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Gnatyuk Maksim, Candidate of Physical and Mathematical Sciences, Associate Professor of the Department of Electronics and Electronical Communications
Гнатюк М.О., кандидат фізико-математичних наук, доцент кафедри електроніки і електронних комунікацій
ORCID: 0000-0002-7512-5671
e-mail: uv5ekr@gmail.com

Boshel Iryna, undergraduate student of the Department of Electronics and Electronical Communications
Бошель І.О., здобувач першого (бакалаврського) рівня вищої освіти кафедри електроніки і електронних комунікацій

Lytvynenko Volodymyr, Candidate of Technical Sciences, Associate Professor of the Department of Electronics and Electronical Communications
Литвиненко В.А., кандидат технічних наук, доцент кафедри електроніки і електронних комунікацій
ORCID: 0000-0003-4950-5168

Sianov Oleksandr, Doctor of technical sciences, Professor of the Department of Electronics and Electronical Communications
С'янов О.М., доктор технічних наук, професор кафедри електроніки і електронних комунікацій
ORCID: 0000-0003-4120-4926
e-mail: alexandr.sianov@gmail.com

Dniprovsky State Technical University, Kamianske
Дніпровський державний технічний університет, м. Кам'янське

THE METHOD OF LUMPED ELEMENT BANDPASS FILTER DESIGN FOR HIGH FREQUENCY RADIO RECEIVERS

МЕТОД ПРОЄКТУВАННЯ СМУГОВОГО ФІЛЬТРУ НА ЕЛЕМЕНТАХ З ЗОСЕРЕДЖЕНИМИ ПАРАМЕТРАМИ ДЛЯ РАДІОПРИЙМАЛЬНИХ ПРИСТРОЇВ КОРОТКОХВИЛЬОВОГО ДІАПАЗОНУ ЧАСТОТ

The most effective approach to design bandpass filters in the short-wave frequency band consists of the creation of a low-frequency prototype filter with a specified cutoff frequency with its subsequent recalculation to bandpass filter, while the orders of the prototype filter and the target filter coincide. The use of impedance inverters in the filter design procedure allows achieving the desired efficiency of the filter circuit using convenient values of physical lumped elements and the most effective circuit topology.

This paper considers a step-by-step procedure for designing a filter circuit based on a normalized prototype filter. Achieving practically implemented values of the filter element parameters is ensured by using parallel LC circuits and impedance inverter circuits. Greater efficiency in implementation is ensured by converting parallel and serial links of the circuit using Kirchhoff's laws. Optimal topologies of electrical filters are presented and their mathematical modeling is carried out.

This work presents an approach to synthesizing bandpass filters for high frequency band radio receivers on lumped elements based on a table of normalized filters. According to the presented approach, a 5th and 7th order bandpass filter circuits were calculated and built. To verify the correctness of the presented approach, the frequency response of the presented filters was modeled at the 14

MHz frequency band and its mathematical study was conducted. The obtained results confirm the effectiveness of the presented methodology for designing bandpass filters.

Keywords: *bandpass filter; impedance inverter; lumped elements; short waves.*

Одним із основних показників якості радіоприймального пристрою є його здатність виділяти корисний сигнал в умовах наявності радіо завад різної потужності та частоти. Для забезпечення цієї функції в схемах радіоприймальних пристроїв в якості вхідних кіл часто використовують пасивні електричні фільтри. Таким чином, проблема проектування електричних фільтрів є однією з найактуальніших задач у галузі радіотехніки. Водночас, через свою складність, вирішення цієї проблеми не має єдиного універсального підходу, а розробка ефективного методу проектування електричних фільтрів є актуальною науково-технічною задачею.

Найефективніший підхід до проектування смугових фільтрів у смузі короткохвильових частот полягає у створенні низькочастотного прототипу фільтра з певною частотою зрізу з подальшим його перерахунком у смуговий фільтр, при цьому порядки прототипу фільтра та цільового фільтра збігаються. Сам низькочастотний прототип розраховується за існуючими таблицями нормалізованих фільтрів. Використання інверторів імпедансу при проектуванні схем фільтрів дозволяє досягти бажаної ефективності схеми як за величиною параметрів реактивних елементів, так і за загальною топологією схеми.

