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ULTRA-WIDEBAND FIVE-TIER LM-MODE FILTERS OPTIMIZED WITH KNOWLEDGE- BASED CAD SYSTEM

Предложена оригинальная САПР последовательного проектирования пятизвенных фильтров на основе волноводно-диэлектрических резонаторов с низшими LM-модами. Ключевая идея разработанной системы заключается в физическом анализе сигнала прошедшего через фильтр, который рассчитывается на основе известного решения электродинамической задачи рассеяния основной волны на многозвенной структуре. Установлены закономерности формирования ультраширокиx полос пропускания фильтров, которые формализованы в виде логических продукций. Проведен сравнительный анализ АЧХ трех- и пятизвенных ультрашироких фильтров, сконструированных системой. Параметры фильтров отвечают новому поколению радиотелекоммуникационных систем миллиметрового диапазона соответствующих новейшим стандартам ECMA-387, WirelessHD, IEEE 802.15.3candIEEE 802.11ad.

Ключевые слова: ультра-широкополосные пятизвенные фильтры, интеллектуальные САПР, WirelessHD, IEEE 802.15.3c, IEEE 802.11ad.

1 Introduction

The observed tendency for increase in density of information channels is objective and will continue to intensify in the future as far as it ensures synchronization and optimization of industrial and technological processes in development of societies. The societies themself possess obvious features of a super-organisms in which each active individual using his/her PC strives to integrate into Internet and telecommunications networks like in a «nervous web» of developing «global mind» [1, 2]. The evident homology of all known creative processes leads to concept of Geo-Solaris, i.e. a view of the Earth embraced with evolving living matter as an intuitively thinking brain bringing about the bio-technological mind of Noosphere [2]. A characteristic feature of this noogenesis [3] is in replication of personal intellectual potential on the level of the mankind: the world population is approaching the number of the nerve cells in an individual brain while the World-Wide Web is acquiring the structure of a neural network [4]. Actually, we observe the rapid growth of wireless networks based on dozens of different standards regulating frequency resources ranging from hundreds of megahertz to hundreds of gigahertz. It is clear that the electromagnetic situation in the air requires constant improvement of electromagnetic interference protection for receivers and ever stricter requirements to transmitters, which are actually the sources of the interference. Traditionally these problems are solved with passive band pass filters mounted on receiver inputs and transmitter outputs. Various filters with different passbands (or stopbands) are used in measuring devices while top-quality filters serves for frequency stabilization in oscillators.

Among the known micro- and millimeter wave filters, the designs based on leucosapphire and quartz partially filled waveguide-dielectric resonators (WDR) placed into cut-off waveguides are distinguished for overall quality of their parameters, such as high unloaded Q's, sparse spectrum of parasitic modes and usable levels of transmitted power [5-7]. Due to electrodynamics of WDR, it is possible to develop filters for wide range of 3 – 100 GHz. Currently industrial usage of millimeter waves (predicted back in the 60s) is widespread because (1) it allows obtaining «sharply directed emission, which is important not only for radar systems but for wireless systems as well, particularly for radio relay lines»; (2) in this waveband, «atmospheric and many types of industrial noise become insignificant; (3) with higher frequencies the density of stations in the air becomes less significant so more stations can work without interference;(4) the lover density allows using noise-resistant wideband modulation systems; (5) greater transmission speed requires greater frequency...» [8]. Such features of this waveband make it «extremely attractive for high-speed ultra-wideband transmission, including transmission of video streams from multiple video cameras, transmission of high definition video and traffic management in cellular networks. Besides, wide band allows a variety of scrambling schemes and error correction codes, provides greater choice of optimal methods for modulation and multiple access in data transfer, which allows data transmission at the specified speed with very low signal-to-noise ratio» [9]. Two most important economic factors should be briefly noted as well: there are no licenses required for usage of this waveband and the equipment necessary is quite small in size. All these circumstances caused a new «innovation wave» here resulting in its turn in great demand for high-quality hardware components [9, 10].

