A MINIATURE HILBERT FRACTAL-BASED BANDPASS FILTER DESIGN WITH TUNING STUB AND 2ND HARMONIC SUPPRESSION

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ABSTRACT
A new compact microstrip bandpass filter design is introduced 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 Hilbert fractal curve geometry. Two microstrip single-mode resonators with structures based on the 3rd and 4th iteration Hilbert fractal-shaped geometries have been modeled at a design frequency of 2.4 GHz. The resulting filter structures based on these resonators, show considerable size reduction compared with the other microstrip bandpass filters based on other space-filling geometries designed at the same frequency. A second set of bandpass filter designs based on the same resonators 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 software package, Microwave Office 2007, from Advanced Wave Research 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 set of filters, based on Hilbert shaped resonators with stubs has less tendency to support the 2nd harmonic.

KEYWORDS:
Microstrip bandpass filter, Hilbert fractal curve, filter miniaturization, tuned microstrip bandpass filter
INTRODUCTION

Fractal geometry has found extensive applications in almost all the fields of science and art, since the pioneer work of Mandelbrot about three decades ago [Mandelbrot, 1983]. Among these fields are the physical and engineering applications. In electromagnetics, fractal geometries have been applied widely in the fields of antenna and passive microwave circuit design, due to the fantastic results gained in the miniaturization and the performance as well. Bandpass filter (BPF) is one of the most important components in microwave circuits. To meet the size requirement of modern microwave communications systems, compact microwave BPFs with narrowband is in high demand. Recently, there has been an increasing interest in planar BPFs due to their ease of fabrication. Filters using various planar resonators such as the open loop, miniaturized hairpin, stepped-impedance, quarter-wave, and quasi-quarter-wave resonators have been proposed for either performance improvement or size reduction.

Dramatic developments in wireless communication systems have imposed new challenges to design and produce high selectivity miniaturized components. These challenges stimulate microwave circuits and antennas designers to seek out for solutions by investigating different fractal geometries [Chen, et.al, 2007, Xiao, et.al, 2007, Wu, et.al, 2008].

Different from Euclidean geometries, fractal geometries have two common properties, space-filling and self-similarity. It has been shown that the space-filling property of fractals can be utilized to reduce filter size. Research results showed that, due to the increase of the overall length of the microstrip line on a given substrate area as well as to the specific line geometry,
using fractal curves reduces resonant frequency of microstrip resonators, and gives narrow resonant peaks [Crnojevic, et al., 2006, Kim, et al., 2006, Xiao, et al., 2007, Wu, et al., 2008]. 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 [Chen, et al., 2007]. Sierpinski fractal geometry has been used in the implementation of a complementary split ring resonator [Crnojevic-Bengin, et al., 2006]. 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. Results showed that the 2nd harmonic of fractal shape filters can be suppressed as the fractal iteration level increases, while maintaining the physical size of the resulting filter design [Kim, et al., 2006]. Minkowski-like and Koch pre-fractal geometries have been successfully used in producing high performance miniaturized dual-mode microstrip bandpass filters [Ali, 2008, Ali, et al., 2009]. In this paper, new microstrip bandpass filters, based on Hilbert fractal geometry, have been presented as a candidate for use in compact communication systems. The proposed single-mode bandpass filters have been found to possess compact sizes with accepted return loss and transmission responses.

**THE HILBERT FRACTAL CURVE**

The Hilbert fractal curve, as outlined in Figure (1), consists in a continuous line which connects the centers of a uniform background grid. The fractal curve is fit in a square section of $S$ as external side. By increasing the iteration level $k$ of the curve, one reduces the elemental grid size as $S/(2^k - 1)$. The space between lines diminishes in the same proportion. For a Hilbert resonator, made of a thin conducting strip in the form of the Hilbert curve with side dimension $S$ and order $k$, the length of each line segment $d$ and the sum of all the line segments $L(k)$ are given by [Barra, et al., 2004]:

$$L(k) = (2^k + 1)S$$

The main idea here is to increase the iteration of the Hilbert curve as much as possible in order to fit the resonator in the smallest area. 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 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 [Barra, et al., 2004]. Both dimensions ($w$ and $g$) are connected with the external side $S$ and iteration level $k$ ($k \geq 2$) by

$$S = 2^k(w + g) - g$$

From this equation, it is clear that trying to obtain higher levels of fractal iterations; this 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
FILTER DESIGN AND PERFORMANCE EVALUATION

At first, a single resonator based on the 3rd iteration Hilbert fractal geometry, has been designed at a frequency of 2.4 GHz. It has been supposed that the modeled filter structures have been etched using a substrate with a relative dielectric constant of 10.8 and a substrate thickness of 1.27 mm. The resulting resonator dimensions have been found to be 4.75 mm × 4.75 mm (which represents 0.1 λg × 0.1 λg), and a trace width of about 0.365 mm. The guided wavelength λg at the design frequency and the stated substrate parameters is calculated by [Hong, et.al, 2001, Chang, et.al, 2004]:

$$\lambda_g = \frac{c}{f \sqrt{\varepsilon_{\text{eff}}}}$$  \hspace{0.1cm} (3)

where $\varepsilon_{\text{eff}} = (\varepsilon_r + 1)/2$.

