Miniaturized Slot-line and Folded-Slot Band-pass Filters

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Abstract —**In this paper the concept of a new class of miniaturized filters using printed circuit technology is presented. The building block of the proposed filter is a miniaturized high-Q printed slot-line resonator, which allows for the realization of both standard coupled-line and cross-coupled quasi-elliptic filters. Each resonator occupies an area as small as $0.03\lambda_0 \times 0.06\lambda_0$ and can be shown to have a Q as high as 200 at 2.4 GHz. Analytical, and numerical methods are employed to outline a design procedure. An integral equation full-wave method is used to macro-model the coupling coefficient between two adjacent resonators as a function of their relative distance and orientation. Filter theory is used to design different filter types. The design procedure is validated by comparing the simulated S-parameters of a two-pole and a four-pole Chebyshev filter with those measured from prototypes operating, respectively at 515 MHz and 400 MHz.**

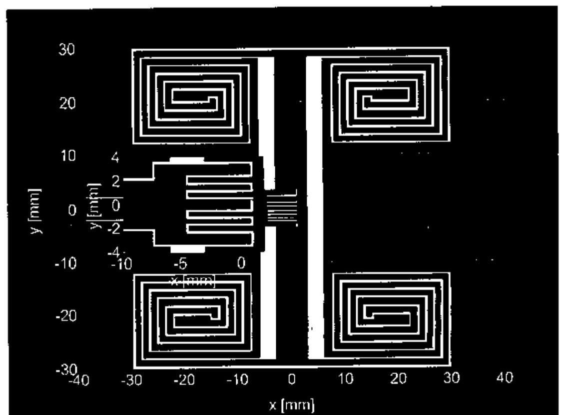

Fig. 1. Schematic of a miniaturized folded slot antenna fed by a capacitively coupled CPW line

I. INTRODUCTION

With the ever-increasing demand for mobile wireless devices, there is a significant interest in low-cost, power-efficient, and miniaturized active and passive RF components. Filters and multiplexers are common components of almost all wireless devices. Hence in recent years, interest in research into novel filter architectures, with an emphasis in filter miniaturization, has been renewed [1]-[3].

In what follows the application of a novel miniaturized slot-line resonator which shows a relatively high Q for the design of different filter types is considered. The basic architecture of these resonators is the basis for a class of miniaturized planar antennas considered for integration on a wireless chip [4]–[6]. For the antenna design, a specific topology was considered to enhance radiation from the antenna structure. However, for the application at hand the resonator topology is modified so that the radiation from different segments of the slot-line resonator would cancel each other in the far-field region and thereby a high-Q non-radiating resonator is achieved.

The ultimate goal here is to incorporate a high efficiency miniaturized on-chip antenna design with the proposed high performance slot-line miniaturized filter to achieve a superior RF front-end performance for mobile wireless devices. The authors have proposed extremely miniaturized slot antenna structures for mobile wireless applications, namely, a miniaturized folded slot antenna [4], and an inductively loaded miniaturized slot antenna [5], which are shown in Figs. 1 and 2, respectively. The dimensions of these two antennas are as small as $0.067\lambda_0 \times 0.067\lambda_0$ and $0.05\lambda_0 \times 0.05\lambda_0$, respectively. These antennas were also shown to be perfectly matched without

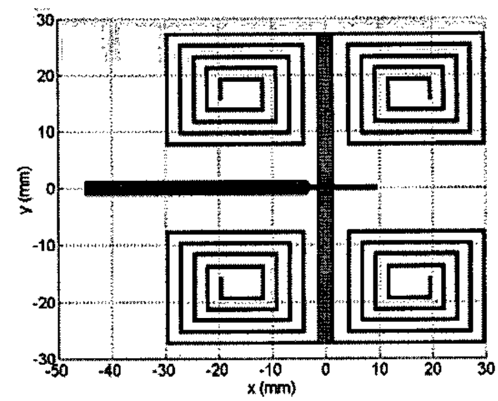

Fig. 2. Schematic of a miniaturized inductively loaded slot antenna fed by a microstirp-line.

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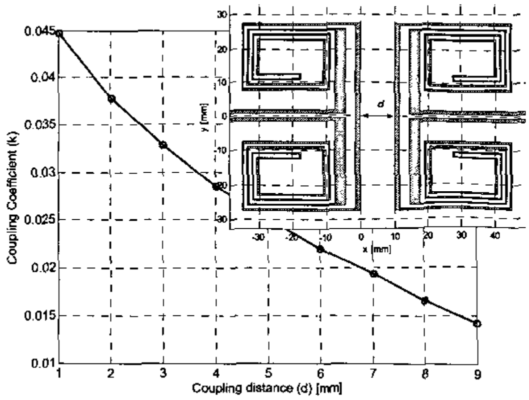


Fig. 3. Extracted coupling coefficient for the back-to-back miniaturized folded slot resonators configuration.

