Using modified Chebyshev functions for approximation in 5G technologies

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ABSTRACT

This research addresses the critical challenge of broadband matching in radio engineering, focusing on enhancing phase-frequency response (PFC) linearity across wide frequency bands. A novel approach, utilizing modified Chebyshev functions, demonstrates significant potential in reducing phase distortions within 5G technology applications. Unlike traditional Chebyshev functions, this method incorporates strategically placed transmission zeros—complex conjugate pairs on the s-variable complex plane—without increasing the filter circuit's order. This innovation results in a low-order filter circuit characterized by uniform phase response and group delay characteristics (GDT), offering an effective solution for matching circuit design with less phase-frequency distortion and improved group delay uniformity across diverse load conditions. The modified Chebyshev approximation outperforms its classical counterpart in both phase linearity and selectivity within the 1 to 1.2 cutoff frequency range. This enhancement is crucial for the development of low-frequency filters, with broader implications for creating high-frequency, band-pass, and band-stop filters via known frequency transformations. Empirical results validate the proposed method's reliability and effectiveness, marking a significant advancement in the field of radio engineering by addressing broadband matching challenges with increased efficiency and simplified design implementations.

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1. INTRODUCTION

Significant advancements in satellite, mobile telecommunications, and radar systems have been closely tied to the utilization of wideband and ultra-wideband signals. Notably, between 2012 and 2013, the development of wideband high-frequency (WBHF) radio technology, also referred to as broadband high frequency (HF) radio communications, emerged to meet the increasing data transmission requirements for North Atlantic Treaty Organization (NATO) armed forces subscribers. This progress prompted a revision of NATO standards, exemplified by the updated editions of military standard (MIL-STD)-188-110C (“Functional compatibility and operational requirements for data transmission modems,” released on January 3, 2012) and MIL-STD-188-141C (“Interoperability and performance requirements for medium and high-frequency radio frequency systems,” released on December 27, 2011). Key modifications stem from the integration of broadband HF radio communication technology, defining a spectrum of broadband modulation types for a radio channel. This includes achieving an amplitude-frequency response (AFC) band for the transceiver path ranging from 3 to 24 kHz in 3 kHz increments. Pioneered by Harris Corporation and Rockwell Collins, leaders in military HF radio communications, this technology focuses on expanding bandwidth and enhancing data transfer rates.

Expanding the bandwidth to 24 kHz in single-sideband mode, coupled with 8-position phase modulation, increases the bit rate from 9,000 bps to 38,400 bps. Moreover, utilizing two independent 24 kHz channels, one in each sideband, raises the total bit rate to 76,800 bps. This approach necessitates specific requirements for the group delay time (GDT) characteristics of the WBHF channel, ensuring minimal disparities between channels and limiting group delay variations for different frequency increments within defined bandwidths. For instance, at a 3 kHz channel, the group delay specifications range from 575 to 2775 Hz, and for the WBHF channel, it extends from 575 to (B - 225) Hz, where B=N×3 kHz, and N=1, 2, 3, 4, 5, 6, 7, or 8. The implementation of two independent WBHF channels, with one in each sideband, necessitates expanding the required bandwidth to 48 kHz. This represents a sixteen-fold increase compared to the standard 3 kHz voice frequency HF radio channel. Consequently, this expansion requires the establishment of specific criteria for the phase-frequency characteristics (PFC) of the frequency-selective circuits within a radio station. To successfully process such signals using a superheterodyne receiver, its components—namely the low pass filter (LPF 8), high pass filter (HPF 3), volume unit (VU 2), and pre-selected pass filter (PPF 5), as illustrated in Figure 1 must meet certain requirements. These include selectivity and minimal distortion of the signal's amplitude and phase spectra.

