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Computer-aided design and simulation of double-band filters for radio systems

***Abstract**: Mathematical model of multiband frequency transformation, synthesis of multiband networks and computer-aided design of double-band filters without of any mechanical commutations are presented in this paper. Multiband filters have a several transmitted frequency bands and some attenuation bands. Computer synthesis program **Multiband** and synthesis of **double-band electric** filters are presented.*

***Streszczenie.** Model matematyczny wielopasmowej transformacji częstotliwości, synteza obwodów wielopasmowych, projektowanie komputerowe i synteza za pomocą programu **Multiband** dwupasmowych filtrów bez żadnych komutacji mechanicznych przedstawiono w artykule. (**Projektowanie komputerowe i symulacja dwupasmowych filtrów dla systemów radiowych**).*

Keywords: EMD, EMC, multiband filters, computer-aided design, double-band filters, and filter's analysis.
Słowa kluczowe: EMD, EMC, filtry wielopasmowe, projektowanie komputerowe, filtry dwupasmowe, analiza filtrów.

Introduction

One of the classic methods for minimization EMD and improving of EMC of different modern radiocommunication systems is using of frequency selective and broadband matching networks [1,2]. Solving of this EMC problems may be more successful with application of special multiband radio engineering devices (filters, amplifiers, etc.) [3].

This paper presents mathematical model, algorithm for computer-aided design of multiband filters and software (**Multiband**) for synthesis of the double-band filters. Results of computer design and simulations of example of such double-band filter are represented.

Theoretical bases for synthesis of multiband filters

Structures of the multiband filters may be obtained by changing of elements *L*, *C* of low-pass filter-prototype by parallel connection of series resonant circuits and series connection of parallel resonant circuits correspondingly (Fig.1). In this case it may be obtained frequency characteristic of multiband filter (Fig.2).

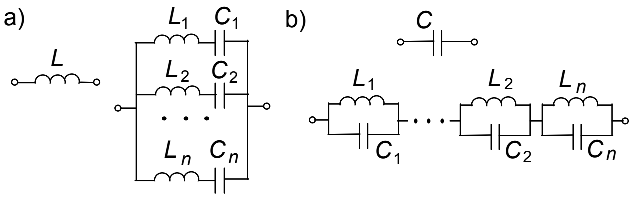

Fig. 1. Exchange of elements of low-pass filter

From condition of admittance equality of the element *L* and corresponding network (Fig.1, a) we have:

$$\frac{1}{PL} = \sum_{i=1}^{n} \frac{1}{pL_i + 1/pC_i}, \tag{1}$$

where *P* – complex frequency for low-pass prototype filter, *p* -transformed frequency for the multiband network. Marking:

$$\omega_{0i} = 1/\sqrt{L_i C_i}, \quad \alpha_i = \rho_i/(\omega_{0i}L) = L_i/L, \tag{2}$$

with $P = j\,\Omega$., $p = j\,\omega$, we have

$$\frac{1}{\Omega} = \sum_{i=1}^{n} \frac{\omega}{\alpha_i\,(\omega^2 - \omega_{0i}^2)} \quad \text{or} \quad \Omega = \beta \frac{\prod_{i=1}^{n}(\omega^2 - \omega_{0i}^2)}{\prod_{i=1}^{n-1}(\omega^2 - \omega_{pi}^2)\omega}, \tag{3}$$

where: Ω - frequency of the low-pass prototype filter, ω_{0i} and ω_{pi} are zeros and poles of multiband filters correspondingly; β is determine ratio of cut-off frequency of the low-pass filter and sum bandwidth of the multiband network:

$$\beta = \Omega_c \Big/ \sum_{i=1}^{n} \Delta\omega_i\,. \tag{4}$$

Values α_i, β, ω_{0i}, ω_{pi} are determined from equations:

$$\begin{cases} \sum_{i=1}^{n} \frac{1}{\alpha_i} = \frac{1}{\beta} \\ \sum_{i=1}^{n} \frac{1}{\alpha_i}\left(\sum_{k=1}^{i-1}\omega_{0k}^2 + \sum_{k=i+1}^{m}\omega_{0k}^2\right) = \sum_{i=1}^{n-1}\omega_{pi}^2 \\ \ldots\ldots\ldots \\ \sum_{i=1}^{n} \frac{1}{\alpha_i}\left(\prod_{k=1}^{i-1}\omega_{0k}^2 \cdot \prod_{k=i+1}^{m}\omega_{0k}^2\right) = \prod_{i=1}^{n-1}\omega_{pi}^2 \end{cases}. \tag{5}$$

