Reconfigurable Quasi-Fractal Transmission Line Structures

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***Abstract* — Several transmission line structures bearing fractal-like characteristics are presented. Using pin-diode switches, the transmission line structures can be reconfigured into quasi-fractal self-similar structures. The reconfigured structures closely resemble the pre-reconfigured transmission line structures both physically and electromagnetically, with the frequency response inversely proportional to the number of segments involved. Proposed quasi-fractal transmission line structures for both microstrip and coplanar waveguide are presented and biasing issues are discussed.**

I. Introduction

Fractal structures can be found in many facets of everyday life. For decades, scientists across various disciplines have studied honeycombs, snowflakes, and the human nerve network among others for the fascinating qualities their fractal characteristics bring. In the microwave regime, however, only a modest number of fractal applications have arisen so far. Samavati et. al. demonstrated a linear capacitor using fractal geometries with enhanced capacitance per unit area [1] while Saleh used self-similar slabs to design microwave filters [2]. Perhaps the most well-known use of fractals is in fractal antennas and arrays, both of which have been studied extensively for their low profile and wideband characteristics [3-4]. With all the potential benefits afforded by fractal structures, it would be advantageous to see whether or not fractal structures and their configurations can be applied to other microwave structures. In this paper, we analyze the feasibility of introducing fractal characteristics into various transmission line structures. We aim to do this by using switches to reconfigure the transmission line structures into quasi-fractal self-similar structures. The self-similarity would allow the transmission lines to exhibit frequency responses similar to the pre-reconfigured state but scaled, a property which is particularly useful for applications in antenna and filter design and in harmonic tuning to name a few. The reconfigurability offered by these proposed quasi-fractal transmission lines would enhance flexibility and make possible new and exciting topologies not possible with ordinary transmission line structures.

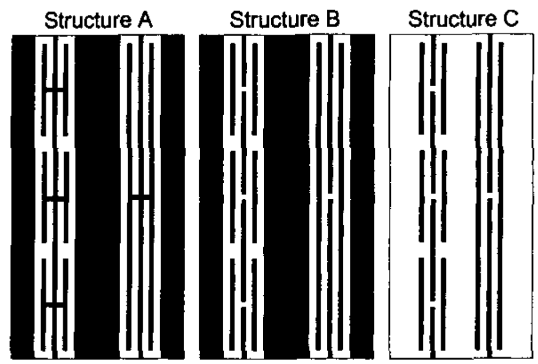

Fig. 1. Proposed quasi-fractal transmission line structures: Structure A: CPW bandstop, Structure B: CPW RBW bandpass, and Structure C: three-line microstrip bandpass. Original states appear to the left and proposed reconfigured states appear to the right.

II. Design Considerations

Although not all fractal objects share this trait, perhaps the most important aspect of most fractal designs is the self-similarity. Self similarity is the inherent trait which gives fractal antennas their multiband characteristics. Traditional fractal objects possess this trait naturally, or in its unperturbed state. In our proposed scheme, we aim to add self-similarity to transmission line structures which are inherently non self-similar. This can be done through the use of reconfigurability. Reconfigurable structures have garnered increased attention recently, particularly for antenna applications in order to reduce antenna size and to increase antenna functionality [5]. The first criterion in designing a quasi-fractal transmission line is to choose a structure which is well suited for this purpose. Periodic structures are ideal candidates, as their repetitious nature strongly suggests a close kinship to fractal structures. However, the definition of fractal as originally defined by Mandelbrot in [6] defines a fractal structure as a fragmented shape that can be subdivided in parts, each of which is a reduced-size copy of the whole. In this sense,

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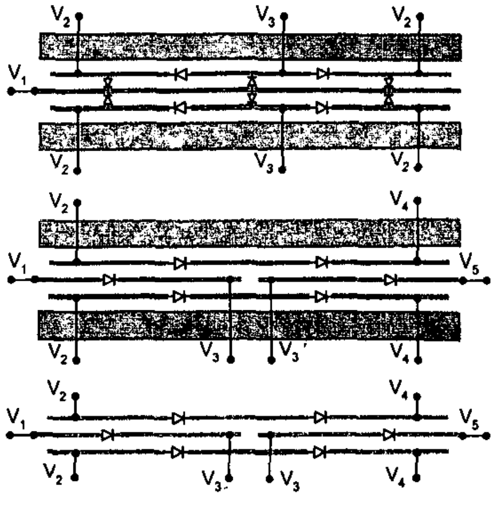

Fig. 2. Diode arrangement and biasing scheme of proposed quasi-fractal transmission lines.

TABLE I
QUASI-FRACTAL BIASING SCHEMES

Structure	V_1	V_2	V_3	V_4	V_5
A	+V	+2V	GND	N/A	N/A
B	NB	NB	NB	NB	NB
C	NB	NB	NB	NB	NB
A (rec.)	+V	+2V	GND	N/A	N/A
B (rec.)	+V	+V	GND	-V	-V
C (rec.)	+V	+V	GND	-V	-V

periodic structures must be distinguished from fractal structures. However, we will show that some periodic structures can be made fractal through reconfigurability.

