting from delay variation (dispersion), but also from loss and loss variation (dissipation loss is, to a very good approximation, proportional to delay). Following are theoretical comparisons of six-resonator configurations with double-passband requirements.

A. Six-Resonator, All-Pole Filters

Let the return loss be specified as 26 dB minimum over the 10-MHz passbands in the previous all-pole examples (960–970 and 1030–1040 MHz), and the stopband loss be specified as 35 dB minimum at 920 and 1080 MHz. Filters with six resonators will be compared: Chebyshev, Zolotarev, and double-diplexed three-resonator equal-bandwidth filters.

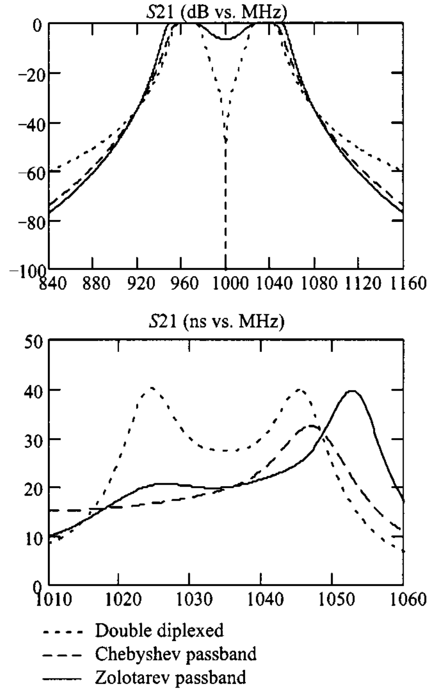


Fig. 7. Loss and delay of all-pole $n = 6$ filters.

The wide-band loss and upper-passband delay responses of the three filters are shown in Fig. 7, with the 35-dB losses converging at 920 and 1080 MHz. The Chebyshev filter has an equiripple bandwidth of 82.2 MHz. The Zolotarev filter's inner passband edges were fixed at 970 and 1030 MHz, and the outer passband edges are 951.5 and 1048.5 MHz. The double-diplexed filters' center frequencies were fixed at 965 and 1035 MHz and the bandwidth of each filter is 13.3 MHz. The maximum and minimum delay and difference (variation) across the 10-MHz-wide passbands are summarized as follows:

Diplexed: 29.75 ns max., 27.38 ns min., 2.36 ns diff.

Chebyshev: 23.23 ns max., 17.78 ns min., 5.45 ns diff.

Zolotarev: 21.48 ns max., 19.75 ns min., 1.74 ns diff.

The Zolotarev-passband filter, with the lowest maximum delay and the lowest delay variation, makes the most efficient use of the six resonators in terms of passband signal distortion.

B. Six-Resonator, Equal-Minima-Stopband Filters

Let the return loss be specified as 26 dB minimum over the 5-MHz passbands in the previous equal-minima-stopband examples (980–985 and 1015–1020 MHz), and the stopband loss be specified as 60 dB minimum at 963 and 1037 MHz. Six-resonator Chebyshev- and Zolotarev-passband filters will be compared. The use of double-diplexed elliptic-function filters is less straightforward and is not considered here; the two paths from input to output may result in up to 6-dB reduction in stopband loss, requiring a corresponding increase in the minimum stopband loss of each filter.

The wide-band loss and upper-passband delay responses of the two filters are shown in Fig. 8, with the 60-dB losses converging at 963 and 1037 MHz. The Chebyshev-passband filter has an equiripple bandwidth of 41.25 MHz. The

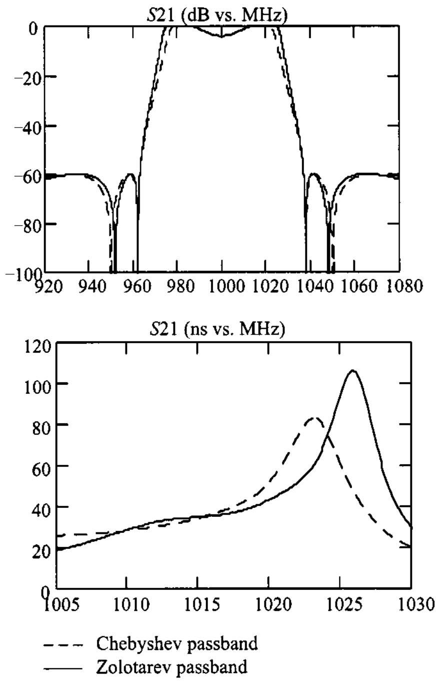


Fig. 8. Loss and delay of equal-minima-stopband, $n = 6$ filters.

Zolotarev-passband filter's inner passband edges were fixed at 985 and 1015 MHz, and the outer passband edges are 975.9 and 1024.1 MHz. The delay characteristics across the 5-MHz-wide passbands are summarized as follows:

$Chebyshev$: 51.68 ns max., 34.37 ns min., 17.31 ns diff.

$Zolotarev$: 43.21ns max., 34.93 ns min., 8.29 ns diff.

Again, the Zolotarev-passband filter exhibits less passband signal distortion.

V. Conclusion

In the examples presented, the location of the loss poles were determined by the type of response (all-pole or equal-minima stopband) in the normalized frequency domain. Using rational approximation in a transformed frequency variable, the low-pass filter synthesis may include loss poles placed at arbitrary finite stopband frequencies for specific rejection requirements, or placed on the real s-plane axis or at complex s-plane frequencies for delay equalization, or both.

In instances where rejection between the passbands is required, but rejection below the lower passband and above the upper passband is not required, high-pass Zolotarev responses may be mapped to a narrow-bandstop response [10].

Realizations in *LC* low-pass ladder form can be transformed into *LC* high-pass, bandpass, or bandstop ladder networks using reactance transformations appropriate for each case, resulting in exact realizations. Zolotarev realizations may also be obtained for commensurate-line networks by including the unit element in the synthesis.

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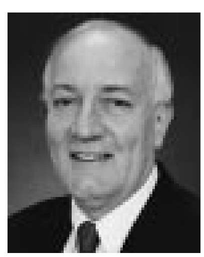

H. Clark Bell (M'67–SM'78–F'97) was born in San Diego, CA. He received the B.S. degree in physics and the M.S. and Ph.D. degrees in engineering from the University of California at Los Angeles, in 1966, 1969, and 1974, respectively.

From 1966 to 1993, he held various staff and management positions in industry, and is currently a consulting engineer doing business with HF Plus from offices in Chatsworth and La Jolla, CA. His specialties include filters and passive components, wire antennas, RF distribution and propagation problems, and forensic engineering in electronics and communications.

Dr. Bell is a licensed Electrical Engineer in the State of California, a senior member of the National Academy of Forensic Engineers, a full member of the Association of Federal Communications Consulting Engineers, and a registered patent agent. He has been active in the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) at the local and national levels. He is currently the patent abstracts editor for the IEEE Microwave and Wireless Components Letters. He was the recipient of the 2000 IEEE Third Millenium Medal.