Progress In Electromagnetics Research C, Vol. 18, 1–8, 2011

COMPACT THICK METAL DIPLEXER WITH MULTI-COUPLED FOLDED HALF WAVELENGTH RESONATORS

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Abstract—A thick metal microstrip diplexer is presented. The circuit is based on compact folded half wavelength resonators and uses a source/load-multi-resonator coupling method providing improved performance and greater design flexibility. Source/load coupling with multiple resonators introduces additional transmission zeros, and this coupling is enhanced by using high-aspect-ratio metal structures. Tall, narrow metal arms connected to the ports and extended to the non-adjacent resonators provide effective multi-resonator bypass coupling. The high-aspect-ratio diplexer fabricated using polymer-based deep X-ray lithography and 0.22 mm thick metal electroplating demonstrates the advantages of thick metal structures for coupled resonator applications.

1. INTRODUCTION

Compact microwave filters and diplexers with high rejection and good isolation are required for modern wireless applications. Diplexers with improved performance can be realized by micromachining thick materials to provide tall vertical structure [1, 2]. Deep exposure polymer-based lithographies, such as deep X-ray lithography and UV

Received 4 October 2010, Accepted 16 November 2010, Scheduled 18 November 2010
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lithography are also being used as thick material microfabrication technologies for realizing high performance microwave devices with additional flexibility in available materials and structure [3, 4]. Thick metal structures with exceptional structural features can be fabricated using deep X-ray lithography with metal electroplating. These metal structures with near 90 degree vertical, optical quality smooth sidewalls can be up to several millimeters in height, and have aspect-ratios up to 100:1. High-aspect-ratio structures fabricated using deep X-ray lithography are excellent for realizing tight coupling requirements in certain microwave circuits as demonstrated in this work.

The synthesis of diplexers classically starts from two port filters and a three port junction that are separately designed and combined in such a way as to maximize the performance [5]. Stopband attenuation of two port filtering devices can be improved by introducing transmission zeros generated by cross coupling of resonators [6]. Additional transmission zeros can be generated by coupling the source and/or load with more than one resonator [7].

An effective source/load-multi-resonator coupling method for miniaturized microstrip filters with half wavelength open loop resonators was proposed in [8]. A tall, narrow side arm connected to the source or load, which is used for obtaining the required external quality factor of the first resonator, is extended up to the second resonator to obtain the coupling of the source/load to the second resonator. The main advantage with this kind of arrangement is that direct and bypass coupling can be controlled easily and more independently.

To experimentally validate the above mentioned source/load-multi-resonator coupling method a second-order high-aspect-ratio microstrip diplexer is designed, and fabricated in 0.220 mm thick metal using deep X-ray lithography. The tight gap coupling possible with the precisely fabricated high-aspect-ratio structures provides the required tight external coupling and bypass coupling, and demonstrates a major advantage of high-aspect-ratio structures for microwave coupled resonator applications.

2. EXTERNAL Q-FACTOR OF HIGH-ASPECT-RATIO OPEN LOOP RESONATOR

The top-view of a high-aspect-ratio microstrip folded half wavelength open loop resonator and the external coupling structure is depicted in Fig. 1. The open loop resonator with narrow (0.200 mm) and tall (metal thickness, $h = 0.220$ mm) traces can be folded into a compact lateral structure. Control over external coupling is greatly assisted by