Currently, there are different CAD systems for designing active and passive microwave components. They use wide range of numerical and analytical methods and provide greater opportunities for component design but come short when it concerns computation error estimation or design optimization. Such systems usually do the optimization using gradient and probabilistic methods whose *low efficiencycan be explained by the fact that most alterations in the task (design) parameters done during the algorithm steps are unjustified from the physical point of view.* Therefore, the development of knowledge-based optimization methods is a prospective and actual task. From a mathematical point of view, this approach is an alternative to well-knownoptimization methods and is also very promising for solving the problem of finding a global extremumof an objective function. For many applications, it is necessary to deal with ultra-wide band frequencies, for which WDR-based filters seem to be very promising. However, only three-tier structures have been comprehensively studied so far [7]. From the fact that it was possible to develop system of the synthesis of three-tier structure, the establishing of the systems of five- and a multi-tier structures does not automatically follow. The problem lies in the adjustment of productions (rules) in such a way as not only to eliminate possible «ringing» of the system, but also regularize them in the correct logical order, ensuring the implementation of rule of inference, i.e. completion of designing stage at all. The number of the productions, by the increasing of the number of filter tiers by two, increases in the half or two times, in this case it is about - from twenty five to fifty, due to significant increases in the number of possible states of the system to be optimized. It should be noted that the formalization of the productions requires a deep electrodynamic understanding of the physics of the process of frequency response of the multi-tier resonance structure forming, that forms a feedthrough filter. In addition, the three-tier filters are used rarely, because of the low steepness of slopes of frequency response, while the five-tier filters are widely used, as they are electrical parameters and overall dimensions optimal.Also, it appears that the implementation of the phased optimization, when the optimized parameters of the simpler systems are passed as input to more complex, for example, from one-tier to a three-tier, and from three-tier to five, it could be expected to solve the problem of finding the global extremum of the cost function, i.e. to create the best design of all. As optimization parameters the width of the cut-off waveguide and the value of the dielectric permittivity are chosen.

In this paper, we outline the key features of an original knowledge-based CAD system for five-tier filters with LM-modes. We also provide examples of the filters optimized with the novel system. These filters conform to the latest standards like ECMA-387, WirelessHD, IEEE 802.15.3c and IEEE 802.11ad [11- 13].

2 WDR Filters with Quasi-LM_{101} Modes

The partial filling by high Q dielectric provides ten-fold increase in unloaded Q of the resonator. The resonators that partially fill the H-plane of the waveguide have sparser spectrum of parasitic modes and somewhat lower unloaded Qs comparing to E-plane resonators. Usually such filters are placed directly into a waveguide main tract. Switching mobile communications to the millimeter wave band requires development of compact filtering elements with high unloaded Qs, therefore the adaptation of WDR filters to planar technologies is considered [14].

Figure 1 presents basic design of five-tier WDR filter with H-plane dielectric plates [5, 6]. In this structure, the problem of scattering H_{10} waves is solved with mode matching method described in [5, 7, 15] where electrodynamics model parameters are discussed in detail and the model validity is illustrated through comparison of calculated values with experimental results shown in Fig. 2. The calculations were done for 30 wave types in a regular waveguide and one wave type in a cut-off waveguide. The comparison reveals fairly good correspondence between the values predicted by the model and the experimental measurements: even with the quite simple approximation used the errors don't exceed 1.5% either for frequency or insertion losses. To eliminate the influence of either calculation error or manufacturing inaccuracy, we provide adjusting screws located symmetrically above each dielectric insert [5, 6, and 15].

The dielectric plates are also separated with a 0.34 mm gap from the waveguide walls. The algorithm of approximate synthesis allowed us to reduce development time and obtain an acceptable filter response even with single iteration.