Determinant of this equation set is:

$$\Delta = (\omega_{01}^2 - \omega_{02}^2)(\omega_{01}^2 - \omega_{03}^2)\ldots(\omega_{0(n-1)}^2 - \omega_{0n}^2)\,. \tag{6}$$

Because of different resonant frequencies a determinant $\Delta \neq 0$ and set (5) have one solution only.
From equations (3) we have:

$$\prod_{i=1}^{n}(\omega^2 - \omega_{0i}^2) = \prod_{i=1}^{n-1}(\omega^2 - \omega_{pi}^2)\,\omega\,\Omega_\Sigma \quad \text{or} \tag{7}$$

$$\omega^{2n} + A_{2n-1}\omega^{2n-1} + A_{2n-2}\omega^{2n-2} + \ldots + A_0 = 0\,. \tag{8}$$

Even coefficients of this equation are determined by values ω_{0i} but odd ones – by values ω_{pi} and Ω_Σ.

It is proven that roots of the equation (8) are cut off frequencies of the multiport filter ω_{u1}, ω_{u2}, . . . ω_{un}, $-\omega_{d1}$, $-\omega_{d2}$, . . . $-\omega_{dn}$ (Fig.2); then equation (8) may be represented as:

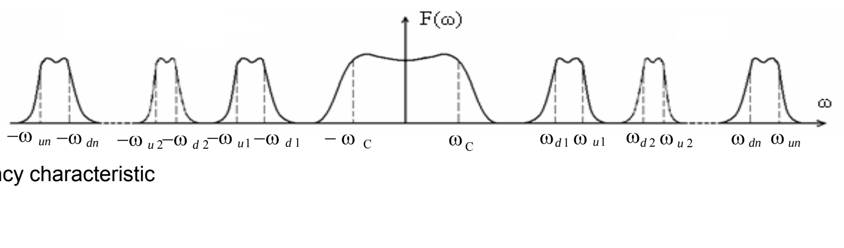

Fig. 2. Multiband frequency characteristic

(9) $\prod_{i=1}^{n}(\omega-\omega_{u\,i})\cdot\prod_{i=1}^{n-1}(\omega+\omega_{d\,i})=0$, $\prod_{i=1}^{n}(\omega^{2}-\Delta\omega_{i}\,\omega-\omega_{g\,i}^{2})=0$,

where $\Delta\omega_i=\omega_{u\,i}-\omega_{d\,i}$ - bandwidth of i^{th} frequency band of the multiband filter, $\omega_{g\,i}=\sqrt{\omega_{u\,i}\omega_{d\,i}}$ average-geometrically frequency for i^{th} frequency band.

Then square of the resonant frequencies $\omega^2_{0\,i}$ are roots of equation from (8) with even coefficients:

(10) $$\omega^{2n}+A_{2n-2}\omega^{2n-2}+A_{2n-4}\omega^{2n-4}+\ldots+A_0=0$$

but square of the resonant frequencies $\omega^2_{p\,i}$ are roots of equation from (8) with odd coefficients:

(11) $$A_{2n-1}\omega^{2n-1}+A_{2n-3}\omega^{2n-3}+\ldots+A_1\omega=0\,.$$

From (7) and (8) we have:

(12) $$-A_{2n-1}=\Omega_{\Sigma}=\sum_{i=1}^{n}\Delta\omega_i\,.$$

It means that sum bandwidth of the multiband filter is equal to bandwidth of the low-pass filter. Reactance elements of the multiband filter are calculated by (2).

Algorithm of multiband filter synthesis.

1. For given values $\Delta\omega_i$ and $\omega_{g\,i}$ of the multiband filter characteristic (Fig.2) using (9) it is defined coefficients of the equation (8).
2. From (8), (10), (11) it is defined values ω_{0i}^2 and $\omega_{p\,i}^2$.
3. Using (12) calculate sum bandwidth of the frequency band Ω_Σ , from (4) it is calculated value β.
4. For defined $\omega_{0\,i}$, $\omega_{p\,i}$ and β it is solved a set of the equations (5) and it is calculated values α_i .
5. Using (2) and (14) it is defined the element's values of the multiband filter.

