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A Design Technique for Dual-Mode Suspended-Substrate Stripline Filter

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Abstract: A new design technique of dual-mode ring-resonator suspended-substrate stripline filter is reported in this paper to achieve low passband insertion loss, high quality factor and good spurious response. A fourth-order bandpass filter was designed and fabricated at the operational frequency of 2.07 GHz with two ring resonators packaged in a metallic cavity where each ring resonance is one wavelength long. By using 90° input and output port arrangement, all transmission zeros of the dual-mode filter can be well controlled and synthesized, thus sharp-skirt selectivity filter response was achieved.

Perturbation notch structure was implemented on each ring resonator to provide the electromagnetic coupling of two degenerate modes, thus dual-mode response of the filter can be synthesized. Measurement results of the first dual-mode filter prototype showed a return loss and an insertion loss of better than 16.42 dB and 0.926 dB, respectively, whilst an out-of-band rejection of up to 55 dB was achieved. The novel filter design technique proved that no cross-coupling is required to obtain the transmission zeros of the filter, thus the sharp-skirt response was achievable.

1. Introduction

In cellular-radio base stations, signals are being transmitted and received simultaneously. In the receive band, there are chances of intermodulation products from the power amplifier being fed to the receiver, thus the transmit filter must have a very high level of signal rejection [1]. Furthermore, the transmit filter must also have low passband insertion loss since it impacts the power transmitted and the overall transmit system efficiency. Recently, filters with dual-mode operation were being investigated due to its ability to produce two degenerate modes using a single physical structure; therefore, the size and cost of the filter can be reduced without compromising any figure-of-merits.

There are many research works in improving the design of the transmit filter by using dual-mode design technique. The microstrip technology is frequently used in designing dual-mode filter due to its advantages such as low profile and fabrication cost. A dual-mode rotational symmetric resonator filter was developed with two transmission zeros generated near the upper and lower passband [2]. Besides, a fourth-order dual-mode microstrip filter with interdigital capacitive loading element was developed [3]. In [3] and [4], compact dual-mode microstrip filters were designed, fabricated and evaluated by using parallel coupled resonator and meander loop resonator, respectively. Furthermore, a triangular microstrip dual-mode filter based on the coupling matrix synthesis method was developed with a good rejection performance obtained [6]. Also, a dual-mode filter with source-load coupling was designed in [7] and [8] demonstrated good filter performance. All previously mentioned microstrip dual-mode filter designs suffered high insertion loss which is on average of approximately higher than 1 to 2 dB at midband frequency.

The suspended-substrate stripline technology offers various attractive advantages, which are comparable to a microstrip or other planar transmission line. Filtering circuits implemented using suspended-stripline structures achieve high signal selectivity, lower insertion loss and good temperature stability. It is because the suspended-stripline technology uses the air as the dielectric material to connect to the ground plane, thus minimising the signal transmission losses associated to dielectric material loss. Another key advantage of suspended-stripline structure is that the circuit patterns can be printed on both sides of the stripline substrate, which enables strong broadband electromagnetic (EM) coupling, as well as the use of a metal housing that prevents the EM fields of the filter from radiating loss. Since suspended-stripline is a purely transverse electromagnetic (TEM) transmission-line structure, therefore, it is non-dispersive, and thus makes suspended stripline as an interesting structure for high-performance filters. Presently, only a dual-mode suspended-substrate stripline was demonstrated using quarter wave resonator and inductor [9]. However, it was designed for broadband frequency and the insertion loss and return loss obtained was worse than 1 dB and 10 dB in the passband frequencies, respectively.

This paper reports on developing a new design of dual-mode suspended-substrate stripline filter to achieve low passband insertion loss, high quality factor (Q) and good spurious response without compromising any other figure-of-merits. The filter is designed to operate at 2.07 GHz with two ring resonators packaged in a metallic cavity where each ring resonance is one wavelength long. By using 90° input and output port arrangement, all transmission zeros of the dual-mode filter can be well controlled and synthesized, thus sharp-skirt selectivity filter response was achieved.