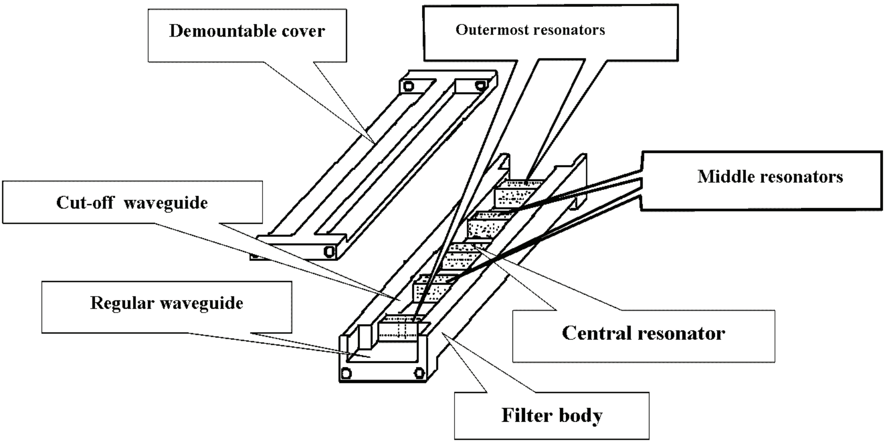

Figure 1 –Five-tier WDR LM_{101}-mode filters geometry

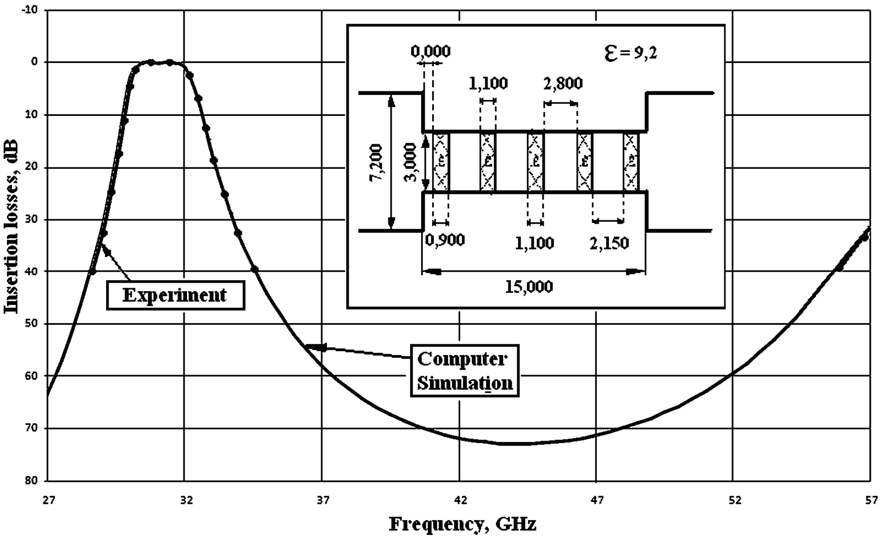

Figure 2 –Calculated values to experimental results comparison

3 Knowledge-based CAD System for Five-Tier Ultra-Wideband WDR LM-Mode Filter

To design such filters, we modified the knowledge-based CAD (KB CAD) system developed previously for *three*-tier microwave filters[7]. Whereas a detailed description of this system is published in an open access journal, we provide here only its brief description focusing on the developments done to process five-tier filters. Thus, basing on formalized physical knowledge about the behavior of coupled resonators, the KB CAD systemanalyses electromagnetic signal passing through a filter structure and makes decisions gradually approaching the optimal filter design through a series of changes in its geometry. The efficiency of the KB CAD system depends only on the accuracy of the solution for the analysis problem and on the accuracy with which the conditions of the rules applied match the actual data. Therefore the efficiency is rather high: the errors don't exceed 2 %. The optimization of a filter design is done in three stages. First, the intellectual system calculates the length of the central resonator and searches for the optimal value of dielectric permittivity ε keeping the length of the resonator within 1 – 0.4 mm limits (depending on frequency), which is a compromise between its unloaded Q factor and manufacturability. At the second stage, the optimized parameters of one-tier filter are input to the block of three-tier filter design. On calculation of three-tier filter frequency response, the system optimizes the filter design for maximum bandwidth reducing its overall length. The first two steps are repeated for different cut-off waveguide widths, thus forming a set of filter designs with their electrical properties. At the third stage, the optimized parameters of three-tier filters are input to the block of five-tier filter design. First, this block performs symmetrization and elimination of marginal and middle pulsations using logical rules like the following: IF there is poor frequency response to the left of the central frequency THEN reduce the length of the outermost resonators; IF there is poor frequency response to the right THEN increase the length of the outermost resonators; IF there are poor frequency responses in the middle THEN reduce the distance between central and middle resonators. Then, the filter is adjusted for central frequency with the following rules: IF central frequency is above the specified value THEN enlarge all resonators; IF central frequency is below the specified value THEN shrink all resonators; etc.