У роботі розглянуто методику розрахунку смугових фільтрів на елементах з зосередженими параметрами. Показано поетапну процедуру проектування схеми фільтру, в основі якої лежить нормалізований фільтр-прототип. Досягнення практично реалізованих значень параметрів елементів фільтру забезпечується використанням паралельних LC-контурів та схем інверторів імпедансів. Більша ефективність в реалізації забезпечується шляхом перетворення паралельних і послідовних ланок схеми за допомогою законів Кірхгофа. Наведено оптимальні топології електричних фільтрів і проведено їх математичне моделювання. Отримані результати підтверджують ефективність представленої методики проектування смугових фільтрів.

Ключові слова: *смуговий фільтр; інвертор імпедансів; зосереджені елементи; короткі хвилі.*

Problem's Formulation

One of the main performance parameter of a radio receiving device is its ability to isolate an informational signal in the presence of radio interference of various power and frequency. To ensure this function, passive electrical filters are often used as input circuits in the topology of radio receiving devices. The physical implementation of such filters depends primarily on the radio receiver operating frequency [1]. Thus, for the high and very high frequency bands the most effective approach is to use limped element filters, which allow achieving a good tradeoff between filter dimensions and its performance. Therefore, the problem of electrical filters design is one of the most urgent problems in the field of radio engineering [2]. At the same time, the solution of this problem does not have a universal approach due to its complexity and a great variety of physical implementations of filters. The procedure for implementing a frequency filter depends on many conditions, namely: the receiver operating frequency range, its topology and the type of signals with which the receiver works [3].

Thus, the development of an effective approach for designing electrical filters is of great scientific and technical problem.

Analysis of recent research and publications

The performance of the radio receiver front-end mainly depends on the preliminary filtering of input signals [1]. Therefore, the problem of designing effective frequency-selective devices is one of the most important in the design of telecommunication devices [2], [3]. The distinguish features of such devices significantly depends on the operating frequency range, which is associated with the physical properties of the elements that provide frequency selection [4].

In the millimeter frequency bands, various waveguide devices show the most effective performance. In [5], a comprehensive review of the design methods for waveguide filters is presented, the coupling matrix method for filter topology synthesis is considered. The main approach, as shown, is to use a low-pass filter prototype with its subsequent transition to a waveguide band pass filter. The methods of dielectric resonators and irises in waveguides are considered.

In work of [6], the use of the equivalent circuit method for the design of circular waveguide band pass filters is shown. The authors give a representation of waveguide discontinuities by capacitors and inductors. As an example a circular waveguide filter with TM01 mode is considered. The effectiveness of the proposed approach is verified by simulation and experimental results.

At lower frequency bands the resonant circuits can be implemented using transmission lines of specific lengths. In work of [7] the mictrostip multiband filter is designed for 6—10 GHz frequency band. In [8] a 5th order mictrostrip wideband band pass filter is designed for 2.5 GHz central frequency. The impedance invertors are implemented using half wavelength microstrip transmission lines. In work of [9] the coupling matrix method is used for designing a tunable microstrip balanced band pass filter for 1.36 and 1.9 GHz frequency bands.

In the high frequency range lumped elements are the main building blocks of frequency filters. In work of [10] a design procedure of a wideband bandpass filter with the frequency range of 1.5—30 MHz is represented. The filter is a series combination of low-pass and high-pass filters.

In [11], a design method of a broadband filter based on lumped elements, which provides a high level of power transfer, is shown. Norton transforms were used to synthesize the filter circuit, which allowed obtaining convenient values of the filter elements and matching the input impedances.

Thus, the most effective approach to designing bandpass filters in the high frequency range is to create a low-frequency prototype filter with a specified cutoff frequency and then recalculate it into a bandpass filter, with the orders of the prototype filter and the target filter coinciding. The prototype filter itself is calculated according to existing tables of normalized filters. The use of impedance inverters in the filter circuits allows to achieve the desired efficiency of the filter circuit with respect to both the values of the parameters of the reactive elements and the general topology of the circuit.

Formulation of the study purpose

The bandpass filter design procedure in the high and ultrahigh frequency bands calls for lumped elements as frequency-selective components. At the same time, the efficiency of such filters depends significantly on the correspondence of real values of element capacitance or inductance to their calculated values. It is obvious that a physical circuit element have a certain deviation of its real parameters from the nominal value. It is obvious that the calculated values of the filter element parameters may not coincide with nominal values of the electronic component. In addition, physical electronic component always has some parasitic parameters. Thus, the purpose of this work is to implement the specified frequency characteristics of the filter using passive components with standardized values of their nominal parameters.

