Design of an Improved Four-Pole Hairpin Resonator Filter

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บทคัดย่อ

บทความนี้นำเสนอวงจรกรองผ่านแถบแบบเชื่อมต่อไขว้ที่ใช้เรโซเนเตอร์แฮร์พินแบบปรับปรุงบนโครงสร้างไมโครสตริป ซึ่งวงจรกรองผ่านแถบมีแบนด์วิดแคบและขนาดเล็ก ในการจำลองและออกแบบการทำงานได้ใช้โปรแกรม IE3D เพื่อการคำนวณขนาดของเรโซเนเตอร์รวมทั้งสัมประสิทธิ์การเชื่อมต่อระหว่างเรโซเนเตอร์ซึ่งผลจากการจำลองการทำงานและจากการวัดชิ้นงานจริงได้ผลที่สอดคล้องกันเป็นอย่างดี

Abstract

This paper proposes a new four-pole bandpass filter based on modified microstrip cross-coupled hairpin-line resonators. The filter provides an improved selectivity characteristic with narrow bandwidth and compact size. The full-wave simulator IE3D has been employed to design the hairpin-line resonator, and to calculate the coupling coefficients of the filter structure. Experimental results have been then performed and found very good agreement with simulation expectation.

1. Introduction

To date there are new challenges of designing wireless communication systems for higher quality, lower cost and more compact size. RF and microwave bandpass filters are key components for most of the recent wireless communication systems desired such higher performances and smaller size. The filters may be designed in several different techniques and materials, however, planar structures are particularly attractive because they are compact and easy to manufacture. Hence, many authors have worked on planar filters and their basic components such as planar resonators [1]. A conventional hairpin-line resonator size is normally very large, therefore a folded hairpin-line in a U-shape structure has been studied for size reduction [2]. Then, two arms of the U-shape microstrip hairpin-line resonator are further folded to form a coupled-line at the ends acted as capacitive loading in order to have smaller size [3]. This filter size is more 50% compact compared with the conventional hairpin-line filter, nevertheless, its selectivity characteristic is still not improved. Recently, several authors have researched and developed the hairpin-line resonator filters in order to improve their characteristics and reduce their sizes [4-6].

In this research, we present a new design of a microstrip four-pole cross-coupled bandpass filter using improved hairpin-line resonators. This proposed filter has compact size compared with the folded hairpin-line filter and provides an improved selectivity.

2. Theory

The proposed bandpass filter is shown in Figure 1. The filter consists of microstrip slow-wave open-loop resonators so that it has a four-pole cross-coupled structure. In this configuration, significant couplings exist between any two nondiagonally neighboring resonators. For our design, the coupling between resonators 1 and 2 and between resonator 3 and 4 are identical and must be determined. The

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couplings between resonators 1 and 3 and between resonators 2 and 4 are assumed to be negligible. Thus, there are three basic coupling structures to be investigated.

The bandpass filter may be represented by an equivalent circuit as shown in Figure 2 (a), where $\omega_0 = 1/\sqrt{LC}$ is the center frequency. In this structure, there are four significant coupling coefficients between adjacent resonators, namely k_{12}, k_{23}, k_{34} and k_{14}. The coefficients k_{ij} specifies the coupling between resonators i and j of the filter. When k_{ij} is evaluated, only resonators i and j are considered in the structure, and all the other resonators are removed.

Q_e is the external quality factor denoting the input and output coupling. The coupling coefficients and the external quality factor may be synthesized from a lowpass prototype filter as shown in Figure 2 (b), where the rectangular boxes represent frequency invariant immittance inverters defined through a transmission matrix of the form [1]

$$\begin{bmatrix} 0 & j/J \\ jJ & 0 \end{bmatrix} \tag{1}$$

in which J is the characteristic admittance of the inverter. The other elements g_0, g_1 and g_2 of the lowpass prototype filter could be determined by synthesizing a standard Tchebyshev filter. The external quality factor and coupling coefficients of the prototype can then be found by