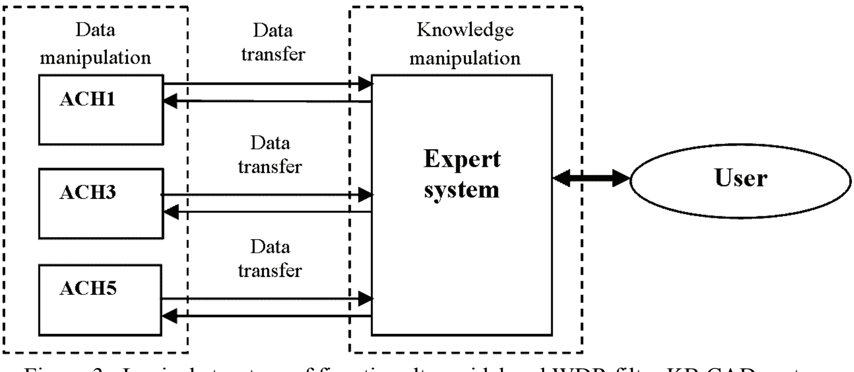

Figure 3 –Logical structure of five-tier ultra-wideband WDR filter KB CAD system

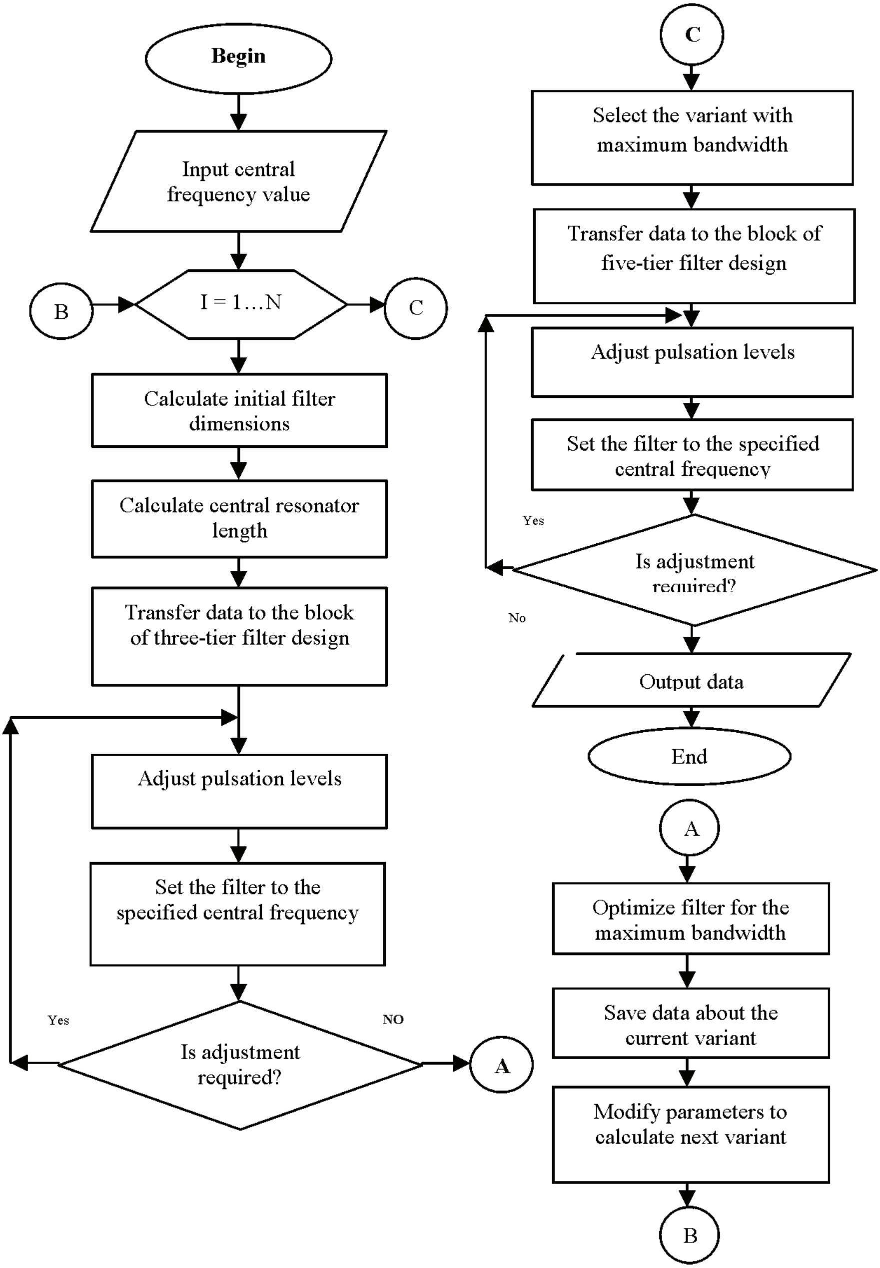

Figure4 –The KB CAD system algorithm for five-tier ultra-wideband WDR filters

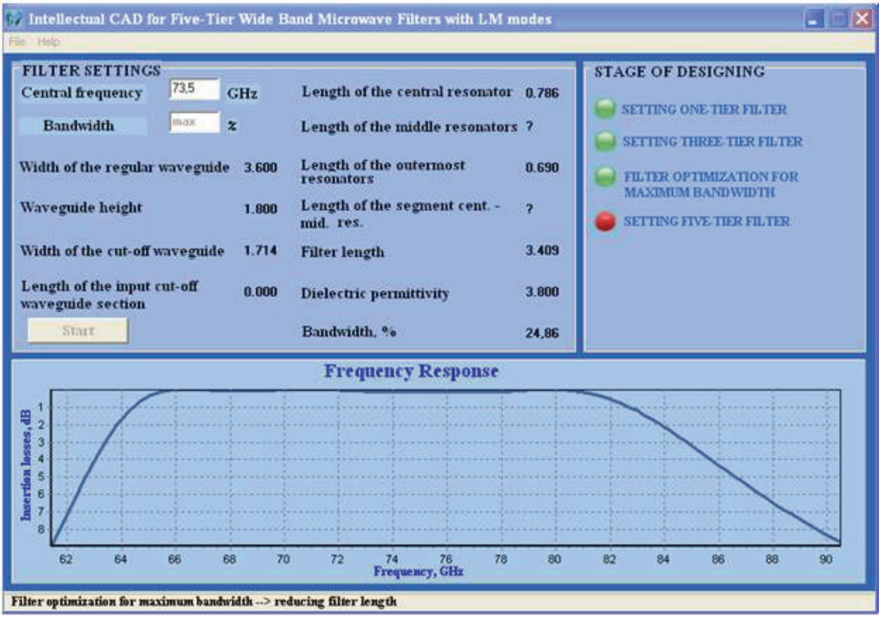

Figure 5 – KB CAD system is optimizing the filter for maximumbandwidth

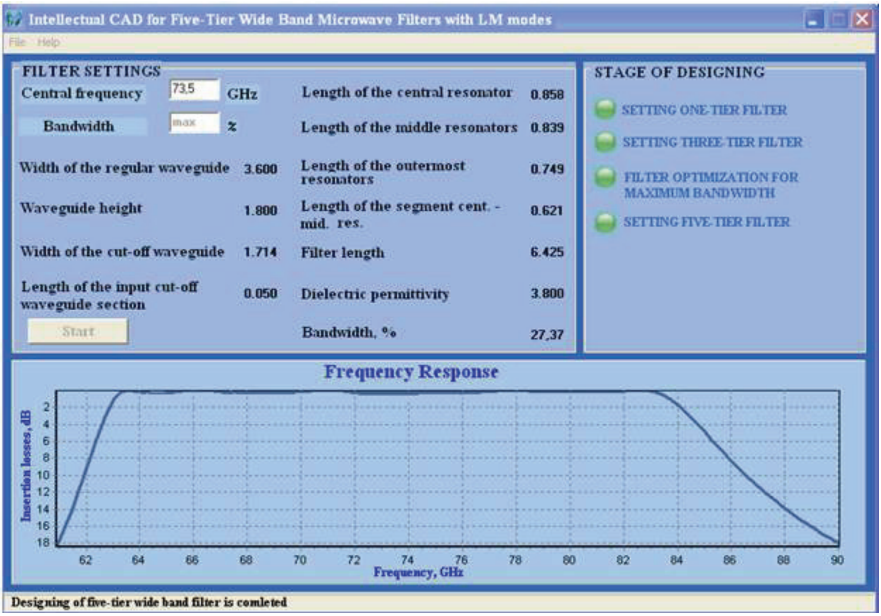

Figure 6 – KB CAD system has completed a filter design

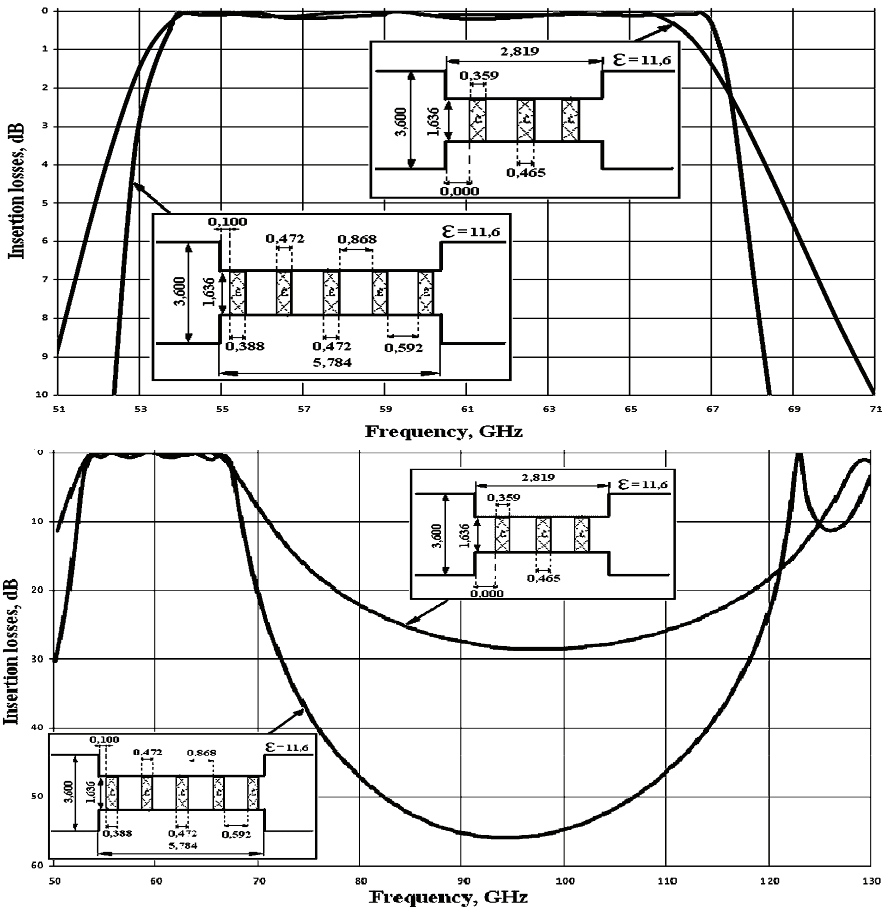

Figure 7 – Frequency responses of the ultra-wideband filters ($\delta f = 26$ %) designed with the KB CAD system in three- and five-tier variants (60 GHz)

Figure 3 shows the logical structure of the novel ICAD system and Figure 4 – the flow chart of its algorithm

The stages of five-tier ultra-wideband WDR filter design are illustrated below (Fig.5-Fig.6). The program window shown in the figures is divided into the following panes:

- *Filter settings pane contains a text box to input working frequency and displays the current values of filter insertion losses as well as the current state of expert system operation.*
- *Stage of designing pane displays information on the intermediate process stages fulfilled.*
- *Frequency response pane plots frequency and amplitude of a signal pass-*

ing through the filter structure.

– *The status line below displays information about the latest logical rule applied or the conclusion achieved.*

Figures 7 - 10 shows the comparative properties of the ultra-wideband filters with the developed KB CAD system in three- and five-tier variants.

As it can be seen from the figures, increasing the number of tiers in the filter from three to five provides significant increase in bandwidth (5–17 %) and two-fold increase in stopband attenuation level. At the same time, there is slight increase in passband irregularities. The parasitic band also gets somewhat closer and wider for the five-tier designs.