Presenting main material

The most effective approach to determine the element values for the specifies filter is to use standardized tables of normalized filters [4]. These values can be further recalculated to an element inductance or capacitance values for a specified operating frequency band. However, direct use of such filter tables often leads to unreal values of the physical parameters of lumped elements. In addition, the physical implementation of the designed filter requires the use of both parallel and series LC-tank circuits, which complicates the final tuning of the filter. To overcome these shortcomings, it is proposed the use of matching transformers and impedance inverters based on L- and Π-shaped circuits.

Consider the step-by-step procedure for designing a bandpass filter that operates as a bandpass input filter for a shortwave radio receiver. The passband of the filter is from 14 MHz to 14.350 MHz, the frequency response of the filter corresponds to the Chebyshev response with a 3 dB ripple. As an example the 3- and 5-order filters are considered. Table 1 shows the values of the normalized coefficients of the low-pass filters prototype for the specified frequency response.

The first step is to calculate the values of capacitance and inductance for a corresponding low pass prototype filter element using following equations:

$$L_n = \frac{g_n}{\Delta\omega} \cdot R; \quad C_n = \frac{g_n}{R \cdot \Delta\omega}. \tag{1}$$

Here, L_n and C_n are the parameter value for a corresponding filter element, g_n is the coefficient value from tabl. 1, R is the input and output filter impedance, $\Delta\omega$ is the cutoff frequency of a prototype and the bandwidth of a bandpass filter. Fig. 1 shows the correspondence between filter elements with different topologies and coefficient values from tabl. 1.

Table 1. The normalized coefficients for *N*-order Chebyschev response filter with 3 dB ripple

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8
3	3.3487	0.7117	3.3487	1.0000	—	—	—	—
4	3.4289	0.7483	4.3471	0.5920	5.8095	—	—	—
5	3.4817	0.7618	4.5381	0.7618	3.4817	1.0000	—	—
6	3.5045	0.7685	4.6061	0.7929	4.4641	0.6033	5.8095	—
7	3.5182	0.7723	4.6386	0.8039	4.6386	0.7723	3.5182	1.0000

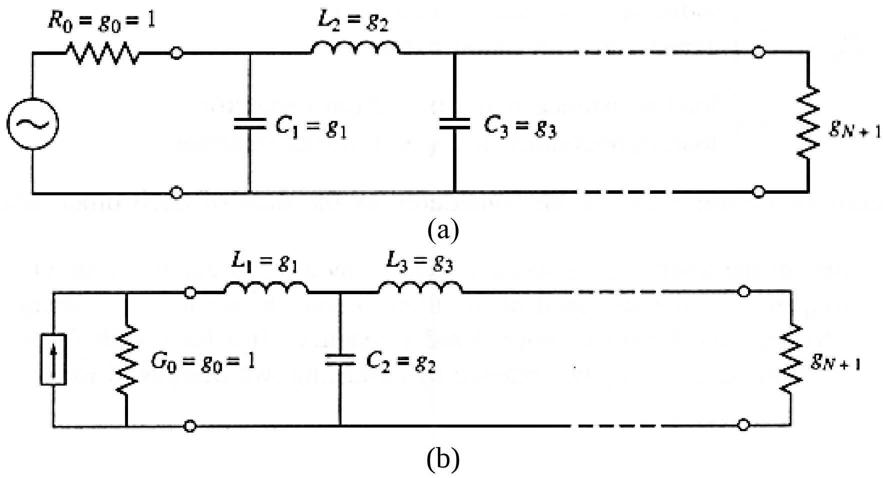


Fig. 1. Low pass prototype filter with (a) П-topology and (b) T-topology

The second step is to add a parallel or series element with inverse impedance to each element of the calculated low-pass prototype filter. Thus, the single parallel or series element of filter prototype is converted to a corresponding parallel or series LC-resonance circuit. The values of these additional components are calculated using Thomson formula:

$$\omega_0 = \sqrt{\omega_L \cdot \omega_H}; \quad L_{add,n} = \frac{1}{\omega_0^2 \cdot C_n}; \quad C_{add,n} = \frac{1}{\omega_0^2 \cdot L_n}. \qquad (2)$$

Here ω_L and ω_H are the lower and upper cutoff frequency of a band pass filter, $L_{add,n}$ and $C_{add,n}$ are the parameter values for a corresponding additional element.