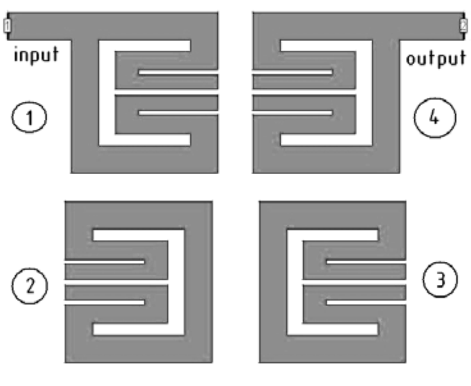
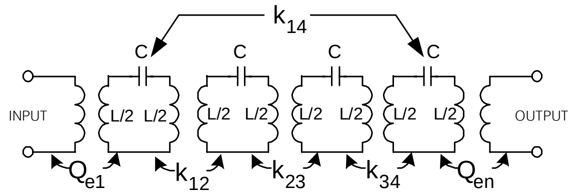
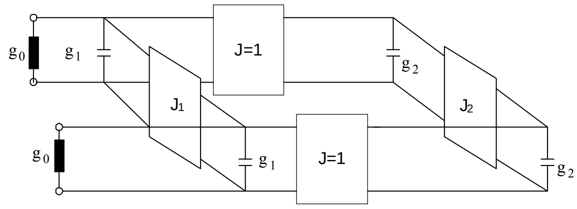


Figure 1 The filter structure realized using microstrip slow-wave open-loop resonators.



(a)



(b)

Figure 2 (a) An equivalent circuit of the four-pole cross-coupled bandpass filter and (b) an associated low-pass prototype filter.

$$Q_{e1} = Q_{en} = \frac{g_0 g_1}{FBW} \tag{2}$$

$$k_{12} = k_{34} = \frac{FBW}{\sqrt{g_1 g_2}}$$

$$k_{23} = \frac{FBW \bullet J_2}{g_2}$$

$$k_{14} = \frac{FBW \bullet J_1}{g_1} \tag{3}$$

where Q_{e1} and Q_{en} are the external quality factors of the resonators at the input and output, respectively, and FBW is the fractional bandwidth of the bandpass filter. To determine these values, for example, a microstrip slow-wave open-loop resonator bandpass filter is designed to have a FBW = 0.02714 at a center frequency f_0 = 2210 MHz. A four-pole (n=4) Tchebychev lowpass prototype with a passband ripple of 0.014 dB is chosen. We also have the values of g_0 = 1.0, g1 = 0.7533, g_2 = 1.2252, J_1 = - 0.08049 and J_2 = 0.9457 Thus,

$$Q_{el} = Q_{en} = 27.75$$

$$k_{12} = k_{34} = 0.02826$$

$$k_{23} = 0.02095$$

$$k_{14} = -0.0029$$

The next step of the filter design is to determine the couplings between adjacent microstrip slow-wave open-loop resonators as well as the external quality factor. It can be shown that each of the three coupling structures has two dominant resonant frequencies, which are split off from the resonance condition due to the electromagnetic couplings.

The coupling coefficient between resonators i and j can be calculated as

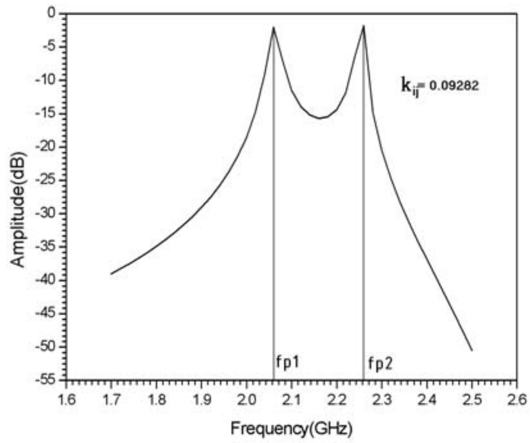
$$k_{ij} = \pm \frac{f_{p2}^2 - f_{p1}^2}{f_{p2}^2 + f_{p1}^2} \tag{4}$$

where f_{p1} and f_{p2} are the lower and higher split resonant frequencies of a pair of coupled resonators when they are decoupled from the remainder. These values could be found in the typical response, as shown in Figure 3 (a). The sign of coupling may only be a matter for cross-coupled resonator filters. However, determination of the sign of the coupling coefficient is much dependent on the physical coupling structure of coupled resonators. This means that if we refer to one particular coupling is the positive coupling, and then the negative coupling would imply that its phase response is opposite to that of the positive coupling. The phase response of a coupling may be found from S parameters of its associated coupling structure.