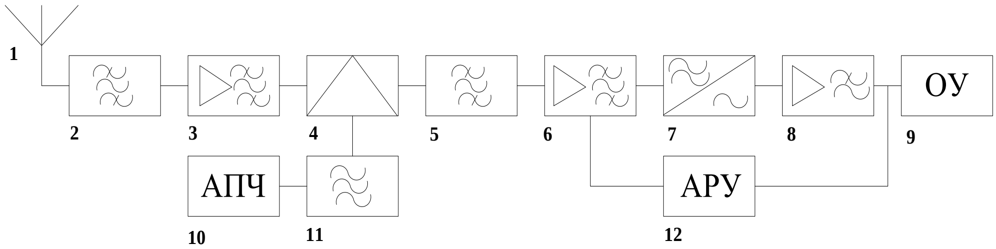


Figure 1. Block diagram of a superheterodyne receiver

In the power amplification path of a radio transmitter, there are three principal components: a wideband transistor power amplifier (PA), a harmonic suppression filter block, and an adaptive antenna matching unit. The efficiency of broadband transistor PAs is greatly influenced by how well the PA's output impedance is matched with the load. A mismatch between the PA's output and the filter-matching device system significantly reduces the power delivered to the load, leading to the generation of a reflected wave at the PA transistors' collectors. This mismatch can cause a noticeable decrease in power output [1]–[3]. Employing complex conjugate matching in the filter-matching path can substantially enhance the power transmission coefficient, making the match between the antenna and the PA output crucial. The matching device, which can vary in design from case to case, is typically a four-terminal network. The input impedance of this network (e.g., an antenna matching device) should always match the characteristic impedance of the cable connecting it to the power amplifier's output. It's important to note that the complex input impedance of antenna matching devices or circuits changes with variations in antenna parameters, such as complex impedances, conductivities, and the magnitude and phase of the reflection coefficient. These parameters can be considered random variables.

Broadband matching circuits play a crucial role in determining key performance metrics such as bandwidth, selectivity, sensitivity, noise immunity, and electromagnetic compatibility. Notably, lower sensitivity values indicate minimal impact of load impedance variations on the power transfer factor level. Currently, most cellular mobile communications operate below 3 GHz, with a maximum channel capacity of 20 MHz. In the Republic of Kazakhstan, 5G networks have been deployed with a maximum channel capacity of 100 MHz within the radio frequency ranges of 3700–3800 MHz and 3600–3700 MHz. These ranges are particularly favorable for rapid and cost-effective deployment. For instance, 5G smartphone antennas employ a dielectric substrate made from new composite materials (e.g., FR-4 with a dielectric constant of 4.3) to achieve high isolation and low loss. To ensure broadband performance, it is essential to synthesize a broadband matching device that maintains stable impedance. Impedance instability, which can arise from various mismatch factors, environmental, and operating conditions, leads to the generation of reflected waves in the path of a radio device, thereby reducing the power of received or transmitted signals. Consequently, the development of 5G radio devices necessitates the creation of broadband matching circuits (BMCs) that possess specific phase-frequency and amplitude-frequency characteristics (PFC and AFC) within a certain frequency band.

In designing broadband matching devices, developers often overlook the load impedance instability resulting from changes in operational conditions, such as temperature, vibration, and varying modes of active components. Given the rapid advancement in wireless communication technologies, developing a theory for the synthesis of wideband matching and filtering networks (WMFNs) has become crucial, especially due to the limitations and challenges posed by existing methodologies. Over the past thirty years, efforts to enhance the performance of matching and filtering circuits have focused on increasing their selectivity and minimizing spectral distortions, all while aiming for the smallest possible weight and size. A significant area of research has been the exploration of new mathematical functions to better approximate the frequency characteristics of filters. While analytical approaches exist for addressing matching challenges involving highly complex loads, these solutions often come with a notable drawback: their applicability is limited when facing a range of intricate matching problems. The exploration of broadband matching challenges has been extensively addressed by notable scientists such as B.S. Yarman, D. Youla, W.-K. Chen, L.I. Babak, G.N. Devyatkov, among others. Their pioneering work laid the groundwork for developing sophisticated algorithms and methods for synthesizing devices with specific amplitude and phase-frequency characteristics. Significant contributions in this field were also made by A.F. Beletsky, A.A. Lanne, I.I. Trifonov, A.D. Artym, and others. Contemporary approaches to synthesizing broadband matching devices primarily focus on creating minimum-phase circuits, engaging only with the amplitude-frequency response of the device. However, when requirements are set for both the amplitude and phase-frequency characteristics simultaneously, the synthesis outcome is likely to yield a non-minimum-phase circuit. A survey of scientific literature reveals a consistent interest among researchers in the addressed issues. In recent years, the implementation of frequency-selective circuits has seen a growing trend towards utilizing modified approximation functions. Therefore, it becomes imperative to scrutinize circuits synthesized through modern modified approximating functions [4]. The accurate selection of an approximation holds great significance in the filter design process as it profoundly influences the resultant behavior of the filter. A crucial characteristic of mathematical functions that approximate the frequency characteristics of filters is the existence of transmission zeros in the frequency region adjacent to the passband, known as built-in transmission zeros [5]–[7]. These zeros are strategically incorporated to modify the Chebyshev approximation function. Their incorporation ensures a more rapid attenuation in the frequency response beyond the filtering band, all while maintaining the equi-ripple nature of the response within the filtering band [8]–[10].