Fig. 2 shows the topology of a band pass filter converted from a low pass prototype filter.

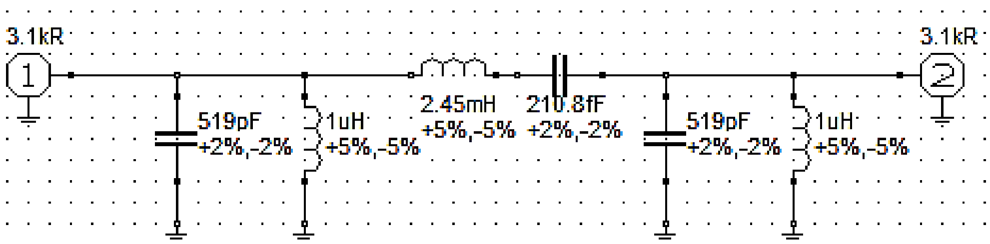


Fig. 2. The band pass filter topology obtained from a low pass prototype filter

Fig. 2 shows that the series LC-circuit appeared as a result of the filter conversion has inconvenient values of element parameters for physical implementation. To overcome such feature it is necessary to use an impedance inverter. Different topologies of impedance inverters are shown in Fig. 3.

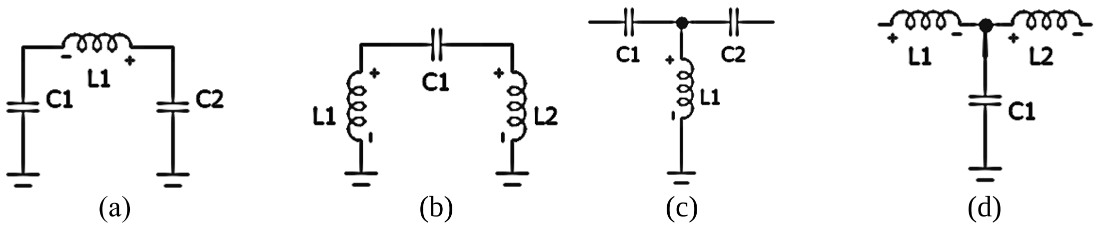


Fig. 3. Low pass (a), high pass (b) П-type and high pass (c), low pass (d) T-type impedance inverters

It should be noted that at the center frequency ω_0 the absolute values of the element impedances of all elements are equal, and can be calculated by following expressions:

$$\rho_{par} = X_{C_n} = \frac{1}{\omega_0 C_n}; \quad n = 1,3,5\ldots$$
$$\rho_{ser} = X_{L_n} = \omega_0 L_n; \quad n = 2,4,6\ldots \qquad (3)$$
$$X_{inv} = \sqrt{\rho_{ser}\rho_{par}}; \quad L_{inv} = \frac{X_{inv}}{\omega_0}; \quad C_{inv} = \frac{1}{\omega_0 X_{inv}}.$$

Here ρ_{ser}, ρ_{par} are the characteristic impedances of a series and a parallel LC-tank at the frequency of ω_0, X_{inv}, X_{Cn}, X_{Ln} are the absolute values of impedances of the inverter, the parallel capacitor *Cn* and the series inductance *Ln* at the frequency of ω_0, L_{inv} and C_{inv} are the values of the inverter inductances and capacitances.

The third step is to implement the calculated impedance inverter to a filter structure. All inverter topologies shown on fig. 3 are equivalent and can be chosen according to the desired final topology of a band pass filter. In this work the circuit in fig. 3 (b) is used to design a filter topology with minimum number of inductances.

The final step is to design a matching circuit. In order to obtain a physically adequate values of lumped element parameters it is necessary to chose the value of *R* in (1) within the range of 10^3—10^4 Ω. The standard value of input and output impedances is 50 Ω. Therefore, a using of matching circuits in a filter topology is required. The simple L-type matching circuit is shown in fig. 4 (a). Such topology allows combining the matching inductance with a filter inductance and designing a filter with minimum number of inductive elements. Fig. 4 (b) shows a Smith chart with a depicted principle of