To this end, we utilize three transmission line periodic structures depicted in Fig. 1. They are the CPW periodic slow-wave structure detailed in [7], the CPW RBW structure in [8], and the three-line microstrip structure which can be found in [9]. All three topologies are compact enough so that they require no more footprint than their equivalent 50Ω reference transmission line counterparts. In the original state, the each structure is a three-cell series cascade, each with some type of intrinsic filtering characteristic. When reconfigured, the structure transforms into a self-similar single unit cell whose length is three times the length of each original unit cell. Self-similarity can clearly be seen when comparing the original and reconfigured states. The switches used to implement

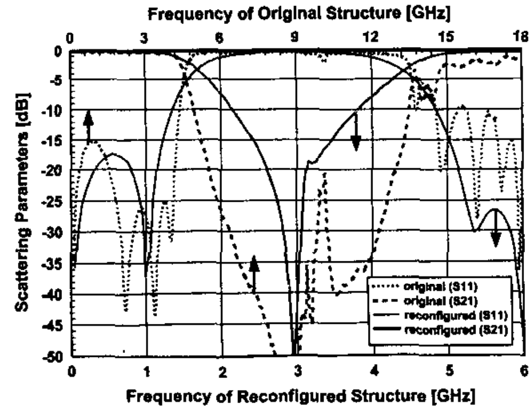

Fig. 3. Measured 3:1 frequency response of reconfigurable CPW bandstop filter (Structure A).

the reconfigurability may be implemented using MEMs or pin-diode switches. The layout and biasing schemes for the original and reconfigured self-similar states are presented in Fig. 2 and Table I, respectively. Note that NB in Table I stands for no bias.

III. MEASURED RESULTS

To demonstrate the viability of the proposed quasi-fractal structures, we first examine two cases where the proposed switching is implemented using ideal shorts. Structure A can be thought of as a 3:1 CPW bandstop filter. This periodic slow-wave structure has broad bandstop characteristics determined by the length of the unit cell. Both the original and reconfigured states of Structure A are fabricated on 50-mil RT/Duroid substrate with dielectric constant of 10.2. The stopband of this CPW periodic structure in the original state is designed to lie from 4.5 to 13.5 GHz. The reconfigured circuit replaces shorted switches with copper metallization for this proof-of-concept demonstration. In this ideal case, the diode short and open states in the reconfigured structure are being modeled as ideal shorts and opens. The measured results are overlaid and presented concurrently in Fig. 3. The 4.5 to 13.5 GHz stopband in the original structure is shifted downward exactly by a factor of three (to 1.5 to 4.5 GHz). This corresponds precisely to the 3 to 1 increase in unit cell length that reconfigurability brings. The rolloff of the reconfigured structure is not as sharp as in the original three cells, but this is as expected as we have one unit cell in the reconfigured state versus three unit cells in the original.

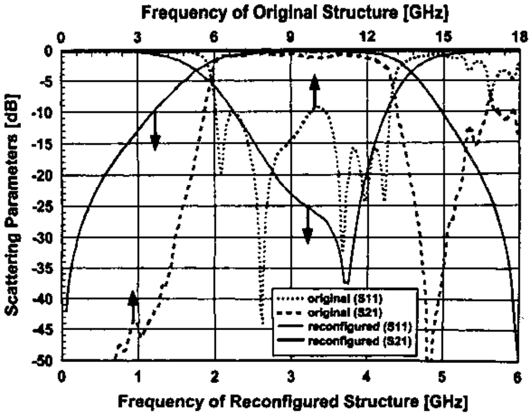

Fig. 4. Measured 3:1 frequency response of reconfigurable CPW RBW bandpass filter (Structure B).

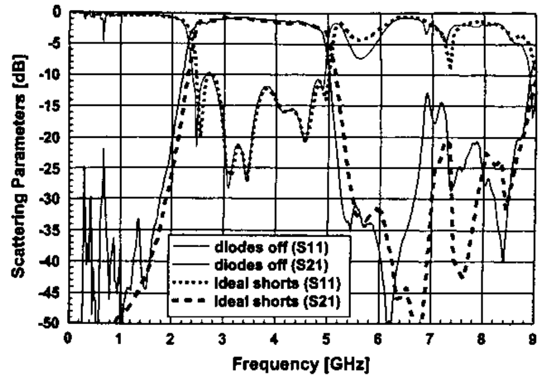

Fig. 5. Measured frequency response of reconfigurable microstrip bandpass filter with biasing circuit attached (Structure C) in original state.