2. METHOD

In constructing radio engineering paths, the complexity of the internal resistance in both the signal source and load necessitates addressing the matching problem. Classical theory approaches wideband matching (WM) through circuitry and technical support to achieve signal transmission with minimal distortion, losses, and reflections [11]. In the traditional synthesis of broadband matching circuits (WMC) for loads that involve one reactive element, the real part of the resistance or conductance of the load is typically treated as constant over the frequency range. Equivalent series or parallel circuits are employed in these cases. However, when dealing with frequencies where the active part of the input resistance or load conductivity changes, it becomes necessary to utilize a load with two randomly connected reactive elements. This approach allows for a representation of the input impedance of complex loads (such as antennas, amplifiers, and converters) within their operating frequency range.

Selecting an appropriate synthesis technique is a fundamental challenge in the development of synthesis frequency converters (SFCs) for impedance variations. Numerous approaches have been devised for the synthesis of broadband SFCs, generally categorized into two major groups: analytical and numerical matching methods. The primary drawback of numerical solutions lies in the complexity of applying calculation results to address non-standard problems. Analytical wideband matching (WM) theory encounters limitations in its inability to provide suitable methods for approximating frequency characteristics. Consequently, the synthesis of SFCs becomes unattainable for many complex loads. To overcome these analytical challenges, several publications exploring solutions to impedance matching problems delve into the use of modified approximating functions (MAFs) [12]–[14]. This research avenue aims to mitigate the analytical limitations in coordinating complex loads by introducing and refining new approximating functions. Selective circuits with a linear phase response exhibit uniform delay for all frequencies, resulting in undistorted output signals but with an appropriate time delay. However, real signals encompass multiple frequencies, and when each frequency is delayed differently, it leads to signal distortion. For instance, in scenarios involving 8-position phase modulation or multi-position quadrature amplitude modulation, a nonlinear phase response is deemed unacceptable. The significance of maintaining a linear phase response becomes pronounced in the passband, where the frequency components of interest are isolated. Typically, a trade-off exists between achieving a linear passband response and fulfilling other filter requirements, such as roll-off and stopband attenuation. Striking a balance between these factors is crucial in designing filters that meet the specific needs of the application.

To meet the above requirements, in recent years filters with modified transfer functions have begun to be used [15]–[17]. Compared to classical approximating functions, modified transfer functions have the following disadvantages: i) greater unevenness in the passband, ii) less attenuation in the stop band, iii) absence of the property of square symmetry, and iv) greater unevenness of the phase response. A new modification of the approximating function is proposed; the analytical expression for the low-frequency prototype has the following form (1):

$$K_m(-s^2) = \frac{k^2}{1+\varepsilon^2 \prod_{q=1}^{N}(s_q-1)\frac{\Psi_m(s)\Psi_m(-s)}{\prod_{q=1}^{N}(s+s_q)}}, \quad (1)$$

where $s = \pm\sigma \pm j\omega$– complex frequency, $\Psi(s)$ is m^{th} order approximating polynomial, ε is coefficient of characteristic unevenness in the passband, s_q is complex frequency at which the function takes on a zero value, k is *коэффициент* (coefficient), not exceeding one ($k \leq 1 -$ constant characterizing the maximum transmission level), q is number of the entered transmission zero, and N is number of input transmit zeros (number of frequencies at which the power transfer function takes a zero value).

The modified function (1) differs from the classical function by the inclusion of transmission zeros in a specific manner. These transmission zeros are generated through the introduction of complex conjugate pairs located on the complex plane of the s-variable. In prior publications [18], the zeros of the transfer function were exclusively positioned along the imaginary axis of the complex s-variable plane. While this placement maximized decay levels and uniformity in the passband of the amplitude-frequency characteristic, it concurrently compromised the uniformity of the phase response. To enhance the phase response's uniformity within the filter passband, the proposal suggests incorporating a quadruple of complex conjugate zeros. The linearity of the phase response more clearly describes the group delay time (GDT). Figure 2 shows the dependence of the group delay scatter on the location of the transfer function zeros on the complex plane for the modified fifth-order Chebyshev function.