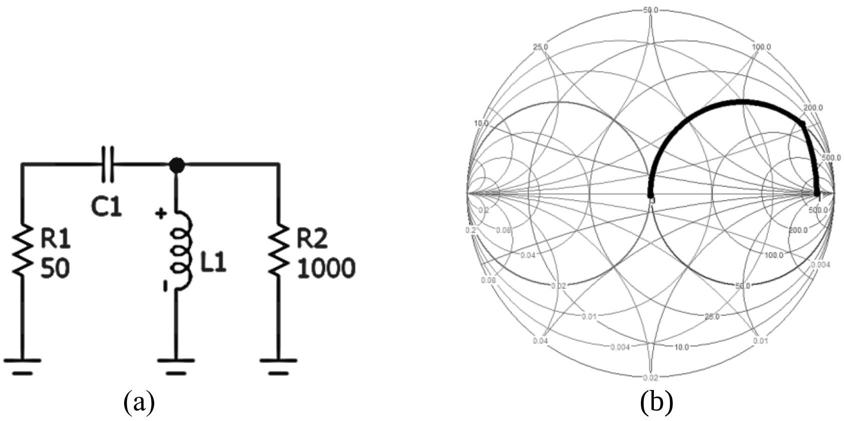


Fig. 4. L-type matching circuit (a) and its operating principle (b)

impedance matching with an L-circuit. In this case the higher impedance (the filter) is connected in parallel to matching inductance and 50 Ω source or load is connected to a series capacitance as shown in fig. 4 (a). The parallel inductance lowers real part of filter impedance and series capacitance compensates the inductive part of obtained complex impedance as it shown on fig. 4 (b).

The element parameters of matching circuit shown in fig. 4(a) can be obtained using the next expressions:

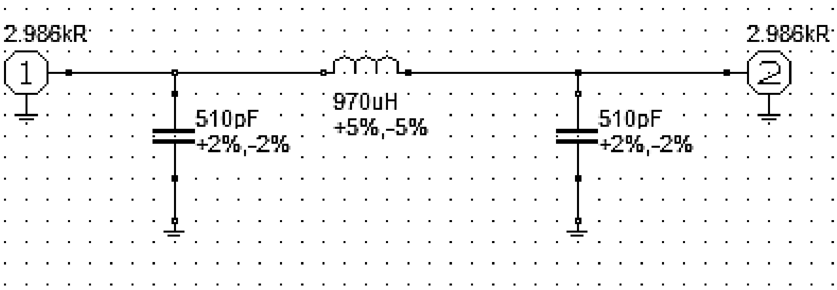
$$X_L = R_1\sqrt{\frac{R_2}{R_1}-1}; \quad X_C = \frac{R_2}{\sqrt{\frac{R_2}{R_1}-1}}. \tag{4}$$

Here X_L, X_C are impedance values of L_1 and C_1 at the frequency ω_0.

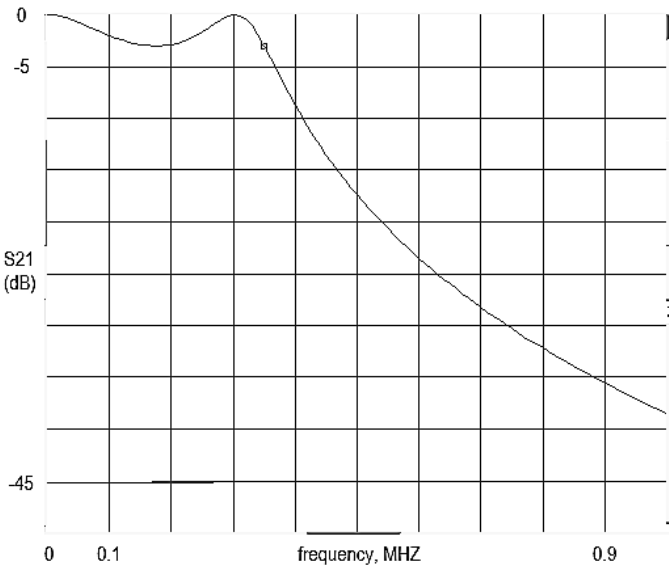
According to a described sequence consider a design procedure of a bandpass filter for a 14—14.350 MHz frequency band for 3rd order Chebyschev response and 3 dB ripple. Prototype filter coefficients from tabl. 1 are:

$$g_1 = 3.3487; \quad g_2 = 0.7117; \quad g_3 = 3.3487.$$

The initial element values of the low pass prototype filter can be calculated according to (1). It should be noted that the value of R needs to be corrected in order to achieve required values of parallel capacitances. For this example the value of R is chosen equal to 2986 Ω, that provide the parallel capacitance values of 510 pF. The obtained prototype filter topology and its frequency response are shown in fig. 5. The mathematical modeling of a filter frequency response is performed using *RFSimm*99 software. Fig. 5(b) shows a frequency response of a low pass filter with cutoff frequency of 350 kHz by level —3 dB.