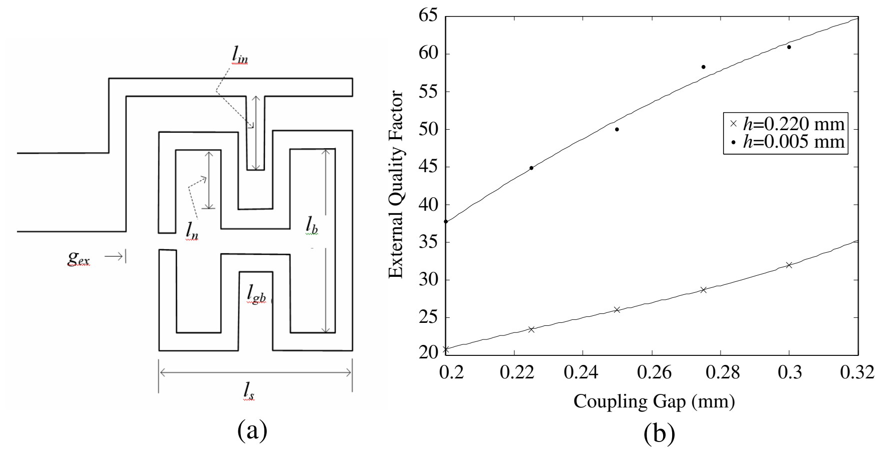

Figure 1. High-aspect-ratio microstrip folded half wavelength open loop resonator and external coupling structure: (a) top-view layout; (b) comparison of external quality factors for high-aspect-ratio (metal height, $h = 0.220\,\text{mm}$) and planar ($h = 0.005\,\text{mm}$) open loop resonators as a function of coupling gap, g_{ex}. ($l_s = 2.050\,\text{mm}$, $l_b = 1.920\,\text{mm}$, $l_{gb} = 0.400\,\text{mm}$, $l_n = 0.590\,\text{mm}$, and $l_{in} = 0.820\,\text{mm}$).

the tall metal surfaces, which allow compact structure while avoiding unmanageably close trace proximity and small gaps. A narrow side arm with one end connected to the main trace is extended along the loop resonator and a short stub is inserted into the folded outer slot to further increase the external coupling (and decrease the external quality factor).

A comparison of external quality factors obtained from electromagnetic simulations using HFSS$^{\text{TM}}$ software [9] for the tall high-aspect-ratio case ($h = 0.220\,\text{mm}$) and the planar case ($h = 0.005\,\text{mm}$), for a fused quartz substrate (relative permittivity, $\varepsilon_r = 3.78$) is illustrated in Fig. 1. The resonator loop traces, the resonator opening, and the narrow coupling arm connected to the $50\,\Omega$ microstrip feedline are all 0.200 mm wide. Tight coupling to the resonator, in other words lower external quality factor, which is normally required for filters with wider bandwidth can be easily realized with the thick metal microstrip structures. According to Fig. 1, there is a difference in external quality factor of at least 17.5 between the structures with $h = 0.220\,\text{mm}$ and $h = 0.005\,\text{mm}$, for the coupling gap range $0.200\,\text{mm} < g_{ex} < 0.320\,\text{mm}$.

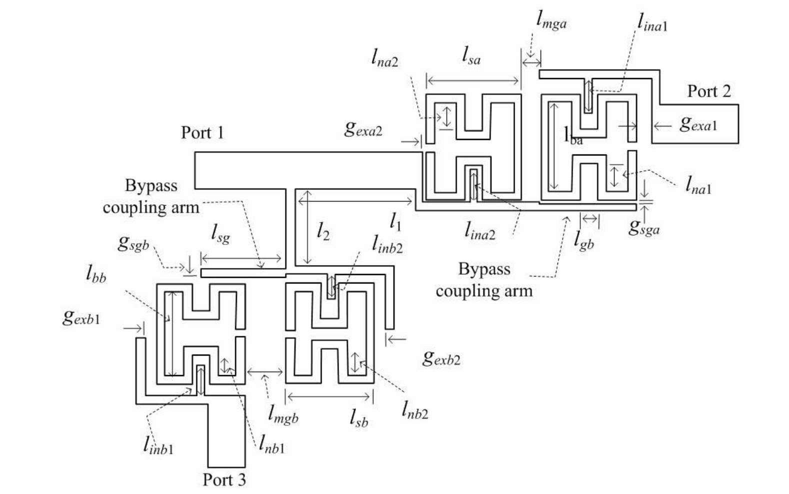

Figure 2. Top-view layout of the second-order thick metal diplexer (metal height, $h = 0.220\,\text{mm}$).