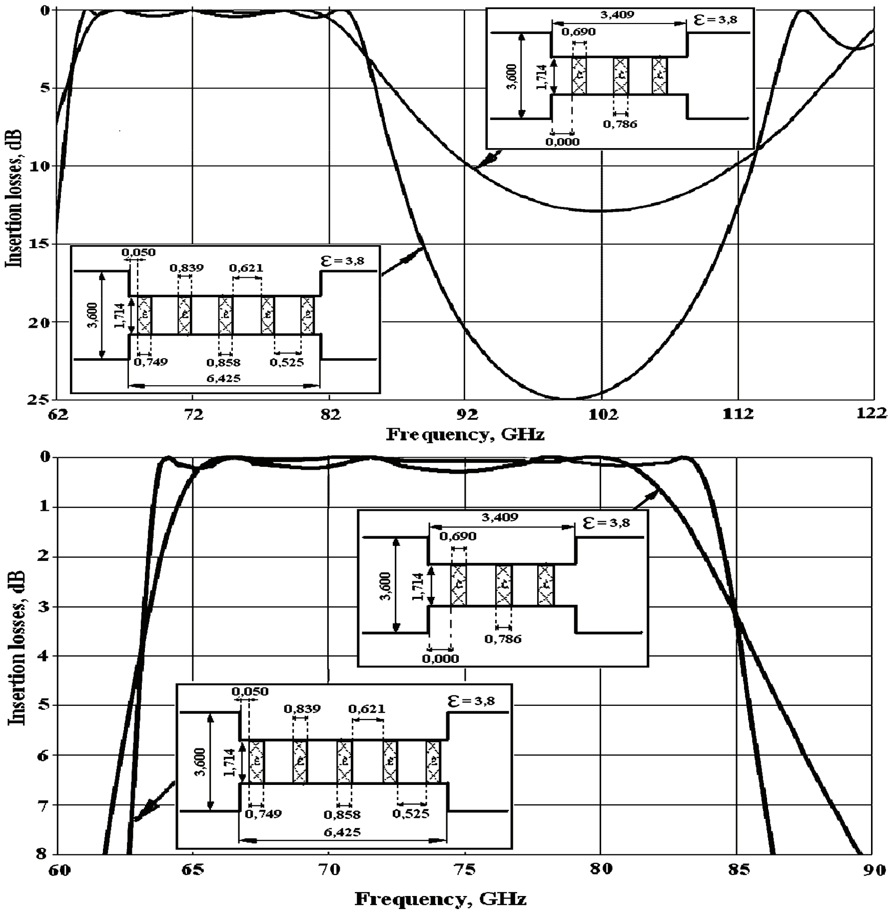

Figure 8 –Frequency responses of ultra-wideband filters ($\delta f = 3$ %) designed with the KB CAD system in three- and five-tier variants (73,5 GHz)

4 Results and Conclusions

The main causes of the new innovation wave in the development of millimeter waveband telecommunication systems and justified the demand for high-quality bandpass filters have been analyzed in this paper. We proposed a novel knowledge-based CAD system for ultra-wideband five-tier filters with LM_{101}-modes and demonstrated the main stages of their development with the system. A comparative analysis of three- and five-tier filter properties and described designs of the letter, which conform to the latest standards like ECMA-387, WirelessHD, IEEE 802.15.3c and IEEE 802.11ad have been provided. It seems that through the optimization with the system, we can obtain high-quality filter designs, which are fairly manufacturable as well. As a whole the successful solution of the task of developing of the knowledge based CAD system for optimization of the five-tiers filters makes the pillar for developing of the optimization system of the seven-tier structure. It should be pointed out that the effective methods of dielectric elements microwave and optical testing have been developed and introduced into the filters manufacturing process [16].

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Запропоновано оригінальну інтелектуальну систему автоматизованого покрокового проектування п'яти-ланцюгових фільтрів на основі хвилеводно - діелектричних резонаторів з нижчими LM-модами. Ключова ідея розробленої системи полягає в фізичному аналізі сигналів, що проходять