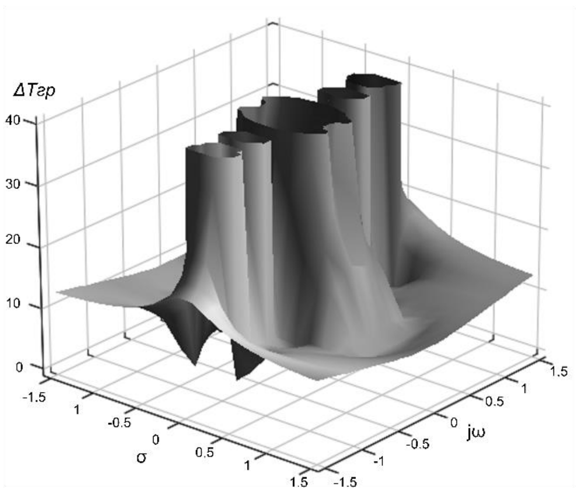
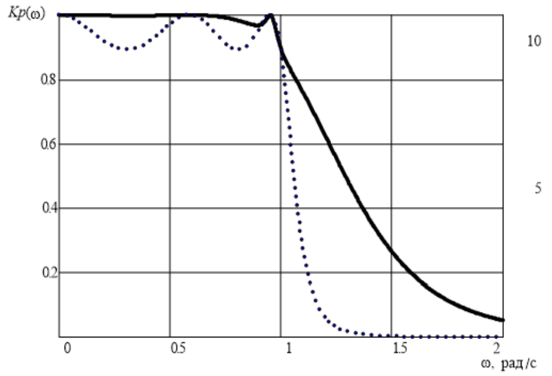
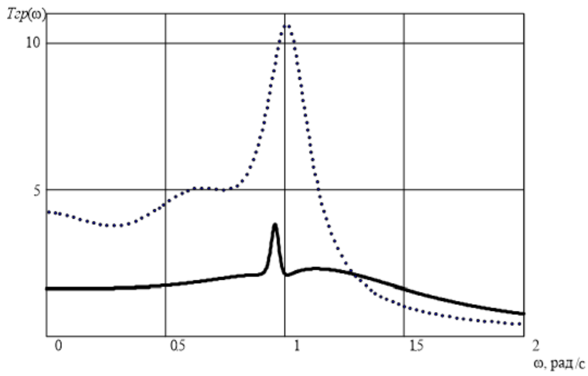


Figure 2. Dependence of the group delay spread on the location of the transfer function zeros for the fifth-order modified Chebyshev function

Figure 2 allows you to determine the location area of the input transmission zeros, in which the group delay spread is minimal. The pair of zeros visible in the figure is located in the region $\sigma = \pm 0.035$ and $j\omega = \pm 0.96$. For these zeros, the dependences of the power transfer coefficient (a) and group delay (b) on the frequency of the modified Chebyshev function of the fifth order (solid line), in comparison with the classical Chebyshev function of the fifth order (dashed line) under the same initial conditions are presented in Figure 3. The power transfer coefficient is shown in Figure 3(a) and the group delay is shown in Figure 3(b) versus the frequency of the modified fifth-order Chebyshev function (solid line) compared to the classical fifth-order Chebyshev function (dashed line).



(a)



(b)

Figure 3. Power transfer coefficient (a) and group delay and (b) from the frequency of the modified fifth-order Chebyshev function (solid line) in comparison with the classical fifth-order Chebyshev function (dashed line)

