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Exact synthesis design theory of analogue broadband bandpass filter

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ABSTRACT

In this article, an exact synthesis design procedure of broadband bandpass filter using step impedance resonator (SIR) and optimum distributed high frequency (ODHF) is presented. SIR provides a large degree-of-freedom owing to its uncomplicated implementation and broad frequency operations. It offers enormous possibilities for its practical applications as well. The filtering function in this work is extracted using the equivalent circuit model. Filtering parameters can be mapped onto Chebyshev type-I polynomials for a narrowband response. However, for broadband filter response this mapping of polynomials will not produce equiripple frequency response. Therefore, the filter polynomials are adjusted such that a required bandwidth with an equiripple response is achieved. The proposed filter structure provides compactness as well as suppression of spurious resonances at high frequencies. Moreover, for the verification purpose, the proposed filter synthesis is also applied to ODHF filter topology. To validate the proposed design procedures, a microstrip-based prototypes are realized. The simulated and measured results are found in good correlation.

1. Introduction

Microwave filter is an integral part of radio frequency front-end modules in modern wireless communication systems. In the recent years, the demand for wide bandwidth operations in wireless communication systems has raised noticeably. Broadband bandpass filters are an essential component of such wireless communication systems, which are usually used at both transmitting and receiving ends. Moreover, the planar microstrip based filters are among preferred structures due to their ease of fabrication, compactness and high selectivity. To this date, many researchers have worked on broadband and ultra-wideband (UWB) bandpass filter topologies [1–21]. These reported SIR topologies are not supported by the proper theoretical model and hence it is difficult to provide a generalized topology model. A proper synthesis procedure provides the merits of physical insight and accuracy. In [1], a novel multiple-mode resonator (MMR) based UWB bandpass filter is proposed by Zhu et. al. The proposed filter consists of two high impedance quarter wavelength coupled lines attached to a low impedance transmission line. The two parallel coupled lines produce two transmission poles whereas, the middle line section produces extra poles depending on its length. MMR is further investigated by various other researchers to achieve better response [2–6]. However, their is no exact synthesis procedure provided in any of the cited papers. In [2], quadruple-mode UWB bandpass filter with sharp out-of-band rejection has been designed. The interdigital parallel coupled lines are used to realize the tight coupling required for ultra-wide bandwidth. For higher selectivity, two finite transmission zeros are inserted by adding two short-circuited stubs. Moreover, by adding two stubs, the out of band resonant frequency moved to passband, hence making fourth order UWB bandpass filter. Although the design is compact but the presence of small coupling gaps requires advanced fabrication process consequently the higher manufacturing cost. Packaged UWB bandpass filters are in demand for UWB system applications. Since packaging assures hermiticity and ruggedness. Han et. al. [3] has developed a packaged UWB bandpass filter with modified MMR topology. Single stage filter design is compact and offers five resonances in the passband. The major disadvantage is the coupling gaps which are hard to realize through standard PCB fabrication technology. A modified MMR is designed in [4], where three open circuit stubs replace the middle line section of MMR. By optimizing the open circuit stub location, this structure produces four transmission poles in the passband with slightly wider stopband. However, the coupling and width of coupled lines are minuscule making it difficult for fabrication. In [5] a dual line coupling structure is used with dual-mode ring resonator to achieve UWB bandpass filter. The measured results show significantly large return loss as compared to simulated response also, the filter size is large as compared to the original MMR topology. Likewise, the hybrid microstrip/coplanar waveguide (CPW) techniques are also used to build UWB bandpass filters [7–10]. Similarly, an optimum highpass filter topology is used to design broadband bandpass filters [11–15]. However, the

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filter size in this topology is significantly large. One intuitive approach has been proposed to design UWB bandpass filters in [16–19] by using cascaded bandstop and bandpass filters or highpass and lowpass filters. This technique is used to realize very wide passband. However, drawback of this method is its large circuit size. In [16], two individually designed lowpass and highpass filter are embedded to realize an UWB bandpass filter. The stepped-impedance lowpass filter is designed to suppress the upper stopband and quarter wave short-circuited stubs are used to obtain the lower stopband. In a similar fashion, UWB filter can also be constructed by cascading broadband bandpass and a bandstop filter. In [17], an UWB bandpass filter is developed using cascading broadband bandpass filter and broadband bandstop filter. The bandwidth of both filters are determined separately by properly selecting the impedances of respective transmission lines. In [18], a highpass and a lowpass filter is used to realize bandpass filter with UWB response. The filter is implemented in the low temperature co-fired ceramic (LTCC) technology. The proposed filter is very compact in size, but with high return and insertion loss characteristics. In [19], an UWB filter is designed with the combination of a lowpass and a highpass filter on suspended stripline (SSL). High impedance lines are used to build lowpass filter section while low impedances are realized by wide strips on the other side of a substrate. This results in small circuit size and a wide stopband. A standard LC equivalent circuit is used as a starting point. Using this LC circuit, physical geometry is extracted including the discontinuity effects. Moreover, for the highpass filter section, strong broadside coupling between wide line sections on opposite sides of the substrate are employed together with narrow strips on the ground. In [21], a triangle-ring multi-mode stub-loaded resonator is used to achieve UWB bandpass response. Two finite frequency transmission zeros are archived in the stop band for improved selectivity. The transmission zeros are controlled by a stub loaded resonator. With this technique, five transmission poles are obtained in the passband. In the filter topologies mentioned above, one common limitation is to achieve high selectivity while maintaining the compact physical size of the filter. Moreover, none of the mentioned articles provide exact synthesis procedure for filter parameter calculation.