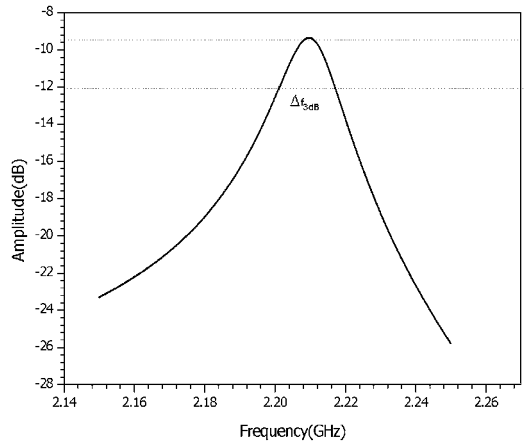
The external quality factor of a single resonator may be found by

$$Q_e = \frac{f_0}{\Delta f_{3dB}} \tag{5}$$

where f_0 and Δf_{3dB} are the resonant frequency and the 3-dB bandwidth of the single hairpin-line resonator when it is externally excited alone (a typical response in Figure 3 (b)).



(a)



(b)

Figure 3 (a) A typical frequency response of a resonator pair for extracting the coupling coefficient and (b) a typical frequency response of a single resonator for extracting the external quality factor.

3. Loss Consideration

Loss can be added to the circuit model for simulating the conductor loss of the real filter. It considerably affects the filter characteristics including narrower the bandwidth and higher insertion loss. It is convenient to use some closed-form expressions to estimate the effects of the dissipation on bandpass filters that are designed from lowpass prototypes [7].

$$\Delta L'_{A0} = 4.343 \sum_{i=1}^{n} \frac{\Omega_c}{FBW \cdot Q_{ui}} g_i \quad \text{dB} \tag{6}$$

where $\Delta L'_{A0}$ is the dB increase in insertion loss at the center frequency and Q_{ui} is the unloaded quality factor of microwave resonators corresponding to g_i, which is evaluated at the center frequency. The cutoff frequency of the lowpass prototype (Ω_c) is set to be 1.

The total unloaded quality factor can be found by adding these losses together in

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} \qquad (7)$$

Q_c is conductor quality factor of its ground plane approximated by

$$Q_c \approx \pi\left(\frac{h}{\lambda}\right)\left(\frac{\eta}{R_s}\right) \qquad (8)$$

The dielectric loss can be taken into account in terms of a complex permittivity of the dielectric substrate $\varepsilon = \varepsilon' - j\varepsilon''$, with the negative imaginary part denoting energy loss. Hence, the loss in a dielectric substrate may be attributed to an effective conductivity $\omega\varepsilon''$. It can be shown that

$$Q_d \geq \frac{\varepsilon'}{\varepsilon''} = \frac{1}{\tan\delta} \qquad (9)$$

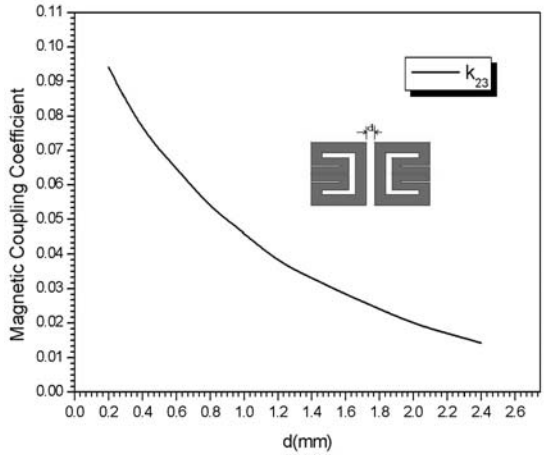
The operating frequency at which the radiation becomes significant may be calculated from the radiation Q factor of a half-wavelength resonator, approximately given by [7]

$$Q_r = \frac{3\varepsilon_r Z_0 \lambda_0^2}{32\eta h^2} \qquad (10)$$

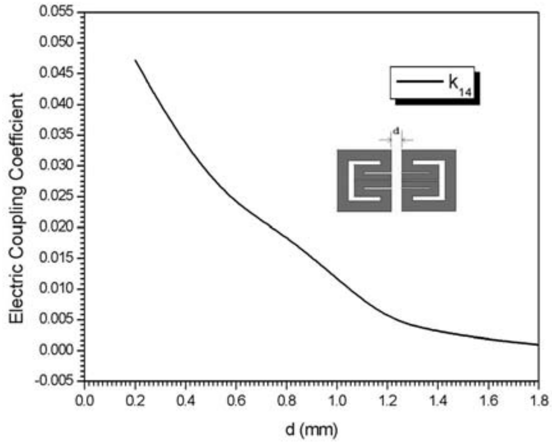
From (8), (9) and (10), we can obtain the following relation

$$\frac{1}{Q_{ui}} = \tan\delta + \frac{15.915}{h\sqrt{f\sigma}} + \frac{8.936\times10^{-4}(fh)^2}{\varepsilon_r} \qquad (11)$$

where tan δ and σ are loss tangent and conductivity in S/m, f is in gigahertz and h is in millimeters.