Analysis of the given dependencies shows that the modified fifth-order Chebyshev function is inferior to the classical transfer function in selectivity, but has greater uniformity in the filtering (matching) band of the transmission coefficient and a more uniform and smaller group delay. This filter option is important in conditions where the requirements for linearity of the phase-frequency response are decisive. The location of the real and imaginary components of the input zero transmission affects the shape of both characteristics. In this regard, the question of the possibility of improving selectivity and simultaneously increasing the linearity of the phase-frequency response when using appropriate modifications is of interest. For the modified Chebyshev function of the 5th order, we take a quadruple of zeros, which will have higher selectivity in the band from 1 to 1.2 cutoff bands than the classical function with $m = 5$, $\varepsilon = 0.349$, $k = 1$. A function with the initial conditions given above in the s-plane forms the surface shown in Figure 4. The section of the shown surface by the plane $s = j\omega$ represents the frequency response of power transmission, shown in Figure 5(a): the dotted line corresponds to the classical Chebyshev approximation; the solid line corresponds to the modified Chebyshev function. Analyzing the curves in Figure 5, we can conclude that the modified Chebyshev approximation has a more linear frequency response in the filter band and is superior in selectivity to the classical Chebyshev function in the band from 1 to 1.2 cutoff frequencies. To determine the quality of approximation, we use the integral quadratic proximity criterion [13]. This criterion allows you to determine the integral error of approximation on a given interval [a; b] in the form (2).

$$P_{[a;\,b]} = \int_a^b [M(\omega) - K(\omega)]^2 d\,\omega \tag{2}$$

where $M(\omega)$ is the reference function on the section [a; b] for normalized functions is equal to 1, $K(\omega)$ is an approximating function for which it is necessary to determine the quality of approximation. The approximation error of the modified function with the given parameters is 2.881×10^{-4}, in turn, the error of the classical Chebyshev approximation with the same parameters is 0.528×10^{-3}, which is more than an order of magnitude higher. The group delay characteristics of the modified approximating function and the classical Chebyshev approximation are presented in Figure 5(b).

Analyzing Figure 5 reveals a notable observation: within the normalized bandwidth, the modified function exhibits higher phase response linearity when contrasted with the classical Chebyshev approximation. This suggests that the modifications introduced to the function contribute to an improved linearity of the phase response over the specified frequency range. The visual evidence from the figure supports the conclusion that the proposed modifications enhance the performance of the Chebyshev approximation in terms of phase linearity.

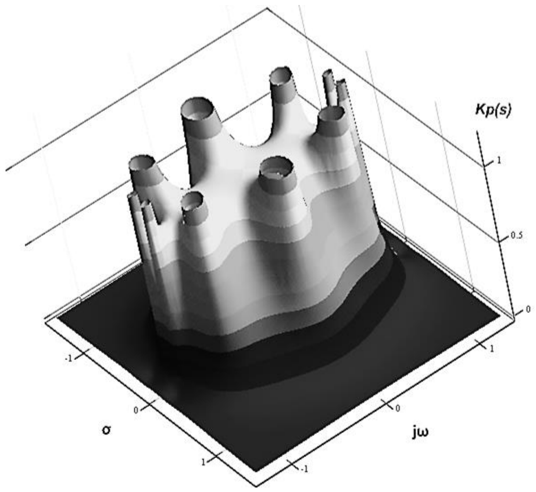
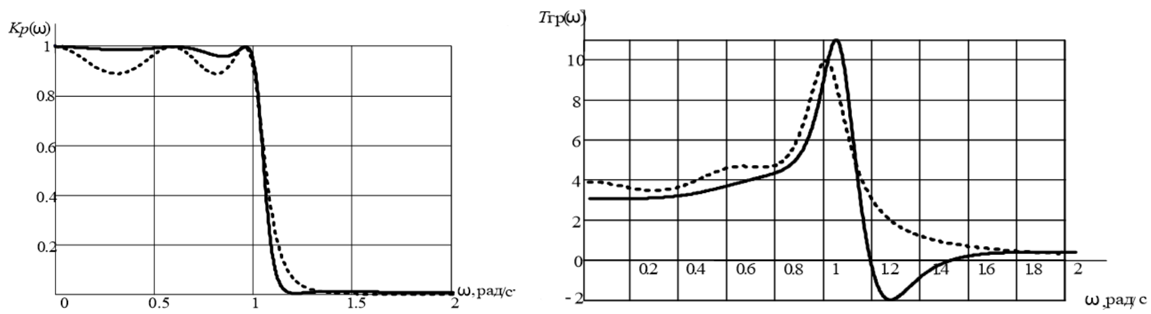


Figure 4. Surface of the modified transfer function (2) in the s-plane



(a) (b)