через фільтр та розраховуються на основі відомого рішення електродинамічної задачі розсіювання основної моди на багатоланцюговій структурі. Було знайдено і формалізовано в вигляді логічних продукцій правила формування ультрашироких смуг прозорості. Проведено порівняльний аналіз АЧХ трьох- та п'яти-ланцюгових ультрашироких фільтрів, що оптимізовані системою. Фільтри розроблено відповідно до наступного покоління міліметрових радіотелекомунікаційних систем новітніх стандартів ECMA-387, WirelessHD, IEEE 802.15.3candIEEE 802.11ad.

Ключові слова: ультра-широкосмугові п'яти-ланцюгові фільтри, інтелектуальні САПР, WirelessHD, IEEE 802.15.3c, IEEE 802.11ad.

An original knowledge-based CAD system for step-by-step automated development offive-tier filters base don wave guide-dielectric resonators with the lowest LM-modes has been proposed. The basic idea of the system created consists in physical analysis of signals passing through the filter, which is performed on the basis of a known solution for electrodynamic problem of scattering of fundamental electromagnetic waves in a multi-tier structure. Regularities in formation of the filter ultra-wide bandwidths and formalized them in the form of production rules for the system were discovered. A comparative analysis of frequency responses for three- and five-tier UWB filters, optimized with the system has been also provided. The designed filters are intended for the next generation of millimeter waveband wireless systems and conform to the latest standards like ECMA-387, WirelessHD, IEEE 802.15.3c and IEEE 802.11ad.

Keywords: Ultra-widebandfive-tier filters, Knowledge-based CAD system, WirelessHD, IEEE 802.15.3c, IEEE 802.11ad.