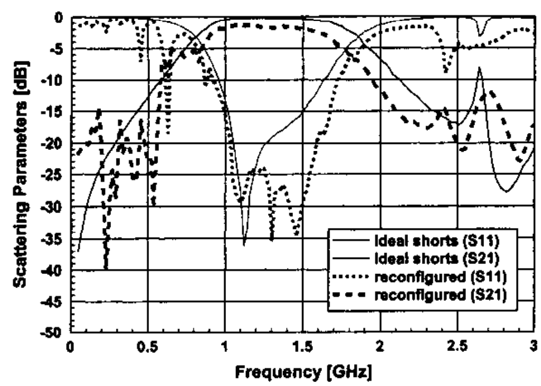

Fig. 6. Measured frequency response of reconfigurable microstrip bandpass filter with biasing circuit attached (Structure C) in reconfigured state.

To further validate these findings, both the original and reconfigured states of Structure B are also built on 50-mil RT/Duroid substrate with dielectric constant of 10.2. Structure B is a 3:1 CPW RBW bandpass filter that possesses a very broad passband. This broad passband is made possible by the enhanced edge capacitance provided by the three conductor configuration in comparison to a conventional two conductor configuration. Fig. 4 shows the measured results from both the original three-cell series cascade of the CPW RBW line and its ideally reconfigured structure. The original passband from 6 to 12 GHz is reconfigured precisely again by a factor of three (to 2 to 4 GHz). This again corresponds directly to the transformation from a series cascade of three unit cells to a single self-similar unit cell three times as long. It should be noted that although all structures shown in this paper have 3:1 topology, other configurations such as 2:1 and 4:1 are easily achievable. The results from both Structures A and B demonstrate how self-similarity allows us to shift frequency responses of transmission lines by integer multiples corresponding to the number of periods reconfigured. This results in very compact reconfigurable filters which offer much larger frequency tuning than conventional tunable filter schemes can afford.

IV. Biasing

A very important component of any non-passive microwave circuit is the biasing network. This is even more so for any reconfigurable circuit, where they may be a large number of switches and or switches in unconventional layouts. Quite often the biasing issue is largely overlooked or taken for granted. The circuit topology of the transmission line structures we have investigated are such that it is possible to achieve the desired reconfigurability if the diodes are laid out in the manner shown in Fig. 2, with the biasing following the scheme presented in Table I. To demonstrate the validity of these schemes and the effect the biasing network may have on circuit performance, Structure C is built on 100-mil RT/Duroid substrate with dielectric constant 10.2. Structure C is equivalent to Structure B, but implemented instead on microstrip transmission line. Like its CPW RBW counterpart, the three-line microstrip transmission line has broad bandpass characteristics. Due to the miniature size of the low-profile transmission lines, the biasing network must be designed so that any disturbance to the propagation along the quasi-fractal transmission line is minimal. Conventional laboratory wet-etching techniques limit the smallest reliable and reproducible line width to a few mils. This limitation prevents us from using traditional planar high impedance lines because the dimensions would be comparable to the line widths on the quasi-fractal transmission lines. Thus, bond wires with a 1-mil diameter are used to directly connect the quasi-fractal transmission line structures to a bias pad on the other end, to which the appropriate bias is then applied. Agilent Technologies HPND-4005 pin-diode switches are placed in the arrangement presented in Fig. 2 and the results are compared to that of an ideal reference structure with no biasing circuitry attached and the shorted diodes are replaced with ideal shorts implemented by copper metallization. Fig. 5 depicts the quasi-fractal transmission line in the original three-cell case for the third transmission line structure, with the bond wires and pin-diodes attached but not turned on because no biasing is required in this original state. The results show good agreement over most frequencies, indicating the biasing network has little effect on the response of the quais-fractal transmission line. In this original state, the broad passband ranges from 2.4 to 5.1 GHz. When the structure is reconfigured into a single self-similar unit cell, the frequency response again scales down precisely by a factor of three. This can be seen in Fig. 5, with the reconfigured passband ranging from 0.8 to 1.7 GHz. The insertion loss in the reconfigured passband is about 1.5 dB higher nominally than that of the ideal reference structure. This is not unexpected, since the pin-diodes are each rated to have an insertion loss of 0.4 dB in a series configuration. As technology progresses and the performance of pin-diode and MEMs switches improve, the performance of the circuit should improve. Some slight resonances near DC occur because the biasing bond wires cannot provide enough inductance between the quasi-fractal transmission line and the biasing pad. Nonetheless, the overall good agreement between the complete quasi-fractal transmission line and its ideal case indicate biasing in these proposed transmission lines can be implemented effectively.

V. Conclusion

The feasibility of using self-similarity for transmission lines was analyzed. Using the notion of reconfigurability, structures that were natively non-fractal in nature were given quasi-fractal characteristics in both the physical and electrical sense. Various examples were implemented on both microstrip and coplanar waveguide transmission lines. Biasing of the circuit, an issue largely ignored in previous reconfigurable topologies, was studied and a working quasi-fractal transmission line complete with biasing was demonstrated. Quasi-fractal transmission lines should find a wide variety of applications in microwave and millimeter wave circuits.

Acknowledgement

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