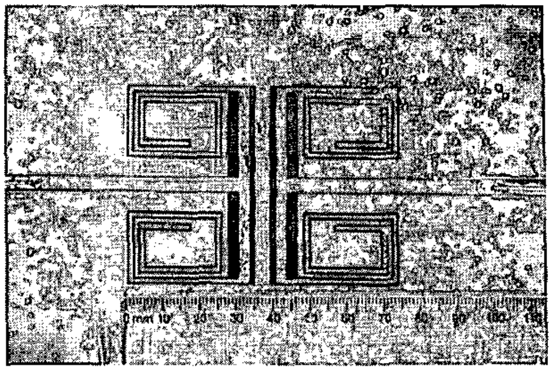


Fig. 4. Photograph of the two-pole filter at 515MHz.

having used any resistive loading, and are therefore, highly efficient. The high efficiency of these antennas indicates that the proposed slotted structures are very good choices for designing low insertion-loss band-pass filters.

In this paper preliminary results related to the design procedure and performance evaluation of the proposed miniaturized filters are demonstrated.

II. Design Procedure

A band-pass filter may be characterized by a set of internally coupled resonators (not necessarily identical) all resonating at the same frequency, and an external quality factor denoting the input and output couplings. The couplings between resonator pairs and the input/output coupling are represented by k_{ij}, and Q_{ext}, respectively. The coupling coefficient between two resonator pairs is extracted from the full-wave simulation of the two-port structure [7], using the pole-splitting method [8]. In the pole splitting method, a relationship is established between the frequency separation of the poles, and the coupling coefficients. Given that f_u and f_l are the frequencies at which the S21 reaches its peak values, the coupling coefficients can be obtained from:

$$k = \frac{f_u^2 - f_l^2}{f_u^2 - f_l^2} \qquad (1)$$

The external quality factor can be characterized using the full-wave simulation of the excited input or output resonators. The external coupling can be expressed in the form of:

$$Q_{ext} = \frac{f_0}{\delta f_{-3dB}}, \qquad (2)$$

where in the above f_0 and δf are the resonant frequency and the –3dB bandwidth of the input and output resonators, respectively. The extracted external couplings obtained from the full-wave Method of Moment (MoM) simulation for slotted structures, however, are not very accurate since the size of the substrate and ground plane is assumed to be infinite, and also the slot ground plane is considered a perfect electric conductor. Thus, the external coupling needs to be fine-tuned experimentally.

III. Miniaturized Folded-Slot Band-pass Filter

Figure 3 shows the schematic of two coupled folded miniaturized resonators, which are inductively excited. The coupling coefficient of this structure is extracted from the full-wave simulation data and plotted in Fig. 3 as a function of resonators' distance (d). Since the two resonators are very compact, two different mechanisms contribute to the coupling between them, and in general both electric and magnetic coupling are present. In this configuration, however, the electric coupling is dominant. The external couplings of these resonators can be controlled by introducing an impedance step between a 50Ω CPW line and the folded miniaturized slot [1].

As the first example, a two-pole band-pass Chebyshev filter with the fractional bandwidth of Δ=2.5% at the frequency of 515 MHz, and pass-band ripple of 0.15 with the return loss of less than −15dB is considered. The required coupling coefficient and external quality factor of this filter is found to be $k=0.0317$, and $Q_{ext}=38.02$, respectively [9]. The coupling coefficient between the two resonators can be realized using the data provided in Fig.3, and the distance between the two resonators is found to be $d=4mm$. This filter was fabricated on a RT5880 Duroid [10] substrate with ε_r=2.2, and $tan(\delta)$ = 0.0009. Fig. 4 shows the photograph of this filter.

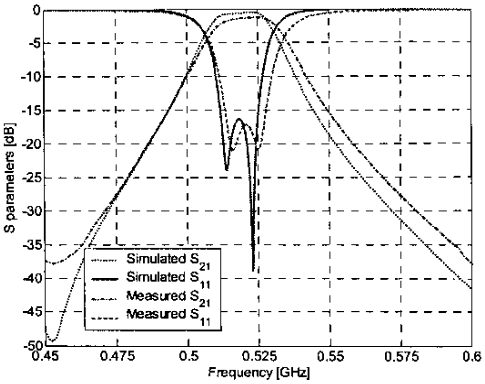
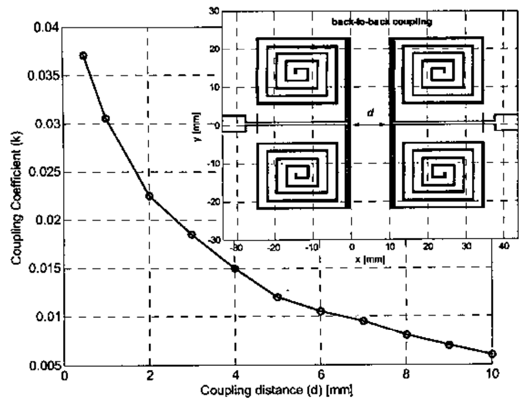


Fig. 5. Comparison between the simulated and measured frequency responses of the filter in Fig. 4.