Figure 5. Power transfer coefficient (a) and group delay and (b) from the frequency of the modified fifth-order Chebyshev function (solid line) in comparison with the classical fifth-order Chebyshev function (dashed line)

3. RESULTS AND DISCUSSION

For the processing of wideband and ultra-wideband signals, stringent selectivity standards apply to the input paths of radio receiving devices. Elements within these input paths must introduce minimal distortion to both the amplitude and phase spectra of the signal. To fulfill these demands, filters employing modified transfer functions have become prevalent [19], [20]. The modified function (1) distinguishes itself from the classical function by the strategic addition of transmission zeros. Importantly, the introduction of these zeros does not augment the order of the approximating function, thereby avoiding an increase in the order of the matching circuit. The ideal equal-frequency response of the filter is achieved by strategically positioning the transmission zeros and poles using appropriate filter design technology. However, the presence of frequency-dependent elements in the denominator of the filter function does not allow the filter to achieve an ideal response. This is due to the distortion introduced by these elements, which cannot be completely eliminated by the placement of transmission zeros and poles alone. To fully compensate for frequency distortion, it is necessary to further modify the filter transfer function coefficients in order to minimize the influence of the frequency-dependent element and maximize the filter's frequency response.

Known classical approximations have no more than two parameters for controlling the shape of the frequency response, which determine the possibility of solving the system of network performance specifications (NPS) constraints [15]. The modified fifth-order Chebyshev function is inferior to the classical transfer function in selectivity, but has greater uniformity in the filtering (matching) band of the transmission coefficient and a more uniform group delay [21]. Note that various factors (such as bending and soldering) can change the electrical characteristics of SFC components and affect their overall performance. Also, coupling between transmission lines can generate additional transmission zeros that cannot be accurately taken into account in the simulation. Holes in the printed circuit board (PCB) create parasitic inductance and capacitance that cause a small frequency shift [22]. There are several factors that can cause a change in the group delay in the SFC passband. Some of the most common factors include the order of the filter, the location and spacing of its poles, and the magnitude and phase response of its transfer function. Other factors that can affect the group delay include the filter's passband ripple, the slope of its transition band, and the frequency response of the filter components. The main purpose of the SFC design is to minimize the variation of group delay within the passband while achieving the desired frequency response characteristics. Thus, by modifying the approximating function in accordance with expression (1), it is possible to significantly reduce the distortion of the phase spectrum of signals, while maintaining the level of selectivity high. Let's consider the option of calculating a low-pass filter. Let's take the modified Chebyshev function (1) of the fifth order with the initial conditions presented above; the frequency characteristics for these conditions are shown in Figure 5. The relationship between the reflection coefficient and the power transfer function (1) has the form (3):

$$K_p(-s^2) = 1 - \rho(s)\rho(-s), \qquad (3)$$

where $\rho(s)$ is reflection coefficient function at the filter input. By isolating the poles and zeros of the function $\rho(s)\rho(-s)$ in the left half-plane, we obtain an expression for $\rho(s)$. Using the well-known relation (4) connecting the reflection coefficient and resistance, we find the filter input resistance function:

$$Z_{\text{вх}}(s) = \frac{1-\rho(s)}{1+\rho(s)} \qquad (4)$$

The synthesis of the resistance function (4) has been successfully implemented to create a broadband matching device circuit for the signal source resistance, depicted in Figure 6. This circuit incorporates a load equivalent and utilizes normalized element ratings for optimal performance. The resulting design aims to efficiently match the signal source resistance with the load, ensuring effective signal transmission across a wide range of frequencies.

$$C_1 = 1.226, L_1 = 1.063, C_2 = 0{,}988, L_2 = 0{,}674, L_3 = 1{,}13, r = 0{,}026, C_3 = 1{,}303, R_{\text{н}} = 1.$$

To verify the results obtained, an experiment was carried out on the practical implementation and measurement of the characteristics of the filter presented in Figure 6. The filter was designed for a cutoff frequency of 2.6 MHz. Together with a modified Chebyshev filter, a classical Chebyshev filter was implemented for comparison for the same initial conditions. The experiment is presented in Figure 7.