In this paper, an exact synthesis procedure is presented. The developed synthesis technique is used to validate the bandpass filter topologies. In the first section step impedance resonator (SIR) topology is used for bandpass filter realisation. The step impedance resonator is used instead of the uniform transmission line to decrease the length of the middle section and hence achieving the compactness. The introduction of SIR also produces the lowpass behavior that suppresses the spurious resonances at higher frequencies. In the next section an optimum distributed highpass filter (ODHF) topology is synthesized using the proposed procedure. Moreover, a compact, higher order broadband filter is fabricated and measured using vector network analyser. Planar profile allows the use of conventional PCB fabrication technologies.

2. Synthesis procedure on SIR topology

The SIR is a TEM and quasi-TEM mode resonator consisting of more than two transmission lines with different characteristic impedances [22]. The proposed broadband bandpass filter along with its equivalent distributed circuit is shown in Fig. 1. The filter consists of two quarter wavelength parallel coupled lines attached to a k step impedance resonators having ascending widths. The length of each step is quarter wavelength at operating frequency. The equivalent circuit shows a quarter wavelength unit element with characteristic impedance z separated by two quarter wavelength open circuit stubs with impedance z_{oo}. The step impedance section represented as a transmission line with different impedance values corresponding to different physical widths.

Now to find the filter design parameters in Fig. 1, first the filtering function is extracted using the equivalent circuit model. Initially all cascaded sections are multiplied to calculate the overall transfer function, that is given in (1).

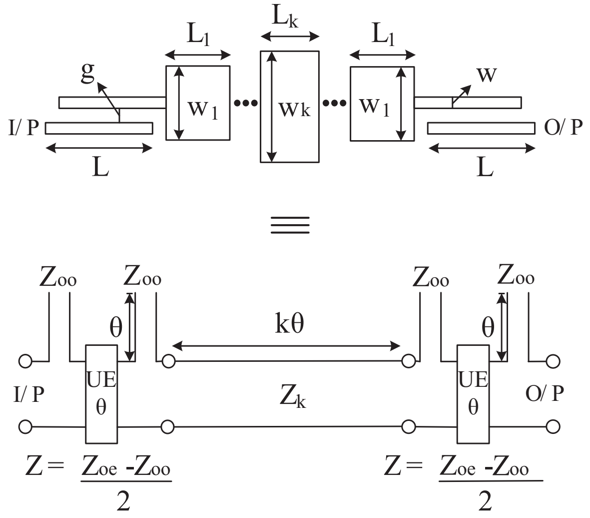

Fig. 1. Generalized schematic of broadband bandpass filter with its equivalent distributed circuit model.

$$[T] = \prod_{q=1}^{4}\begin{bmatrix} 1 & \dfrac{-iz_{oo}}{\tan(\theta)} \\ 0 & 1 \end{bmatrix} \times \prod_{q=1}^{2}\begin{bmatrix} \cos(\theta) & iz\ \ \sin(\theta) \\ \dfrac{i\sin(\theta)}{z} & \cos(\theta) \end{bmatrix} \times \prod_{s=1}^{k}\begin{bmatrix} \cos(\theta) & i\sin(\theta)z_s \\ \dfrac{i\sin(\theta)}{z_s} & \cos(\theta) \end{bmatrix} \tag{1}$$

The first, second and third matrix shows the transfer function of the four open circuit stubs, two unit elements and the k step impedance resonators respectively. Now to synthesize the given filter topology k is assigned value of 3. The relationship between the filter order and step impedance length factor k is $N = k + 3$. Once the transfer function is determined using (1), the transmission coefficient S_{12} is evaluated using the well-known relationship shown in (2). The next step is to extract filtering function from the transmission coefficient [25] by using (3).

$$S_{12} = \frac{2}{A + B + C + D} \tag{2}$$

$$|S_{12}(j\omega)|^2 = \frac{1}{1 + \varepsilon^2 F_N^2(\omega)} \tag{3}$$

Here the $F_N(\omega)$ is a N order filtering function and ε is the corresponding ripple level. Now, the derived filtering function for the chosen filter order (N = 6) is

$$F_6(\omega) = \frac{A\cos^6\omega + B\cos^4\omega + C\cos^2\omega + D}{\sin\omega}, \tag{4}$$

where, $A \neq 0$ and the filter coefficients A, B, C and D are calculated as

$$A = \frac{[(z + z_{oo})^2 - 1](z_1 + z_{oo} + z)^2(z_1 + z_2)^2}{2z^2z_1^2z_2}, \tag{5}$$

$$\begin{aligned} B = {} & \Bigg\{-2\Bigg[\Bigg(-\frac{3}{2} + 2zz_{oo} + z^2 + z_{oo}^2\Bigg)z_1^3 + z_1^2[(z^2 + z_{oo}^2 \\ & + 2zz_{oo} - 2)z_2 + \Bigg(z^2 - \frac{1}{2}\Bigg)(z + z_{oo})\Bigg] + \frac{1}{2}[(z^2 + z_{oo}^2 \\ & - 2 + 2zz_{oo})z_2 - 2z_{oo} - 2z + 4z^3 + 4z^2z_{oo}]z_2z_1 \\ & + \frac{1}{2}z_2^2(z + z_{oo})(z_{oo}^2 + 2zz_{oo} - 2 + 3z^2)\Bigg](z_1 + z_{oo} \\ & + z)\Bigg\} \times \{2z^2z_1^2z_2\}^{-1}, \end{aligned} \tag{6}$$