(a)

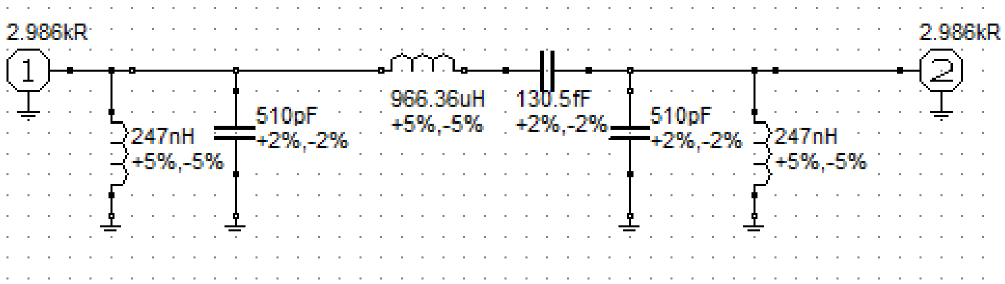


(б)

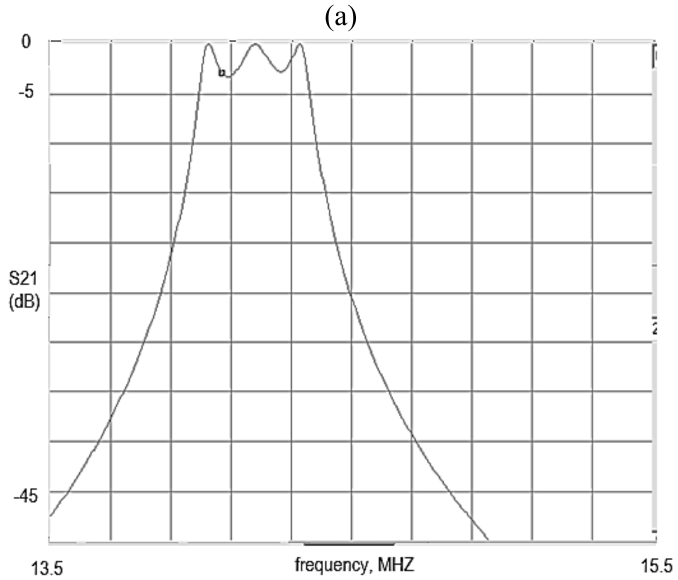
Fig. 5. The prototype filter topology (a) and its frequency response (b)

According to (2) add to a filter circuit the elements with inverse impedance as shown in fig. 2. The initial band pass filter topology is shown in fig. 6 (a) and its frequency response is depicted in fig. 6 (b). The values of the impedance inverter elements can be obtained using equations (3). Therefore ρ_{ser} = 86061 Ω is a characteristic impedance of a series LC-tank and ρ_{par} = 22.019 Ом is an impedance of a parallel LC-tank at a frequency ω_0 = 14.174 MHz, that are already exist in a filter circuit (fig. 6 (a)). Than:

$$X_{inv} = \sqrt{\rho_{ser}\rho_{par}} = 1376.6\Omega; \quad L_{inv} = 15.46\mu H; \quad C_{inv} = 8.16 pF .$$



(a)



(b)

Fig. 6. Bandpass filter topology (a) and its frequency response (b)

Therefore, the impedance inverters are placed before and after the series LC-tank which is replaced by parallel circuit with 510 *pF* capacitor and 247 *nH* inductance. Hence, the band pass filter circuit now consists of three identical LC-tanks. The topology of the filter circuit is shown in fig. 7. It is obvious that in this step the inductances connected in parallel can be replaced with a single inductance and the filter circuit can be simplified as shown in fig. 8.