(a)



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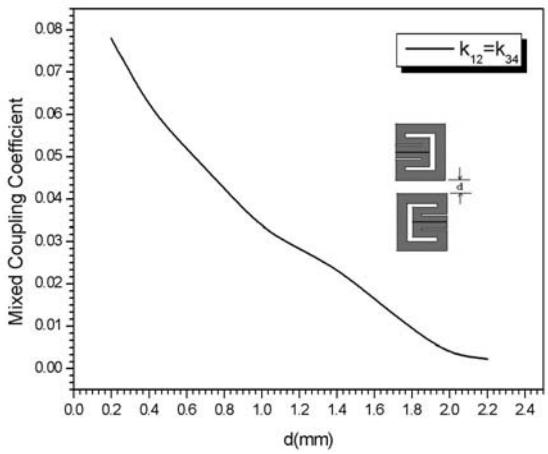


(c)

Figure 4 Modeled coupling coefficients of coupled microstrip resonators. (a) Magnetic coupling, (b) electric coupling, and (c) mixed coupling.

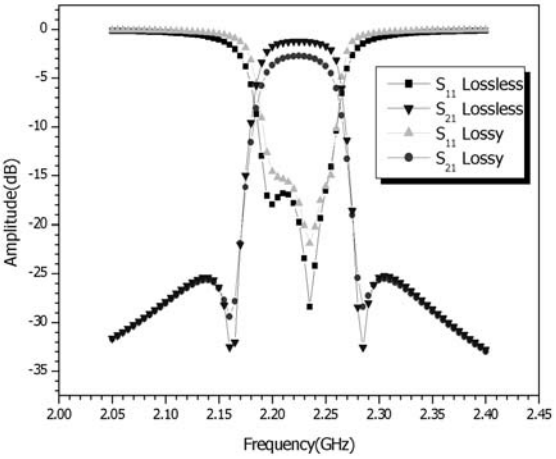


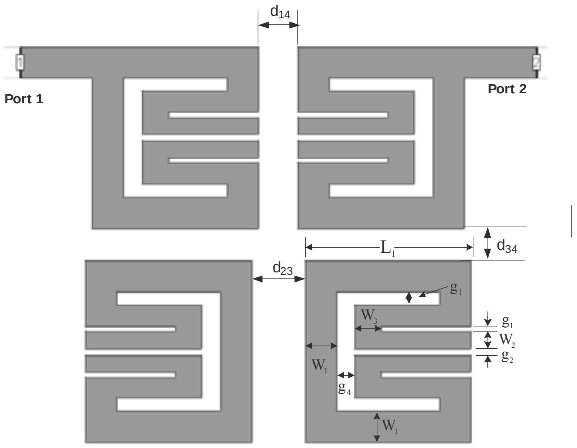
Figure 5 Simulated S-parameters (S_{11} and S_{21}) of the proposed filter for both lossless and lossy models.

4. Design, Implementation and Results

The steps of designing can be concluded as follow :

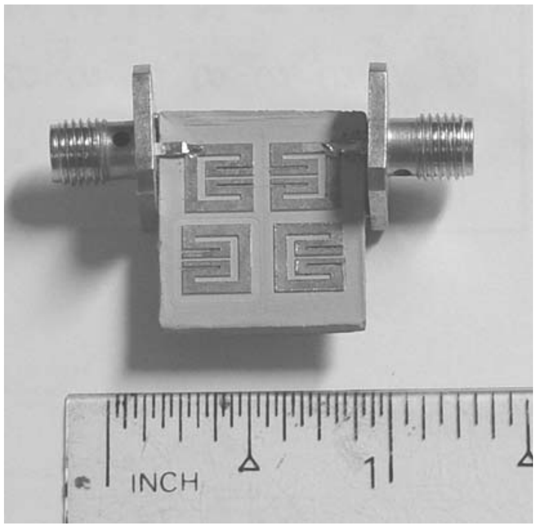
- Specify the center frequency, passband ripple and the bandwidth of the bandpass filter
- Design a single half-wavelength resonator
- Calculate the fractional bandwidth FBW
- Calculate the Tchevbyshev lowpass prototype
- Calculate the external quality factor from eq. (2)
- Calculate the desired coupling coefficients for each pair of resonators using eq. (3)
- Calculate the coupling coefficients for each pair of resonators using IE3D [8] and eq.(4) at various coupling gaps, resulting in graphs in Figure 4
- Determine the actual gaps between the resonators using the values of desired coupling coefficients and graphs in Figure 4
- Predetermine the loss of the actual filter using eq. (6)
- Layout the circuit and then using IE3D to determine the actual loss, as shown in Figure 5
- Optimize the filter circuit for the desired responses employing IE3D