3. DIPLEXER DESIGN, FABRICATION & RESULTS

When designing diplexers combining two adjacent channels, minimal channel interference can be achieved by introducing transmission zeros to the response of one channel at the passband of the other channel and vise versa. For the channel between Ports 1 and 2 (see Fig. 2), an asymmetric high-aspect-ratio bandpass filter with 4% bandwidth centered at 10.5 GHz and one transmission zero located at 11.4 GHz is designed as described in [8]. For the channel between Ports 1 and 3, a high-aspect-ratio bandpass filter with 3.6% bandwidth centered at 11.6 GHz and the transmission zero at 10.66 GHz is designed [8]. These filters are combined to form the thick metal microstrip diplexer. A T-junction with matching lines of lengths l_1 and l_2 is used to combine the filters as shown in Fig. 2. The lengths of the matching lines (l_1, l_2) were selected such that the channel interference is minimum, and also to provide physical separation of the two filter structures. The impedance of the matching line with length l_2 is increased in order to minimize the loading of the second channel on the first channel.

The bypass couplings of Port 1 are achieved by extending the tall narrow arms along the non-adjacent resonators as shown in Fig. 2, avoiding difficulties commonly associated with implementation of filtering circuits with dual mode resonators. Here, the designer can enjoy the freedom of independently controlling the length of the

Table 1. Dimensions of the thick metal diplexer.

Dimension (mm)		Dimension (mm)		Dimension (mm)		Dimension (mm)	
g_{exa1}	0.370	l_2	1.755	l_{na1}	0.678	l_{sg}	1.975
l_{gb}	0.400	g_{sgb}	0.130	l_{ina1}	0.820	l_{bb}	1.920
g_{sga}	0.071	g_{exb1}	0.256	l_{ba}	2.050	l_{inb1}	0.700
l_{mga}	0.438	l_{nb1}	0.450	l_{sa}	2.200	l_{mgb}	0.950
l_{na2}	0.618	l_{sb}	2.050	l_{ina2}	0.750	l_{nb2}	0.618
g_{exa2}	0.035	l_{inb2}	0.600	l_1	2.790	g_{exb2}	0.210

extended arm and the coupling gap with the non-adjacent resonator, while maintaining the required direct coupling with the adjacent resonator. Thick microstrip avoids the extremely narrow coupling gaps which would otherwise be required, were thin conductors used to realize direct and bypass couplings.

The diplexer circuit is designed for a nominal electroplated nickel height of 0.220 mm on a 0.5 mm thick fused quartz substrate (ε_r = 3.78). The width of the 50 Ω lines at the ports is 0.875 mm, while the width of the narrow conductors comprising open loop resonators and coupling arms is 0.200 mm. The width of the resonator openings is 0.100 mm. The other dimensions are listed in Table 1. The bypass coupling gaps (g_{sga} and g_{sgb}), the external coupling gaps to Port 1 (g_{exa2} and g_{exb2}), and resonator lengths were fine-tuned to optimize the diplexer for the desired response.

The high-aspect-ratio microstrip diplexer is fabricated using deep X-ray lithography with metal electroplating as in [3]. Fig. 3 shows inclined images of the fabricated diplexer. The approximately 1/4 mm nickel metal height is clearly evident in Fig. 3(a), which shows the connectorized diplexer mounted for testing. Fig. 3(b) is a scanning electron microscope (SEM) micrograph of the stub inserted into the folded resonator slot region indicated in Fig. 3(a), highlighting the extremely smooth and vertical tall sidewalls. Fig. 3(c) is an SEM micrograph of the external coupling gap corner indicated in Fig. 3(a). It is evident that the required tight coupling gap g_{exa2} (refer to Fig. 2) with the targeted gap of 35 μm, even with a 0.22 mm thick metal structure, has been fabricated very accurately. The required coupling gap for the bypass coupling (g_{sga}) of the first channel is 71 μm.

In Fig. 4, the experimental diplexer response is compared with the simulated responses obtained from EM simulation for the diplexer, using an adaptive mesh with about 90000 tetrahedral elements.