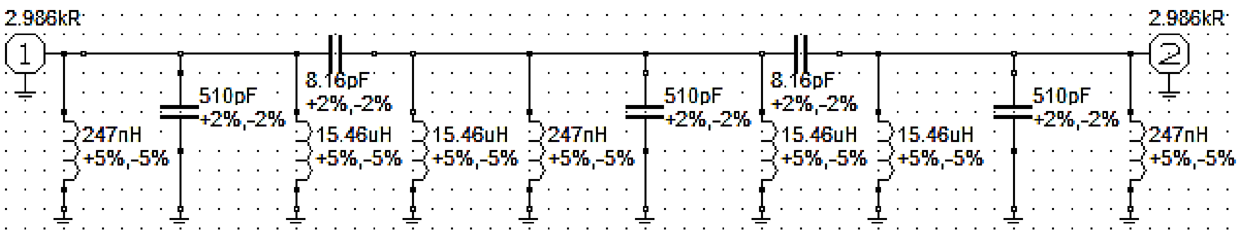


Fig. 7. Bandpass filter topology with impedance inverter circuits

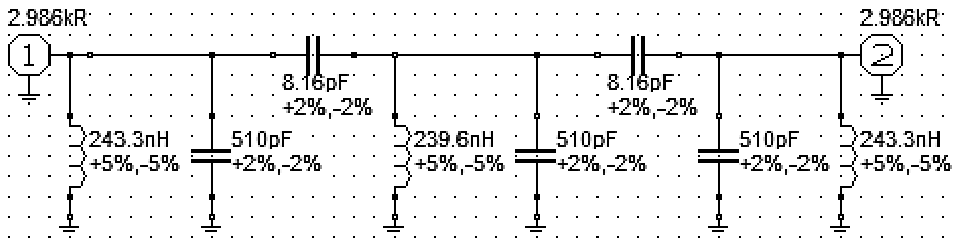


Fig. 8. Bandpass filter topology with all-parallel LC-tanks

The values of L-type matching circuit elements for 50 Ω input impedance can be calculated using equations (4). Than:

$$X_L = 50\sqrt{\frac{2986}{50} - 1} \approx 390\Omega; \quad X_C = \frac{2986}{\sqrt{\frac{2986}{50} - 1}} \approx 383\Omega .$$

Recalculate these values to capacitance and inductance at the frequency ω_0 which gives $L_{match} = 4.37\ \mu H$ $C_{match} = 29.3\ pF$. Combining the matching inductance with filter one allows to obtain the final topology of the bandpass filter, as shown in fig. 9. The main feature of the designed filter topology is the use of similar capacitors in parallel branches. Also, values of inductances differ from each other less than 5 %. Such approach simplifies significantly manufacturing and tuning of band pass filter.

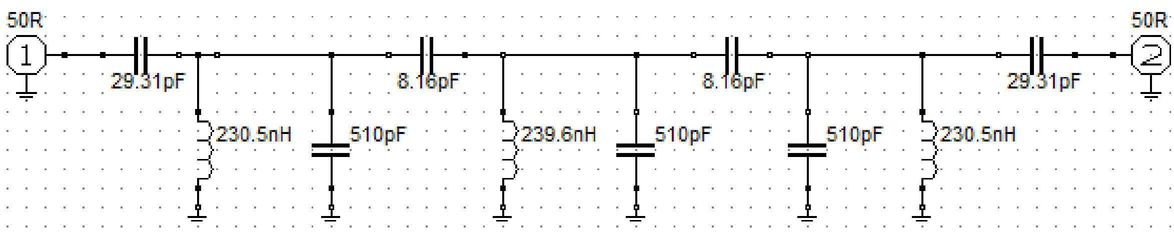
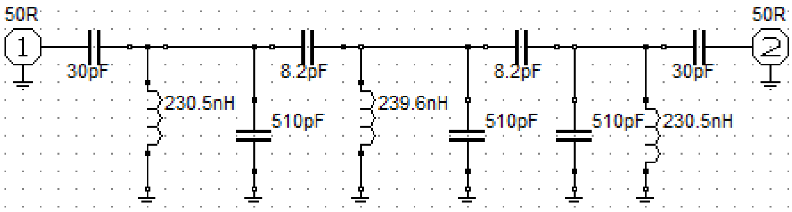


Рис. 9. The bandpass filter topology for frequency band 14.0—14.35 MHz with 50 Ω input/output impedance