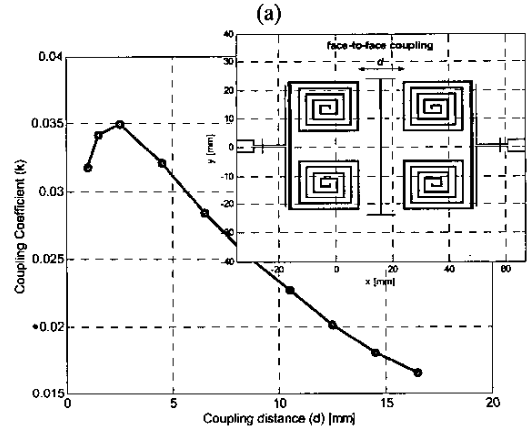
The simulated and measured frequency responses of this filter have been compared in Fig. 5, where a very good agreement between the two is observed. This filter can be fit in a rectangular area of $0.09\lambda_0 \times 0.12\lambda_0$. The minimum insertion loss of this filter is measured to be 1.2dB. As mentioned earlier the MoM simulation used here cannot model the metallic loss of the structure and that is why there is a slight difference between the insertion loss predicted by the simulation and the measured one.

III. MINIATURIZED SLOT-LINE BAND-PASS FILTER

The next example entails a four-pole miniaturized band-pass filter design, with a bandwidth of Δ=3.0% at about 390MHz. In this example, the inductively loaded miniature resonators [2] are employed. The size of each single resonator, used to design this filter, is $0.032\lambda_0 \times 0.058\lambda_0$ where λ_0 is the free space wavelength at the center frequency. The miniaturized resonator pairs, in this filter structure, are coupled in back-to-back and face-to-face configurations. Each of these configurations has been studied, and its corresponding coupling coefficients were extracted. Fig. 6(a) and 6(b) show the schematic of these two configurations, in addition to the extracted coupling coefficients. A slot incision is introduced in the face-to-face coupling configuration to reduce the coupling between the resonator pairs, without having to increase the separation between the pairs, and therefore, to achieve a more compact design. Fig. 7 depicts the photograph of this filter fabricated on a RT58850 Duroid substrate similar to the one used for in the previous example. The dimensions of this four-pole filter are as small as $0.058\lambda_0 \times 0.15\lambda_0 = 0.009\lambda^2_0$ at the center frequency. A comparison of the measured and simulated frequency responses of this filter is illustrated in Fig. 8, where a very



(a)



(b)

Fig. 6. Extracted coupling coefficients for two different coupling configurations: (a) back-to-back configuration; (b) face-to-face configuration with an incision.

good agreement is observed. In this example, an insertion loss of 3.7dB is achieved. Obviously, because of introducing an incision in the face-to-face coupling configuration, a zero associated with the mixed electric and magnetic couplings appears in one side of the rejection band. Note that the observed zero here is coming from a mechanism different than that for an elliptical filter, while in elliptical filters, the pass-band zeros are the results of the cancellation of multi-pass signals through different resonators.

V. CONCLUSION

In this paper, two novel miniaturized slot-line resonator structures were proposed. The slot-line and folded slot-line miniaturized resonators were shown to be excellent candidates to design low insertion-loss band-pass filters. Moreover, the size of these resonators can be varied depending on the magnitude of the inductive loading of the resonator with a moderate decrease in the resonators'

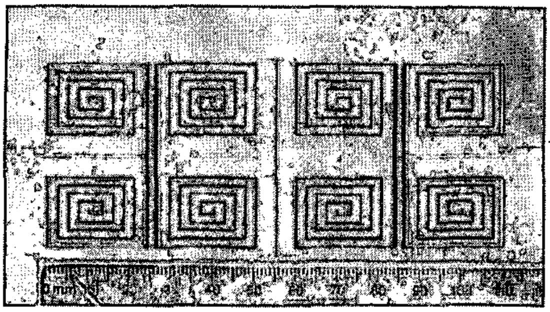


Fig. 7. Photograph of the four-pole miniaturized slot-line filter.

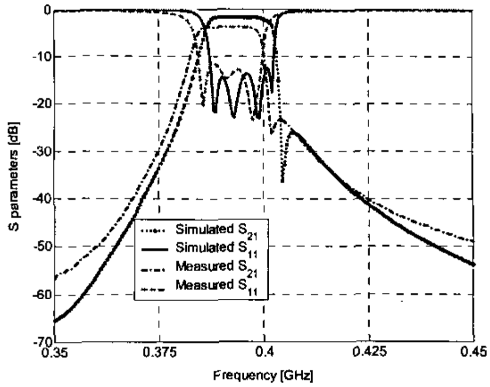


Fig. 8. Comparison between simulated and measured frequency responses of the filter shown in Fig. 7.

Q. Different types of coupling mechanisms, including electric, magnetic, and mixed coupling is feasible by proximity and only depending on the mutual orientation of the resonator pairs. A few of these coupling configurations were characterized and employed to design two prototype filters. One was a two-pole band-pass filter with a fractional bandwidth of Δ=2.5% at 515MHz and an insertion loss of 1.2dB, which only occupies an area as small as $0.09\lambda_0 \times 0.12\lambda_0$. The other example is a four-pole band-pass filter with Δ=3.0% at 400MHz, with an insertion loss of 3.7dB, and dimensions of $0.058\lambda_0 \times 0.15\lambda_0$.

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