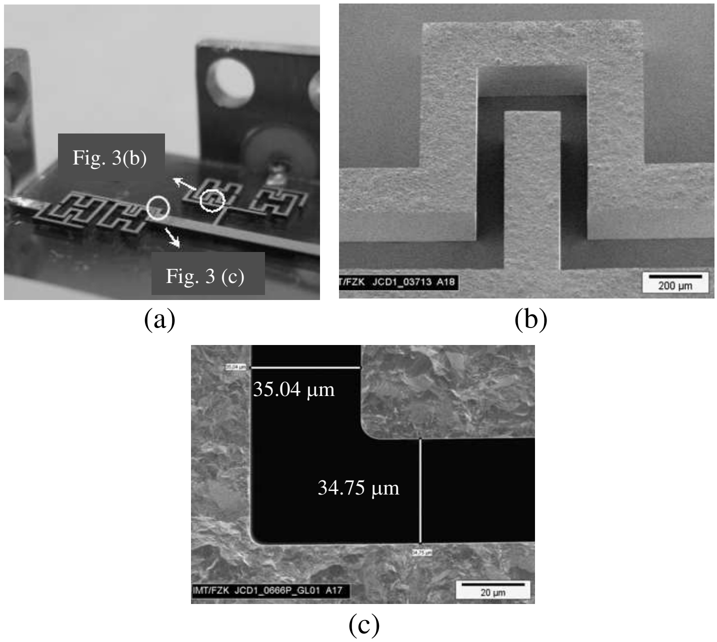

Figure 3. (a) Photograph of deep X-ray lithography fabricated high-aspect-ratio diplexer. (b) SEM image of the stub inserted into the folded resonator slot region indicated by the circle in (a). (c) SEM image of the external coupling gap corner indicated by the circle in (a).

The experimental response is generally in good agreement with the simulated response. In the simulated response, the transmission zero of S_{21} (insertion loss between Port 1 and 2) is aligned with the passband of S_{31} (insertion loss between Port 1 and 3) at 11.35 GHz and the transmission zero of S_{31} is aligned with the passband of S_{21} at 10.51 GHz, increasing channel isolation S_{23} in these regions. In the experimental response, the transmission zero of S_{21} is located at 11.21 GHz while the transmission zero of S_{31} is located at 10.87 GHz. The measured channel isolation is more than 25 dB across both channel passbands, and is increased to more than 30 dB in the regions around the transmission zeros. Higher order channel filters with transmission zeros can be implemented with this approach to obtain higher stopband isolation if required. Increased passband loss and a slight shift in frequency are attributed to height variation in the tall electroplated metal structures. Height homogeneity across large areas is difficult to control due to different electroplating growth rates associated with

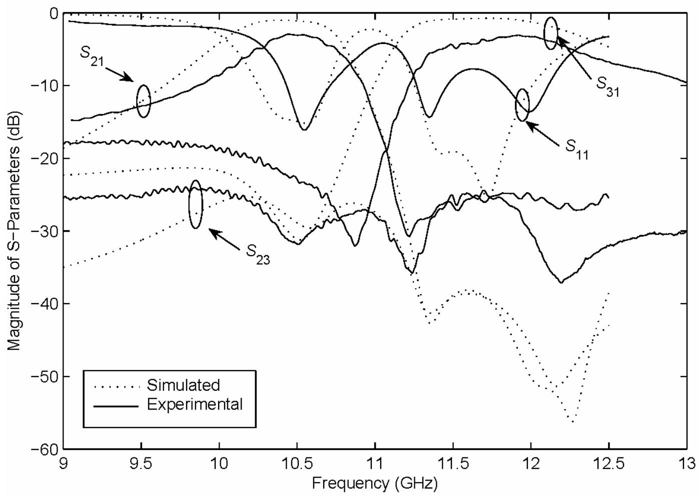

Figure 4. Comparison of experimental response with simulated response of the diplexer with transmission zeros.

layouts comprising both large and small lateral feature sizes. A process of planarization to reduce metal height variation in the tall electroplated structures, combining the steps of lapping, mechanical polishing, and electropolishing is currently being developed [10].

4. CONCLUSION

An effective source/load-multi-resonator coupling method which is conducive for generating additional transmission zeros at finite frequencies with fewer single mode resonators was utilized in designing the diplexer. The bypass coupling of the source or load to its non-adjacent single mode resonator was realized by extending the tall coupling side arms past the adjacent resonator, to include coupling to the non-adjacent resonator. There is greater design flexibility with this method in designing source/load multi-resonator coupling. A fabricated high-aspect-ratio diplexer effectively combining two filters with transmission zeros created by the above source/load multi-resonator coupling method, and with very accurate lateral dimensions, was presented, highlighting the advantages of deep X-ray lithography fabricated structures for realizing tight coupling circuits.

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