Figure 8 shows the frequency characteristics of the filters. Figure 8(a) shows the power transfer ratio and Figure 8(b) shows the group delay vs. frequency of the modified fifth-order Chebyshev function (blue line) compared to the classical fifth-order Chebyshev function (red line). The measurements were made using a ZNB4 vector network analyzer (signal and measurement port with a characteristic impedance of 50 Ohms), operating in the range 9 kHz-4.5 MHz. The measurement accuracy is less than 0.05 dB (when measuring transmission parameters) and 0.5 dB (when measuring reflection parameters) [23]–[25].

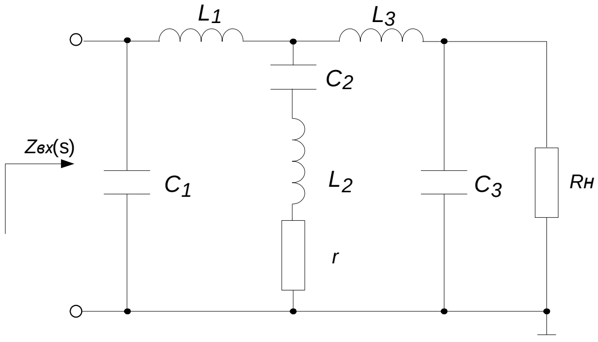


Figure 6. Canonical circuit shape for input

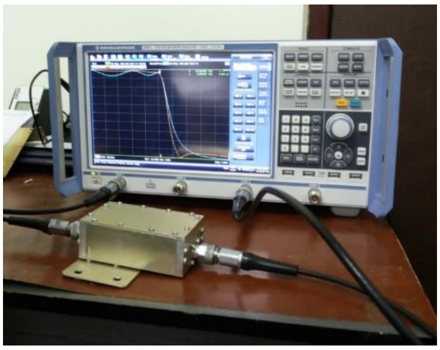
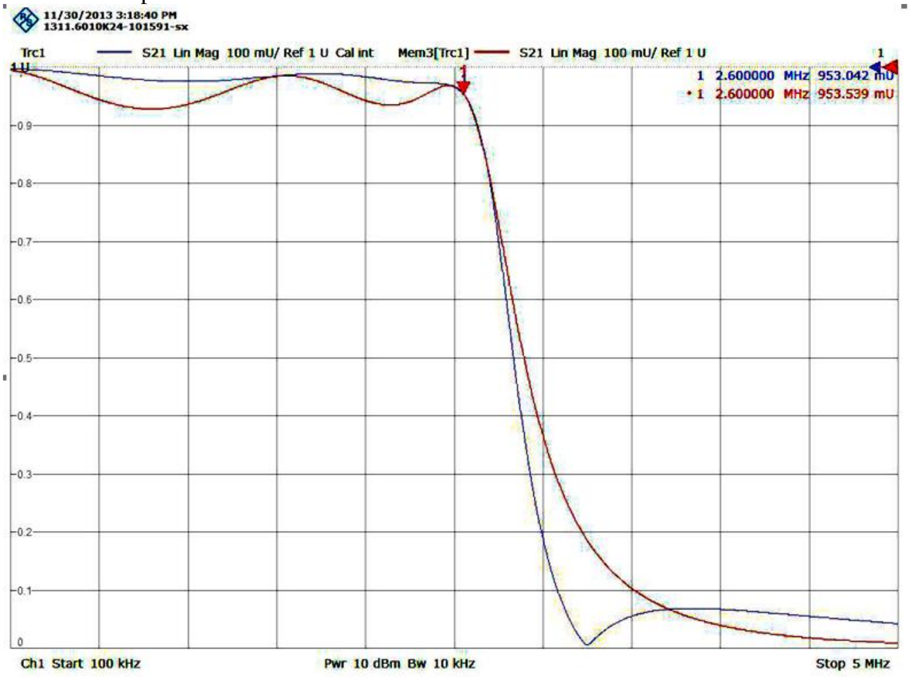
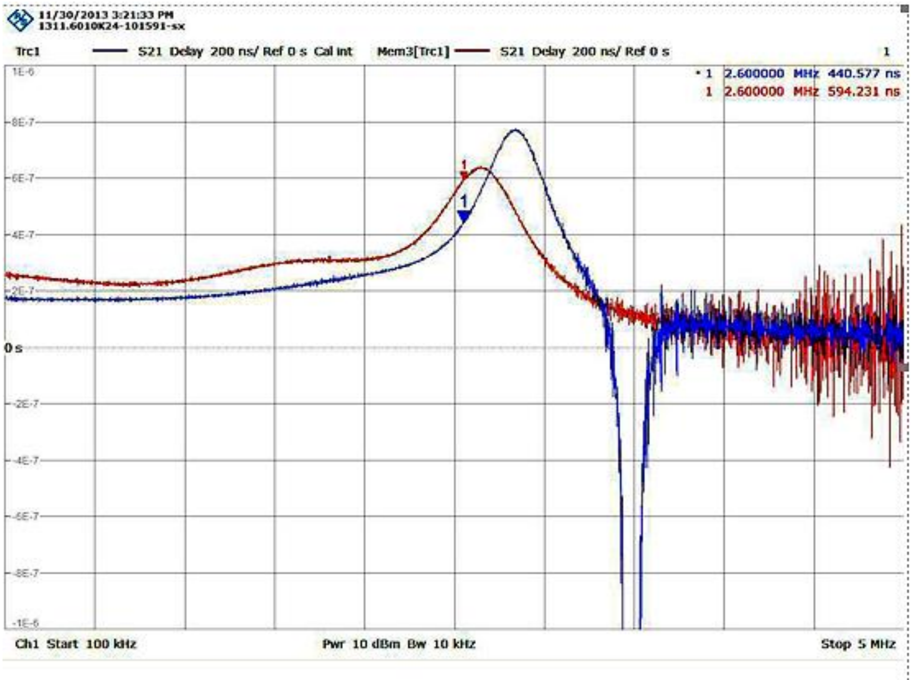