1.1. Previous Work

There are many previous works in designing dual-mode filters. Filter prototypes in [6] and [7] demonstrated compact dual-mode response. In [3] and [4], compact dual-mode filters were designed, fabricated and evaluated by using parallel coupled resonator and meander loop resonator, respectively. Furthermore, a triangular microstrip dual-mode filter based on the coupling matrix synthesis method was developed with a good rejection performance obtained [6]. Also, a dual-mode filter with source-load coupling was designed in [7] and [8] demonstrated good filter performance. All previously mentioned microstrip dual-mode filter designs offer good return loss and sharp-skirt selectivity due to its ability to generate transmission zeros. Nonetheless, they
long. By properly design a 90° input and output port arrangement, transmission zeros cab be fully controlled and generated, thus a sharp-skirt selectivity filter response is achieved. In this new design technique, no cross-coupling is needed to achieve high selectivity filter response. Moreover, a perturbation notch is implemented on the ring resonators to provide the coupling of two degenerate modes, thus dual mode responses can be synthesized. Therefore, this new design technique solves the disadvantage of the conventional suspended-substrate stripline technology. The dual-mode suspended-substrate filter design was fabricated and measurement results show, in the passband, a return loss of better than 16.42 dB, an insertion loss of 0.926 dB and a bandwidth of 57.7 MHz was achieved.

2. Dual-Mode Ring Resonator Filter

To investigate the harmonic suppression effect, a wavelength long ring resonator dual-mode filter is designed and simulated at 2.07 GHz. Fig. 1 and Fig. 2 depict the top and front view of the ring resonator filter with a metal post implemented at the centre of the ring resonator, respectively. The metal post is placed at the centre of the cavity to create a short circuit to the ground plane and used to improve the first harmonic of the ring resonator filter. Rogers RT/Duroid 5880 with dielectric constant $\varepsilon_r = 2.2$ and thickness $h = 0.254$ mm was selected as the substrate for the filter design. A full-wave EM simulator (HFSS) is used to investigate and synthesize the dual-mode resonance frequency and harmonics [10]. Table I and Table II represents the simulated eigenmode solution of a ring resonator design without and with a metal post shorted to ground. The first harmonic frequency and Q-factor are improved from 3.34 GHz to 4.05 GHz and from 1486.26 to 1569.43, respectively, when the metal post is implemented in the dual-mode filter design. This is because the electric field distribution at the centre of the cavity was pushed towards the ring edges due to the metal post, thus increase the frequency distance of the first harmonic frequency. Fig. 3 shows the electric-field distribution of EM mode 1 of the ring resonator without and with a metal post at the centre of the resonator structure. Fig. 4 shows the electric field distribution of mode 3 of the ring resonator without and with a metal post at the centre of the resonator structure. For this case, the electric field distribution of this mode was pushed away from the centre of the cavity when a metal post was implemented at the centre of the ring resonator structure. Therefore, the simulation results show that a wider out-of-band rejection; as well as better spurious are achievable by adding the metal post at the centre of the ring resonator.

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<th>Table 1 Simulated Eigenmode solution for ring without metal post</th>
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<th>Table 2 Simulated Eigenmode solution for ring with metal post</th>
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<td>Mode 3</td>
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Fig. 1 Top view of a ring resonator structure with a metal post shorted to ground

Fig. 2 Front view of a ring resonator structure with a metal post shorted to ground

Fig. 3 Electric field distribution for mode 1 of a ring resonator (a) without and (b) with a metal post
structure. Therefore, filter design technique based on ring resonator structure with metal post at the centre of the resonator is utilised for superior dual-mode filter design.

3. Analysis and Design of Dual-Mode Filter

The ring resonator was analysed as two transmission lines with electrical length of $\theta_1$ and $\theta_2$ connected in parallel as shown in Fig. 5, where the characteristic impedances $Z_0$ of the transmission lines is assumed to be $1\Omega$. The $Y$-matrix of the transmission line is:

$$[Y] = \begin{bmatrix} -j & j \\ \tan \theta & \sin \theta \\ j & -j \\ \sin \theta & \tan \theta \end{bmatrix}$$

Since the two transmission lines are connected in parallel, therefore, we get:

$$[Y] = j \begin{bmatrix} 1 & 1 \\ \tan \theta_1 & \sin \theta_1 \\ 1 & 1 \\ \sin \theta_2 & \tan \theta_2 \end{bmatrix}$$

If the $Y$-matrix is presented as a $\pi$ network and the equivalent circuit of the two-port network is pictured in Fig. 6 where the $\pi$ network is represented as admittance inverter $K_{12}$. Therefore

$$jK_{12} = Y_{12}$$

And from (2)

$$Y_{12} = \frac{j}{\sin \theta_1} + \frac{j}{\sin \theta_2}$$

Hence, the transmission zeros of this matrix are the zeros of $Y_{12}$ and occur when

$$\sin \theta_1 + \sin \theta_2 = 0$$

The external coupling is also referred as input and output coupling. The external quality factor ($Q_e$) was first calculated from

$$Q_e = \frac{f_o}{BW \times M_{14}}$$

Where $f_o$, $BW$ and $M_{14}$ are the operating frequency, bandwidth and normalized coupling value respectively. The normalized coupling value is extracted from the coupling matrix synthesis software (CMS) [11] based on the desired specification requirements. The input and output coupling depends on the gap distance between the input/output feeding transmission line and the ring resonator. The exact gap distance for the input and output coupling are determined from the external quality factor ($Q_e$) versus gap distance graph as shown in Fig. 7.