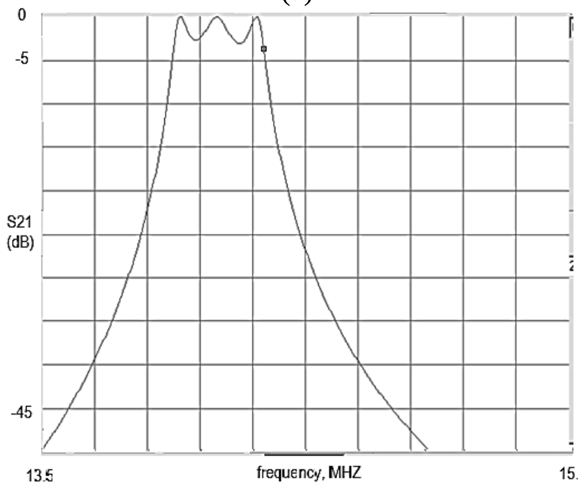
Fig. 10 (a) shows the designed filter topology with lumped elements which parameters correspond to E24 value series. Therefore, input capacitors takes value of 30 *pF* and series ones are equal to 8.2 *pF*. Frequency response of such filter is shown in fig. 10 (b). The comparison of fig. 6 and fig. 10 (b) shows that the parameter variations of series capacitors do not effect significantly on an overall frequency response.

The proposed approach allows designing band pass filters of higher order. Fig. 11 (a) shows the topology of a 5th order Chebyschev filter with 3dB ripple. During the design procedure the value of a filter impedance R is chosen equal to 3104 Ω, which allows using a capacitor with capacitance value of 510 *pF*. The impedance inverters are calculated in order to achieve the maximum number of similar capacitors in the filter circuit. A single capacitor with non standard value of 665 *pF*, can be combined using two standard values of 620 *pF* and 43 *pF* or 47 *pF*.

Fig. 11 (b) shows the frequency response of the designed filter obtained using *RFSimm*99 software. It can be seen that the proposed approach in filter design allows to obtain acceptable result with high variability of lumped element values.

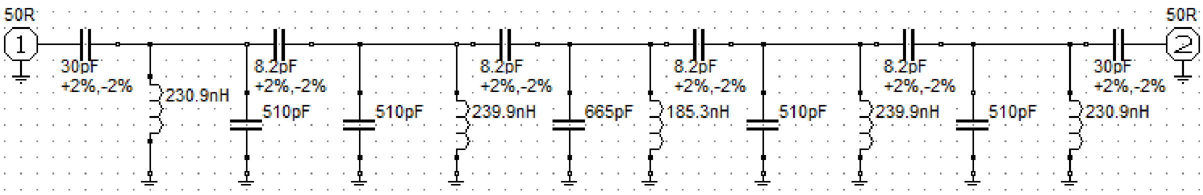


(a)

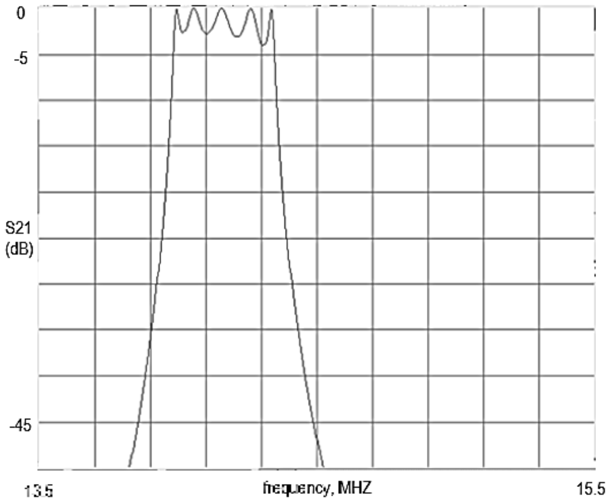


(b)

Fig. 10. The band pass filter topology with E24 lumped elements (a) and its frequency response (б)



(a)



(b)

Fig. 11. The 5th order filter topology with standard values of lumped element (a) and its frequency response (b)

Conclusions

The paper presents a bandpass filter design method for shortwave radio receivers with lumped elements. The design procedure is based on tables of normalized filters. The use of impedance inverters and matching circuits allows achieving high adaptability of the presented filter design method to various conditions of filter implementation. The presented method allows calculating the values of filter elements for a wide range of input and outputting impedances. In addition, it allows to take into account physical features of the filter. Based on the presented method, bandpass filter circuits with fixed frequencies for operation in amateur shortwave frequency ranges were calculated and constructed. To verify the correctness of the presented method, the frequency response of the presented filters was simulated for the 14 MHz range and its mathematical study was conducted. The results obtained confirm the effectiveness of the presented method for designing bandpass filters.

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