Figure 7. Experiment on practical implementation

impedance and measurement of filter characteristics



(a)



(b)

Figure 8. Frequency characteristics of the implemented filters: power transmission coefficient (a) and group delay (b) from the frequency of the modified fifth-order Chebyshev function (blue line) in comparison with the classical fifth-order Chebyshev function (red line)

The comparison of dependencies in Figures 5 and 8 reveals a commendable consistency between theoretical predictions and experimental outcomes. Notably, the absence of trimming elements in the filter designs underscores the low sensitivity of the filter characteristics to nominal values of the elements. This observation highlights the robustness of the filter design, contributing to its reliability in practical applications.

4. CONCLUSION

A mandatory requirement for modern radio communication systems is to ensure reliable and high-quality communication, adapted to any manifestations of negative impacts. The growing demand for compact, economical and complex wireless systems has created a need for the development of passive matching-filtering microwave components characterized by high selectivity, effective suppression of distortion, and reliable signal transmission. Also, one of the main trends in the development of communication systems is the active use of broadband radio communications. Traditional filter theory, based on the concept of narrowband filters, has inherent limitations and is inherently unsuitable for the development of ultra-wideband filters. The modified function of the form (1) proposed in this work allows us to simultaneously reduce the unevenness of the filter's frequency response in the filtering band, increase its selectivity and the linearity of the phase-frequency response. This result is achieved by placing the four complex conjugate zeros of the modified function on the complex plane. It was previously noted that the modification method used has a number of advantages compared to known modifications. All this gives reason to consider the use of this class of filters in analogue paths of telecommunications and radar equipment as promising. The presented results for a low-frequency filter prototype do not reduce the scope of application, since the use of known frequency transformations makes it possible to obtain high-frequency, band-pass and band-stop filters with similar properties. The proposed filter design meets the requirements of low cost, improved out-of-band rejection and low loss, and minimization of in-band group delay variation while achieving the desired frequency response characteristics. This all plays a major role when working with other circuits/antennas. to improve performance. radio communication systems. Low-loss filters help minimize signal loss during transmission, and compact sizes are necessary for devices with limited space.

Solving the problem of synthesizing broadband matching devices that ensure a stable level of power transmission over a wide range of operating frequencies and under conditions of variable load resistance is very relevant for radio equipment of 5G technology. This will maximize the transmitted/received signal power to the load, and will also ensure the maximum range of radio links in various operating conditions, and, as a result, will increase the stability of modern radio communication systems in various operating and environmental conditions

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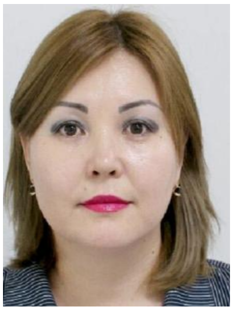

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