A new miniature Peano fractal-based bandpass filter design with 2nd harmonic suppression

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A New Miniature Peano Fractal-Based Bandpass Filter Design with 2nd Harmonic Suppression

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Abstract—A new compact microstrip bandpass filter design is presented in this paper as a candidate for use in modern wireless communication systems. The proposed filter structure is composed of two fractal-based microstrip resonators. The structure of each resonator is in the form of the 3rd iteration Peano fractal curve. The resulting filter structure based on these resonators, shows a considerable size reduction compared with the other microstrip bandpass filters based on other space-filling geometries designed at the same frequency. A second bandpass filter design based on the same resonator but with a tuning stub has been also presented, in an attempt to provide practically useful means to tune the filter to the specified performance with a considerable tuning range. The performance of the resulting filter structures has been evaluated using a method of moments (MoM) based electromagnetic simulator IE3D, from Zeland Software Inc. Results show that the proposed filter structures possess good return loss and transmission responses besides the size reduction gained, making them suitable for use in a wide variety of wireless communication applications. Furthermore, performance responses show that the second filter, based on Peano shaped resonator with stub, has less tendency to support the 2nd harmonic.

Keywords— Microstrip bandpass filter; filter miniaturization; Peano fractal curve geometry; 2nd harmonic suppression

I. INTRODUCTION

A wide variety of applications for fractal has been found in many areas of science and engineering, since the pioneer work of Mandelbrot [1]. An example of such area is fractal electrodynamics [2] in which fractal geometry is combined with electromagnetic theory for the purpose of investigating a new class of radiation, propagation, and scattering problems. One of the most promising areas of fractal electrodynamics research is its application to the antenna and microwave circuits design.

Fractals represent a class of geometries with very unique properties that can be attractive for microwave circuit designers. Fractal space filling contours, meaning electrically that large features can be efficiently packed into a small area. Since the electrical lengths play such an important role in microwave circuit design, this efficient packing can be used as a viable miniaturization technique. The space filling properties lead to curves that are electrically very long, but fit into a compact physical space. This property can lead to the miniaturization of antenna elements.

Recent development in wireless communication systems has presented new challenges to design and produce high-quality miniaturized components. These challenges stimulate microwave circuits and antennas designers to seek out for solutions by investigating different fractal geometries.

Among the earliest predictions of the use of fractals in the design and fabrication of filters is that of Yordanov et al., [3]. Their predictions are based on their investigation of Cantor fractal geometry. Hilbert fractal curve has been used as a defected ground structure in the design of a microstrip Lowpass filter operating at the L-band microwave frequency. Based on this fractal curve, compact high temperature superconductor microstrip bandpass resonator filters have been designed for wireless communication applications [4]. Sierpinski fractal geometry has been used in the implementation of a complementary split ring resonator [5]. Split ring geometry using square Sierpinski fractal curves has been proposed to reduce resonant frequency of the structure and achieve improved frequency selectivity in the resonator performance. Koch fractal shape is applied to mm-wave microstrip bandpass filters integrated on a high-resistivity substrate [6]. Results showed that the 2nd harmonic of fractal shape filters can be suppressed as the fractal factor increases, while maintaining the physical size of the resulting filter design [7].

It is worth to note here, that most of the previously mentioned fractal geometries have been first applied to design compact size multiband antennas. In this context, the Peano fractal curve has been successfully used in
producing multiband compact antennas [9-12]. Up to the author's knowledge, it has not been yet reported in the literature to use such a fractal curve in the miniaturization of microstrip bandpass filters.

In this paper, a novel narrow-band microstrip bandpass filter design has been presented for use in the modern compact communication systems. Based on the 3rd iteration Peano fractal curve geometry, a 2nd order Chebyshev bandpass resonator filter has been designed at a frequency of 1.95 GHz with a fractional bandwidth of 10%. The resulting filter has been found to possess a considerable miniaturization owing to its remarkable space-filling property together with good transmission and return loss responses.

II. THE PEANO FRAC TAL CURVE

The Peano curve, proposed by Peano in 1890, was, in fact, the first set of space-filling curve [9]. One interesting feature of the Peano-curve algorithm is that it has a relatively higher compression rate than the Hilbert-curve algorithm in filling a 2-D region, which suggests that the Peano resonator may resonate at a lower fundamental resonant frequency than a comparable Hilbert resonator of the same iteration order \( k \). This fact has been outlined in Fig. 1; where the steps of growth up to the 3rd iteration are shown for Peano (Fig. 1a) and Hilbert (Fig. 1b) pre-fractal curves respectively. In both cases, the fractal curve is fit in a square with a side length \( S \).

For a Peano resonator, made of a thin conducting strip in the form of the Peano curve with side dimension \( S \) and order \( k \), the length of all the line segments \( L(k) \) is given by [9]

\[
L(k) = (3^k + 1)S
\]  

(1)

![Figure 1. The first three steps of growth for (a) Peano and (b) Hilbert pre-fractal curves.](image)

Generally, in order to fit the resonator in the smallest area, this requires increasing the iteration level of the space-filling curve as much as possible. However, it has been found that, when dealing with space-filling fractal shaped microstrip resonators, there is a tradeoff between miniaturization (curves with high \( k \)) and the quality factor of the resonator. For a microstrip resonator, the width of the strip \( w \) and the spacing between the strips \( g \) are the parameters which actually define this tradeoff [5]. Both dimensions \((w, g)\) are connected with the external side \( S \) and iteration level \( k \), for \( k \geq 2 \), by

\[
S = 3^k (w + g) - g
\]  

(2)

This equation implies that trying to obtain higher levels of fractal iterations will lead to lower values of the microstrip width, thus increasing the dissipative losses with a corresponding degradation of the resonator quality factor. Hence, for these structures, the compromise between miniaturization and quality factor is simply defined by an adequate fractal iteration level. However, it has been concluded, in practice, that the number of generating iterations required to reap the benefits of miniaturization is only few before the additional complexities become indistinguishable [13].