**Fig. 4** Electric field distribution for mode 3 of a ring resonator (a) without and (b) with a metal post

**Fig. 5** Equivalent circuit representation of the ring resonators

**Fig. 6** Equivalent circuit representation for the two-port network

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The normalized coupling constants of mode 1-2 and mode 3-4 which are referred to $M_{12}$ and $M_{34}$, respectively, are defined and controlled by the perturbation size of the ring resonators. The new dual-mode filter design is initially under weak capacitive coupling with a perturbation located $135^\circ$ to the input and output feeding port of the ring resonators to investigate the influence of varying the notch radius to the dual-mode filter response. The location and size of the notch of the ring resonators are two important design parameters, where it influences the electrical filter performance. Fig. 8 depicted the relations between the first three resonant modes and notch radius of the ring resonators. As notch radius increases, one of the degenerate modes remains unchanged while the other one slowly moves downwards, thus separating these two modes from each other. Therefore, the notch radius controls the mode splitting of the degenerate modes. Fig. 9 represent the plot of the relationship between the coupling bandwidth and the notch radius. The wider filter bandwidth is achievable with the increasing notch radius of the ring resonators. Hence, the suitable notch radius can be chosen to split the two degenerate modes based on the required coupling bandwidth obtained from [11].

The coupling constant between two rings is referred as $M_{12}$, which is controlled by the gap spacing between the metal strip and the two rings, as shown in Fig. 10. The inter-ring coupling was first extracted from [9]. The ring resonators was initially loosely coupled and the inter-ring coupling was adjusted until $S_{21}$ between two peaks is roughly -30 dB to -40 dB to synthesize loose coupling. The inter-ring coupling was computed from [12] with

$$K = \frac{f_H^2 - f_L^2}{f_H^2 + f_L^2}$$

(7)

Where $f_H$ is frequency of the upper peak while $f_L$ is the frequency of the lower peak.

4. Fourth-Order Filter Design

A fourth-order bandpass filter is designed at the operational frequency of 2.07 GHz and a bandwidth of 50 MHz as depicted in Fig. 10. The overall dual-mode filter length, width and height are 140 mm, 67 mm and 10 mm respectively. Fig. 11 shows the simulation result of the dual-mode filter with a return loss of better than 15.33 dB and an insertion loss of approximately 0.66 dB at the center frequency of 2.088 GHz. Besides, the two pairs of transmission zero are synthesized to be below and above the passband with a band rejection of up to 74 dB because when a ring was fed at $90^\circ$, there are two separate paths exist with one path of $\pi/4$ while the other one is $3\pi/4$ in which it creates $180^\circ$ phase difference. The $180^\circ$-phase difference thus naturally creates zero transmissions of the dual-mode filter design. Moreover, the notch in the ring resonator structure separates out the interference so that the transmission zeros can be synthesized at below and above the passband frequencies. Therefore, the selectivity of the filter response is enhanced by using this new design technique. Fig. 12 shows the measurement result of the fabricated filter with a return loss of approximately 16.42 dB, an insertion loss of better than 0.926 dB and a bandwidth of 57.7 MHz. Two pairs of transmission zeros were observed in the measurement results, which agreed well with the simulation outcomes. A shifting in the resonance frequency is caused by the tuning screws and fabrication tolerance. Fig. 13 and Fig. 14 represents the fabricated filter where the ring resonators are located on the top layer while the coupling strip and transmission lines are implemented on the bottom layer.
5. Conclusion

In this paper, a fourth-order dual-mode suspended substrate stripline filter has been presented where the influence of metal post was investigated. The first harmonic was suppressed nearly doubled the fundamental frequency by adding metal puck. Using 90° input and output port arrangement, transmission zeros were obtained. In other words, no cross-coupling is needed in order to achieve a sharp skirt response. The obtained frequency response indicated that the dual-mode suspended substrate stripline filter enables the achievement of low-loss filter response, good spurious, high Q-factor as well as high selectivity without any cross-coupling connection.

6. References


