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Microstrip Interdigital Bandpass Filters: Design analysis

Atul Makrariya, P.K. Khare
Department of Postgraduate studies in Physics & Electronics, Rani Durgavati University, Jabalpur , MP,
makrariya@rediffmail.com

Abstract: Conventionalmicrostriplowpass and bandpass filters such as stepped-impedance filters, open-stub filters, semi-lumped element filters, end- and parallel-coupled half-wavelength resonator filters, hairpin-line filters, interdigital and combline filters, pseudocombline filters, and stub-line filters are widely used in many RF/microwave applications. Modern RF and microwave communication systems, specifically mobile and satellite communications required high performance, wide band filters with linear phase. Most communication systems require an RF front end, where RF/microwave filters and low noise amplifiers perform analog signal processing. Microwave filters are commonly used in receivers and transmitters operating in 800 MHz to 30 GHz frequency range. A lot of research work has been done in design and analysis of RF/microwave filters such as, design of low pass, high pass and band-pass, and band-stop filters using lumped elements or microstrip techniques [1-3], application of DGS, EBG, in microwave filters [4-8], etc. Microwave band-pass filters are essential components in the development of wireless communication systems. The advanced performance of modern communication systems has imposed stringent requirements on filters including compact size, minimal insertion loss, low cost, and high selectivity.

It is the purpose of this paper to present the designs and analysis and advantages of Interdigital Bandpass filters with instructive design examples.

Keywords: Interdigital Band-Pass Filter, Fractional Bandwidth (FBW), Group Delay, High Frequency Structure Simulator (HFSS).

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1. Introduction:

Interdigital band pass filters have several features such as they are very compact structures.The tolerances required in manufacturing are relatively relaxed because of the relatively large spacing between resonator elements. In most cases, the resonator length is slightly shorter than λ/4 (typically, 0.9λ/4), which allows the filter to be tuned to the center frequency with the tuning elements just breaking the cavity wall. This facilitates both case of tuning and maximum unloaded quality factor of each resonator. The coupling to the input and output is accomplished via contact at the low impedance point of the resonator.The second pass-band is centered at three times the center frequency of the first pass-band. Besides that, there are no possibilities of spurious responses in between.For the filters with parallel-coupled, half-wavelength resonators, a spurious pass band at around twice the mid-band frequency is almost always excited.The Filter can be fabricated in structural forms, which are self-supporting so that dielectric material need not be used. Thus, dielectric loss can be eliminated.Strength of the stop band and rates of cutoff can been enhanced by multiple order poles of attenuation at dc and even multiples of the center frequency of the first pass band.They typically have lowerloss than comb-line structures and are easier to tune.This via-hole, Interdigital bandpass filter is particularly suited to wider bandwidth filters because the dimensions of the filter are more realizable than the side-coupled filters. There are also several implementations in addition to the microstrip medium, including stripline, coplanar waveguide and slotline.

2.Interdigital bandpass filter Structure:

Figure 1 shows a type of interdigital bandpass filter commonly used for microstrip design. The filter configuration, as shown, consists of an array of n TEM-mode or quasi-TEM-mode transmission line resonators, each of which has an electrical length of 90° at the midband frequency and is short-circuited at one end and open-circuited at the other end with alternative orientation. In general, the physical dimensions of the line elements or the resonators can be different, as indicated by the lengths $l_1, l_2 \cdots l_n$and the widths $W_1, W_2 \cdots W_n$. Coupling is achieved by way of the fieldsfringing between adjacent resonators separated by spacing $s_{i,i+1}$ for $i = 1 \cdots n - 1$. The filter input and output use tapped lines with a characteristic admittance Y_t, which may be set to equal the source/load characteristic admittance Y_0. An electrical length θ_t, measured away from the short-circuited end of the input/ output resonator, indicates the tapping position, where $Y_1 = Y_n$denotes the single microstrip characteristic impedance of the input/output resonator.

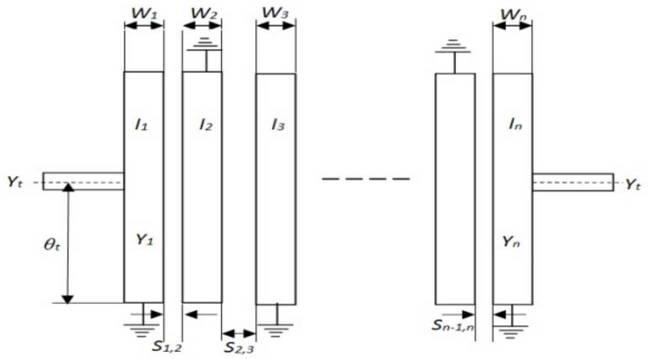

Figure 1: Generalized schematic of an n-pole Interdigital BPF [5]

This type of microstripbandpass filter is compact, but requires use of grounding microstrip resonators, which is usually accomplished with via holes. However, because the resonators are quarter-wavelength long using the grounding, the second passband of filter is centred at about three times the midband frequency of the desired first passband, and there is no possibility of any spurious response in between.