III. FILTER DESIGN

At first, a single 3rd order Peano microstrip resonator with \( w/g = 1 \) has been modeled to resonate at a frequency of 1.95 GHz. For the purpose of comparison with 4th order Hilbert microstrip resonator reported in [5], the Peano resonator has been assumed to be patterned on YBCO thin film on MgO substrate. The material properties of the MgO are: the relative dielectric constant \( \varepsilon_r = 9.6 \), thickness \( h = 0.508 \text{ mm} \), and loss tangent of \( 10^{-6} \). The resulting 3rd order Peano resonator has been found to resonate at the specified frequency when it has the dimensions of \( w = g = 75 \) microns and \( S = 3.5 \text{ mm} \) (about 0.055 \( \lambda_g \) where \( \lambda_g \) is the guided wavelength) which is slightly less than that realized by the 4th order Hilbert microstrip resonator in [5].

The design strategy adopted in this work is that developed by Swanson [14]. Swanson combined the concepts of Dishal [15], the EM simulation, and the port tuning method to outline a general and powerful procedure for a narrow-band multi-resonator filter design. Dishal's design method for narrow-band filters offers a very simple and intuitive approach that can be applied to different filter technologies and topologies. It makes use of measured experimental hardware to generate two design curves. Based on these design curves, a complete Chebyshev bandpass multi-resonator filter structure with the required order and specifications can be obtained in a very efficient and potentially more accurate way, compared with the older experimental method [14].

According to this design strategy, two design curves have to be generated. The first design curve is for coupling coefficient as a function of distance between
two resonators that are tuned to the center frequency of the filter and the second design curve maps external quality factor to the position of the tap on the resonator. Once these design curves are available for a particular topology, it is a simple matter to map the desired coupling coefficient, $K$, and the external quality factor to physical dimensions. Some dimension adjustments are required in the filter prototype. Only one design curve can be extracted for the Peano bandpass filter presented in this paper. This curve will correlate the coupling coefficient of the resonators with the distance between them. The other curve, which correlates the feed tap positions with the external quality factor, cannot be extracted. This is attributed to the fact that the Peano resonator cannot provide a continuous physical contact with the feed taps along its whole length as in the case of quarter wavelength resonators used in parallel-coupled or hair-pin microstrip bandpass filters. Instead, manual tuning has to be carried out of the tap positions along the side lengths of the two resonators of the resulting filter prototype and monitoring the filter responses until reaching the required performance.

For the proposed filter design, it has been postulated that the filter is with an $N = 2$, centered at $1.95$ GHz, with a $10\%$ fractional band-width. The lowpass prototype ripple level is $0.036$ dB (20.8 dB return loss). No specific insertion loss or stopband rejection goals were set for this design. Additional tuning for the inter-resonator spacing and the feeding tap positions has been carried out, in an attempt to reach design specifications. The major tuning variables are the resonator spacing, and the tap position. Fig. 2 shows the layout of the resulting modeled filter. The filter occupies an overall area of $3.5$ mm $\times$ $7.65$ mm with the previously stated Peano resonator dimensions and spacing between the resonators of $0.55$ mm.

**IV. Performance Evaluation**

The 2nd order Chebyshev bandpass filter model has been built in a MoM-based EM field solver, IE3D, from Zeland Software Inc., [16]. A suitable grid, in the EM solver, has to be chosen to make a good compromise between geometrical resolution and solution time. Fig. 3 shows the resulting filter performance curves after tuning. It is clear that this filter possesses a Chebyshev response centered at the specified design frequency with a fractional bandwidth of about $13\%$ and an in-band return loss of about $-23.5$ dB, enabling the filter prototype almost to meet the predetermined design specifications.

The bandpass filter, with the layout shown in Fig. 2, has been remodeled but with an additional stub connected to one end of each resonator, keeping the resonator side length $S$, the inter-resonator spacing and the tap positions constant. The stub length has been varied from zero (no stub exists) to a maximum value of $S$ (the resonator side length) in steps of one-third $S$. Fig. 4 shows the layout of the new filter.

Four projects, corresponding to the new filter with four different values of the added stub length, have been implemented in the EM solver. Fig. 5 demonstrates the transmission responses of the four cases. It is clear that the additional stub provides a useful tuning feature, where a stub of a length $S$ provides a tuning frequency range of about $120$ MHz, which is considered important in practise.
Furthermore, it has been found that, besides the frequency tuning the additional stub presents, it also affects the overall filter performance. Fig. 6 shows the out-of-band transmission responses of the two filters; with and without stubs. It is clear that, the filter with stubs offers better 2nd harmonic suppression than the other filter does.

V. CONCLUSION

A novel narrow-band microstrip bandpass filter design, for use in modern compact wireless communication systems, has been presented in this paper. This filter structure is based on microstrip resonators with 3rd iteration Peano fractal geometry. It has been found that this filter possesses a size slightly less than that offered by a bandpass filter based on 4th iteration Hilbert fractal curve.

It has been found that adding a stub to each resonator provides the designer with a practically useful means to tune the resulting filter response to the specified design frequency. Moreover, performance responses show that the new filter has less tendency to support 2nd harmonic. Results showed that, these filters possess a progressive size reduction with reasonable return loss and transmission responses.

REFERENCES