Synthesis of double-band filters

For synthesis of double-band electric filters corresponding formula (3) is:

(13) $$F=\beta\,(f^2-f_{01}^2)(f^2-f_{02}^2)\big/ f\,(f^2-f_{p1}^2)\,,$$

where resonant frequencies $f_{0\,1}$, $f_{0\,2}$ are calculated from equation as (9), (10): $f^4+A_2f^2+A_0=0$, but resonant frequencies $f_{p\,1}$ are calculated from equation as (9), (11): $A_3f^3+A_1f=0$,where coefficients are defined by formulae:

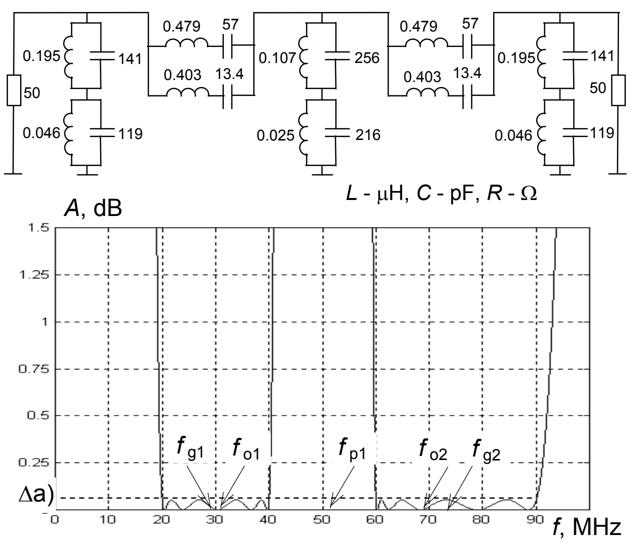

Fig. 3. Scheme and attenuation of the double-band frequency filter

(14) $$\begin{cases} A_3=-(\Delta f_1+\Delta f_2)=-\Delta f_{\Sigma}\\ A_2=-(f_{g1}^2-\Delta f_1\cdot\Delta f_2+f_{g2}^2)\\ A_1=\Delta f_1\cdot f_{g2}^2+\Delta f_2\cdot f_{g1}^2\\ A_0=f_{g1}^2\cdot f_{g2}^2\end{cases},$$

where $\Delta f_i=f_{u\,i}-f_{d\,i}$ and $f_{g\,i}=\sqrt{f_{d\,i}\cdot f_{u\,i}}$ are bandwidth and average-geometrical values of corresponding frequency bands of the double-band filter. It is very interesting that resonant frequencies of the circuits $f_{0\,i}$ are not equal to corresponding average-geometrical frequencies $f_{g\,i}$.

Then coefficients α_i are determined from set of linear (for $1/\alpha_i$) equations:

(15) $$\begin{cases}1/\alpha_1+1/\alpha_2=1/\beta\\ f_{02}^2/\alpha_1+f_{01}^2/\alpha_2=f_{p1}^2\end{cases}.$$

Values of all elements of double-band filter are defined form (2).

Algorithm and computer program (software **Multiband**) for synthesis of the double-band frequency filters based on formulae (13) - (15) are designed in the work.

The software **Multiband** consists of comfortable data entering and calculation modeling systems, visualization windows of dates and results of the simulations of the frequency characteristics of the double-band filters.

Program works out synthesis and computer simulation of the different double-band filters to **5th** order and represents **7** frequency characteristics: input impedance, Z_{in} , input admittance Y_{in} , module of input reflection coefficient $|S|$, *TWR*, *SWR*, normalized output power value P/P_{max} and normalized output power in dB.

Example of the synthesis of the double-band filter with double-side loads is presented Required parameter's values for the synthesis of this filter are: frequency bands **20-40MHz** and **60-90MHz**; then average-geometrical frequencies $f_{g\,1}$=**28.3MHz** and $f_{g\,2}$=**73.5MHz**; double-side loads $R_g=R_0=$ **50**Ω, Π-structure, **5th** order, TWR_{min} = **0.8**, Δa = **0.054**dB (Fig.3). After calculations we have received resonant frequencies $f_{0\,1}$ = **30.4MHz** (larger of $f_{g\,1}$), $f_{0\,2}$ =**68.4MHz** (smaller of $f_{g\,2}$) and $f_{p\,1}$ =**51.4MHz**. Frequency characteristics of attenuation *A* is presented in Fig.3.

Conclusions

Important problem of synthesis of multiband electronic devices for modern radio systems is considered in the paper. Theoretical bases, mathematical model and algorithm of synthesis of the multiband filters for different structure and order are described.

Computer program (software **Multiband** in medium **Matlab**) for design of the double-band filters, results of synthesis and computer simulations of the frequency characteristics of such filter are represented.

This method may be use to synthesis of multiband matching networks for antennas and others complex loads too. Using of those multiband devices may to decrease undesirable radiation's EMD and improve EMC of different radiocommunication systems.

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