3.Design steps for Interdigital band-pass filter:

1. Calculate electrical length θ for a given bandwidth FBW

$$\theta = \frac{\pi}{2}\left(1 - \frac{FBW}{2}\right) \qquad (1)$$

2. Now expressing Y in terms of Y_1 using θ as

$$Y = \frac{Y_1}{\tan\theta} \qquad (2)$$

Y_1 is admittance of input line

3. Calculate $J_{i,i+1}$using following equation

$$J_{i,i+1} = \frac{Y_1}{tan\theta\sqrt{g_i g_{i+1}}}, \text{ for } i = 1 \text{ to } n\text{-}1 \quad (3)$$

where, g_i represents the element values of a ladder-type low-pass prototype filter with a normalized cut off frequency at $\Omega_c=1$.

4. Calculate $Y_{i,i+1}$ from $J_{i,i+1}$[5]

$$Y_{i,i+1} = J_{i,i+1}\sin\theta, \qquad \text{for } i = 1 \text{ to } n\text{-}1 \qquad (4)$$

5.Calculate characteristic admittance Y_t, of the tapped lines

$$Y_t = Y_1 - \frac{Y_{1,2}^2}{Y_1} \qquad (5)$$

Now substituting Y_t=1/50 and obtaining Y_1.

We have studied symmetrical inter-digital band-pass filter where all microstrip resonators have equal widths i.e. $W_i = W$, for $i = 1$ to n. Using equation from 1 to 5, the characteristic admittance of the input resonator is calculated and since the inverse of the admittance is equal to the impedance,the characteristic impedance Z_1 of the input resonator is $Z_1 = 1/Y_1$.

For the microstrip resonator with characteristic impedance Z_1, the width W can be calculated using following formula[6]

$$\frac{W}{h} = \frac{8\left(\frac{7\varepsilon r+4}{11\varepsilon r}.A+\frac{\varepsilon r+1}{0.81\varepsilon r}\right)^{1/2}}{A} \qquad (6)$$

while,

$$A = exp.\left(\frac{Z_1}{42.4}\sqrt{\varepsilon_r + 1}\right) - 1$$

where, ε_r is the dielectric constant of the substrate, h is the thickness of the substrate.

6. Electrical length θ_t from the short circuited end of the input/output resonator can be obtained as [7]

$$\theta_t = \frac{\sin^{-1}\left(\sqrt{\frac{Ysin^2\theta}{Y_0 g_0 g_1}}\right)}{1-\frac{FBW}{2}} \qquad (7)$$

7. C_t i.e., the capacitance to be loaded to the input and output resonators in order to compensate for resonant frequency shift because of the effect of the tapped input and output can be calculated as [7]

$$C_t = \frac{\cos\theta_t sin^3\theta_t}{\omega_0 Y_t\left(\frac{1}{Y_0^2}+\frac{cos^2\theta_t sin^2\theta_t}{Y_t^2}\right)} \qquad (8)$$

8. Now the even and odd-mode impedances of the n-coupled line resonator can be determined as [8]

$$Z_{0_e 1,2} = \frac{1}{Y_1 - Y_{1,2}}, \qquad Z_{0_o 1,2} = \frac{1}{Y_1 + Y_{1,2}}$$

$$Z_{0_e i,i+1} = \frac{1}{2Y_1 - 1/Z_{0_e i-1,i} - Y_{i,i+1} - Y_{i-1,i}}, \quad \text{for } i = 2 \text{ to } n\text{-}2$$

$$Z_{0_o i,i+1} = \frac{1}{2Y_{i,i+1} + 1/Z_{0_e i,i+1}}, \qquad \text{for } i = 2 \text{ to } n\text{-}2$$

$$Z_{0_e n-1,n} = \frac{1}{Y_1 - Y_{n-1,n}}, Z_{0_o n-1,n} = \frac{1}{Y_1 + Y_{n-1,n}} \qquad (9)$$

Using above equation coupling factor can be derived as

$$k_{i,i+1} = \frac{Z_{0_e i,i+1} - Z_{0_o i,i+1}}{Z_{0_e i,i+1} + Z_{0_o i,i+1}} \qquad (10)$$

Once the coupling factor is obtained the spacing can be obtain easily.

9. After obtaining the width and spacing of the microstrip line resonators, the equivalent length l_i of the resonators can be calculated [5].

$$l_i = \lambda_{g0i}/4 - \Delta l_i \qquad (11)$$

Where, λ_{g0i} is the guided wavelength and Δl_i is correction length of microstrip open end associated with resonator *i*.