The same resonator with depicted dimensions and substrate specifications has been used to build a two-resonator microstrip bandpass filter. The input/output feed tab positions and spacing between the resonators are the most important parameters affecting the filter performance [Hong, et.al, 2001, Swanson, 2007]. The topology of this filter is shown in Figure (2). The overall dimensions of this filter are of about 4.75 mm × 9.9 mm. The corresponding return loss and transmission responses are shown in Figure (3).

The previous steps have been repeated, but now with a microstrip resonator based on the 4th iteration Hilbert fractal geometry, designed at the same frequency and using a substrate with the same depicted specifications. In this case, the resulting microstrip single-mode resonator has been found to possess an occupied area of about 3.1 mm × 3.1 mm, (which represents 0.066 λg × 0.066 λg). It is clear that the microstrip resonator based on the 4th iteration Hilbert fractal curve possesses a further size reduction of about 66% as compared with that based on the 3rd iteration. Figure (4) shows the topology of the resulting dual-resonator microstrip bandpass filter, where the overall dimensions in this case are of about 6.4 × 3.1 mm², with a trace width of 0.1 mm. The corresponding simulation results of return loss, S11, and transmission, S21, responses of this filter are shown in Figure (5). It is clear, from Figures (3) and (5), that the resulting bandpass filters based on the 3rd and 4th iterations Hilbert fractal geometries offer good quasi-elliptic transmission responses with transmission zeros that are symmetrically located around the design frequency with return losses are of about 13.2 and 9.08 dB and insertion losses of about 0.235 and 0.577 dB respectively.

FILTER DESIGN WITH TUNING STUB

The bandpass filters, with the layout shown in Figures (2) and (3), have 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. Figures (6) and (8) show the layout of the new filters based on the 3rd and 4th iterations Hilbert fractal geometries with stubs. 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-quarter S. Four projects, corresponding to the new filter with four different values of the added stub length, have been implemented in the EM solver. Figures (8) and (9) demonstrate 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 300MHz and 180 MHz for 3rd and 4th iteration respectively which are considered important in practice. Furthermore, it has been found that, besides the frequency tuning the additional stub presents, it also affects the overall filter performance. **Figures (10) and (11) show the out-of-band transmission responses of the two filters; with and without stubs for the 3rd and 4th iteration resonator filters respectively. It is clear that, the filter with stub offers better 2nd harmonic suppression than the other filter does. Inspection of Figures (10) and (11) reveals that, the presented filter in both iteration levels offer higher a resonant frequency when provided with a tuning stubs. This is attributed to the fact that the additional stub will make the overall length of the resonator larger, and hence resonates at a higher frequency. Appropriate dimension scaling might be carried out to bring the resonance to be at the design frequency. The proposed filter designs can be applied to many other wireless communication systems; the filter dimensions can easily be scaled up or down depending on the required operating frequencies.**

**CONCLUSIONS**

A two-pole microstrip bandpass filter design as a candidate for use in modern wireless communication systems has been introduced in this paper. The proposed filter structures have been composed of two coupled resonators based on 3rd and 4th iteration Hilbert fractal curves. Because of the significant space-filling property the proposed filter structure offers, the resulting filter topology has been found to possess a high degree of miniaturization with reasonable passband performance. Consequently, the proposed technique can be generalized as a flexible design tool for compact microstrip bandpass filters for a wide variety of wireless communication systems. Also, it has been found that adding a tuning stub to each resonator provides the designer with a practically useful means to tune the resulting filter response to the specified design frequency. With this stub a considerable tuning range of about 10% can be satisfied. Furthermore, performance responses show that both filters show less tendency to support 2nd harmonic which conventionally accompany the bandpass filter responses. In this context, the filters with stubs perform better than those without stub regardless of the fractal iteration order.

**REFERENCES**


Figure (1) Hilbert curve steps of growth: (a) 1\textsuperscript{st} iteration (b) 2\textsuperscript{nd} iteration (c) 3\textsuperscript{rd} iteration, and (d) 4\textsuperscript{th} iteration.

Figure (2) The layout of the two-pole microstrip bandpass filter based on the 3\textsuperscript{rd} iteration Hilbert curve geometry.
Figure (3) The return loss ($S_{11}$), and transmission ($S_{21}$) responses of the filter structure based on the 3rd iteration Hilbert curve geometry depicted in Fig. (2)

Figure (4) The layout of the two-pole microstrip bandpass filter based on the 4th iteration Hilbert curve geometry
Figure (5) The return loss ($S_{11}$), and transmission ($S_{21}$) responses of the filter structure based on the 4th iteration Hilbert curve geometry depicted in Fig. (4).

Figure (6) The layout of the modeled two-pole microstrip bandpass filter based on 3rd iteration Hilbert resonators with tuning stubs.
Figure (7) The transmission responses ($S_{21}$) of the filter structure based on the 3rd iteration Hilbert curve geometry with stub depicted in Fig. (6)

Figure (8) The layout of the modeled two-pole microstrip bandpass filter based on 4th iteration Hilbert resonators with tuning stubs.
Figure (9) The transmission responses ($S_{21}$) of the filter structure based on the 4th iteration Hilbert curve geometry with stub depicted in Fig.(8)

Figure (10) The out-of-band transmission responses of the proposed filters based on the 3rd iteration Hilbert curve geometry; with and without stubs.
Figure (11) The out-of-band transmission responses of the proposed filters based on the 4th iteration Hilbert curve geometry; with and without stubs