In this work, we design the bandpass filter at the center frequency at 2210 MHz and the bandwidth of 60 MHz. A substrate of $\varepsilon_r = 10.2$, thickness = 1.27 mm



W_1 = 1.187 mm, W_2 = 0.5846 mm, W_3 = 0.6698 mm, L_1 = 6.3 mm, L_2 = 6.904 mm, L_3 = 3.406 mm, g_1 = 0.4032 mm, g_2 = 0.3608 mm, g_3 = 0.5 mm, g_4 = 1.088 mm d_{14} = 1.512 mm, d_{23} = 2.02 mm, and d_{34} = 1.24 mm

(a)

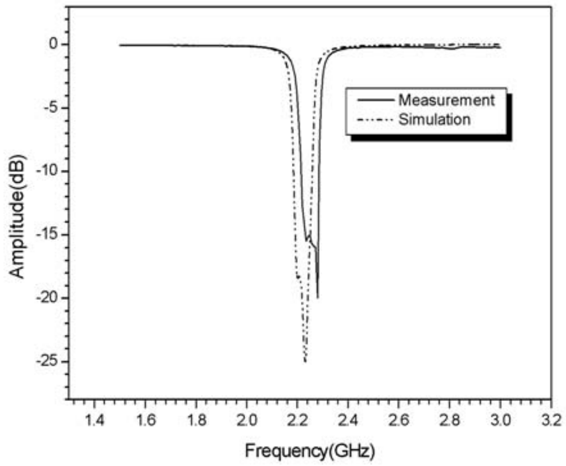


(b)

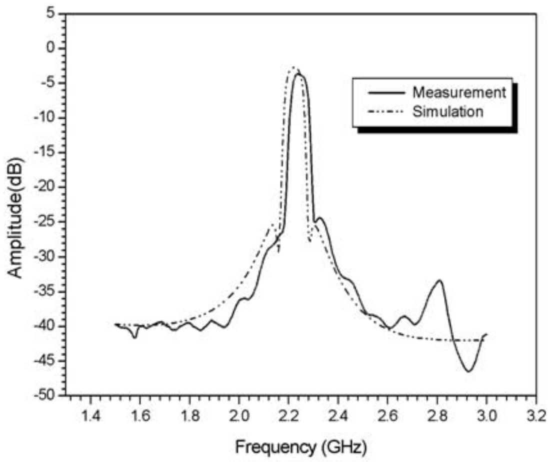
Figure 6 (a) A schematic and (b) a constructed circuit.

and loss tangent = 0.003 has been utilized. Therefore, the circuit layout has been obtained, as displayed in Figure 6 (a). The circuit pattern has been then produced on a given substrate using LPKF milling machine. The constructed filter is finally shown in Figure 6 (b).

The constructed filter has been tested using a calibrated network analyzer. Measured results of S_{11}



(a)



(b)

Figure 7 Simulation and measurement results (a) and (b).

and S_{21} are shown in Figures 7 (a) and (b), respectively. We can see good agreement of the measurement and simulation results, and also notice a very sharp response of selectivity.

5. Conclusions

We have presented the theory and design of a four-pole cross-coupled filter using improved hair-pin-line resonators. The design is based on the knowledge of the coupling coefficients of the three basic coupling structures. A method for calculating coupling parameters using IE3D has been also demonstrated. The experimental results show excellent performances and agree well with the simulation. This proposed bandpass filter has a compact size, low insertion losses ($\approx$3 dB) and very high selectivity, therefore, it is very attractive for further development and could be potentially applied for modern wireless communications.

6. Acknowledgement

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