As the interdigital filter is symmetric therefore the guided wavelength can be obtained as

$$\lambda_{g0i} = \frac{\lambda_0}{\sqrt{\varepsilon_{re}}} \qquad (12)$$

where, ε_{re} is the effective dielectric constant given by[5]

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2}, \text{ for W/h } \geq 1 \qquad (13)$$

Now the Δl_i can be determined using the empirical formula for microstrip open end validated for the range of 0.01 ≤ *W/h* ≤ 100 and $\varepsilon_r \leq 128$ given in [10]

$$\frac{\Delta l_i}{h} = \frac{\xi_1 \xi_3 \xi_5}{\xi_4} \qquad (14)$$

10. Now, a capacitance C_t is loaded on the input and output resonators due to the tapped lines, which can be achieved by an extension in the length Δl_c of the input and output resonators which can be calculated as [5]

$$\Delta l_C = \frac{\lambda_{g01}}{2\pi}\tan^{-1}\left(\frac{2\pi f_0 C_t}{Y_1}\right) \qquad (15)$$

Therefore, the final lengths l_1 and $l_n$for the input and output resonators are

$$l_1 = l_n = \lambda_{g01}/4 - \Delta l_1 + \Delta l_C \qquad (16)$$

11. Finally the physical length l_t measured from the input/output shorted end to the tapped line is calculated by [5]

$$l_t = \frac{\theta_t}{2\pi}\lambda_{g01} \qquad (17)$$

Using above design steps we can obtained the design parameters for n pole interdigital band-pass filter.

4.Electromagnetic Simulation:

To design and study the transmission characteristics of an-pole interdigital band-pass filter, we have carried out Finite Element Method (FEM) based simulation on a proposed structure using commercial software ANSOFT HFSS v13. To create a model in HFSS as shown in Figure1, we have taken a substrate thickness in mm with dielectric constant (ε_r) and loss tangent(tanδ) . For designing line resonators and ground we should use copper conductor with thickness in mm. The microsrip resonators were shorted to ground using via holes of radius in mm. The via-holes are filled using copper conductor of same bulk conductivity as that for the resonators and ground.The filter parameters will be calculated using the design equations and are optimized using HFSS software to achieve desired response. The final design parameters of the interdigital band-pass filter such as :

Widths: $W_1 = W_2 = W_3 = W_4 = W_5$ *and*
Length: $l_1 = l_5$ *and* $l_2 = l_3 = l_4$.
Spacing: $S_{1,2} = S_{4,5}$ *and* $S_{2,3} = S_{3,4}$*and*
Tapping length: l_t*Will be calculated and all in mm.*

To carry out simulation for our studies, we should use driven modal solution type. The wave ports will be assigned for port excitation. An air box is created to cover the device and to provide the appropriate boundary conditions. The interdigital band-pass filter will be simulated using fast mode for a frequency range after defining an operating frequency in the HFSS model.

5.Result and Discussion:

To study the transmission behaviour of filter, the $|S_{21}|$will be considered to study the fractional bandwidth (FBW). One another important filter parameter is group delay. The group delay is the measure of the time delay of the frequency spectrum of a signal. The group delay can also be defined as the rate of change of transmission phase angle with respect to frequency. Mathematically group delay can be expressed as

$$\tau_g = -\frac{\Delta\varphi}{\Delta\omega} \qquad (18)$$

where, Δφ is change in phase angle of $|S_{21}|$ in radians and Δω, is the change in frequency. It is always desirable to have a minimum and uniform group delay so as to achieve minimum signal distortion. In high speed communication system if the group delay is not uniform then the information of the signal can significantly be distorted.

6. Conclusion:

In this paper we have studied the design step and simulation of an-pole symmetrical interdigital band-pass filter centered at a frequency of some GHz. The designs must be analyzed using existing quasi-static TEM approximations followed by simulations by finite element analysis based commercial software HFSS v13. The Group delay is a very important parameter of a filter to evaluate its performance and applicability for high speed digital systems. In most cases group delay degrades the system performance. Higher the group delay poor the performance. It will observe in the design simulation that the group delay is uniform over the entire pass band frequency. Also, we will observe that as we reduce the spacing between the line resonators, fractional bandwidth increases i.e. FBW is dependent on the coupling between the line resonators. Therefore, Interdigital BPF can find many applications in positioning, imaging, short-range high-data-rate communications systems and wireless personal area networks where the very high bandwidths are required. The Filter can be fabricated in structural forms, which are self-supporting so that dielectric material need not be used. Thus, dielectric loss can be eliminated. This via-hole, Interdigital bandpass filter is particularly suited to wider bandwidth filters because the dimensions of the filter are more realizable than the side-coupled filters.

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