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Microstrip 3-Bit Fractal-based Phase Shifter

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***Abstract*— This paper presents the implementation of a 3-bit microstrip fractal-based phase shifter operating in the 430 MHz to 470 MHz frequency range. The fractal structure is used to confine different delay line lengths in the same area due to the space-filling properties of the used Hilbert fractal curve. The proposed design has three bits corresponding to 45, 90, and 180 degrees phase changes selected according to the switching circuit based on a Double Pole Double Throw (DPDT) switch implemented with PIN diodes. Comparisons between simulated and measured results are shown according to the chosen degree of use of PIN diodes.**

***Index Terms*— Hilbert's fractal, Miniaturization, Phase shifter, Switched-line.**

I. INTRODUCTION

In telecommunication applications, such as interferometry [1], antenna array [2], and frequency translators [3], it is often required that a signal is delayed in comparison to a given reference. A phase shifter is a two-port component that provides a variable phase shift to an incoming signal [2].

Phase shifters can be designed using various techniques such as couplers [4]-[5], MEMS [6]-[7], MMIC [8]-[9], FSS [10]-[11], etc. Microwave phase shifters can be constructed with embedded PIN diode switching elements to produce a reconfigurable phase shift. Compared with ferrite phase shifters, diode phase shifters have the advantages of small size, integrability with planar circuitry, and high speed [2].

The switched-line phase shifter is the most straightforward way to create a digital phase shifter. The signal is routed through one of two delay lines with different lengths using a DPDT switch made with PIN diodes. For a good quality dielectric substrate as Duroid Rogers 3010, the dielectric constant is stable in a wide frequency range (0 to 50 GHz) and the loss response presents linear behavior, so one can use the expression below with good approximation to calculate the phase delay (ϕ_d).

$$\phi_d = f\,\Delta\tau_n \times 360° \quad (1)$$

where f is the frequency of the signal, $\Delta\tau_n = \tau_{ref} - \tau_n$ with τ_{ref} being the reference line time delay and τ_n the longest time delay path.

One of the drawbacks of using switched delay lines is the large physical length required for large phase shifts, such as 180 degrees and can be used to confine long lines inside a limited area [12]-[16].

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In this implementation, the Hilbert fractal is used to compress the delay lines.

In order to serve a UHF antenna array system with a bandwidth of 10 MHz, this project was developed to operate with a central frequency of 450 MHz. Previous related work includes the simulation and concept with no experimental demonstration [17].

In this paper, the design, simulation, fabrication and measurements of a 3-bit switched line microstrip phase shifter corresponding to 45, 90, and 180 degrees phase shift is presented. To the best of the author's knowledge, there is no miniaturized 3-bit phase shifter based on the fractal Hilbert Curve in the literature.

II. PHASE SHIFTER DESIGN

The phase shifter design is based on three switched-line phase shifters connected in series; each delay line provides a different phase shift. One of the advantages of using this concept is that the phase shift depends only on the line length, thus the phase shift is linear with respect to frequency [18]. The concept of the traditional switched line phase shifter is shown in Fig. 1, using the first three iterations of the Hilbert fractal for miniaturization of the delay lines. Three phase delays are designed to provide 180, 90, and 45 degrees phase shifting.

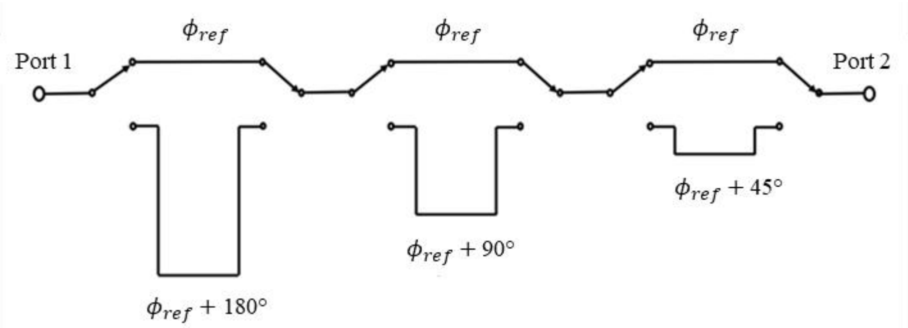

Fig. 1. 3-bit switched line phase shifter.

A. PIN diode Switch

The switching circuit design is based on a DPDT switch implemented with PIN diodes. An Infineon BAR50 diode is used. For simulations, the model shown in Fig. 2 is used. This model is the same used in [16] and was obtained from an optimizer software that compared the model's insertion and reflection losses to those provided by the manufacturer.

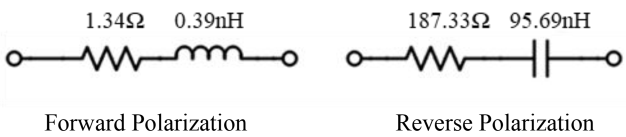

Fig. 2. The equivalent circuit model for forward and reverse biased PIN diode.

Fig. 3 shows the switching circuit in detail. Capacitors in series with the ports are used to block DC from RF components. Each bit is composed of four PIN diodes with the cathodes connected to the GND through an inductor to obtain the correct polarization of the diodes. A voltage Vn or -Vn is applied to the anodes, through inductors used as bias chokes to isolate the DC probes from the RF signal, the "n" represents the bit index (n = 1, 2, or 3). To obtain the phase shift, the voltage Vn must be greater than the Diode's knee voltage.

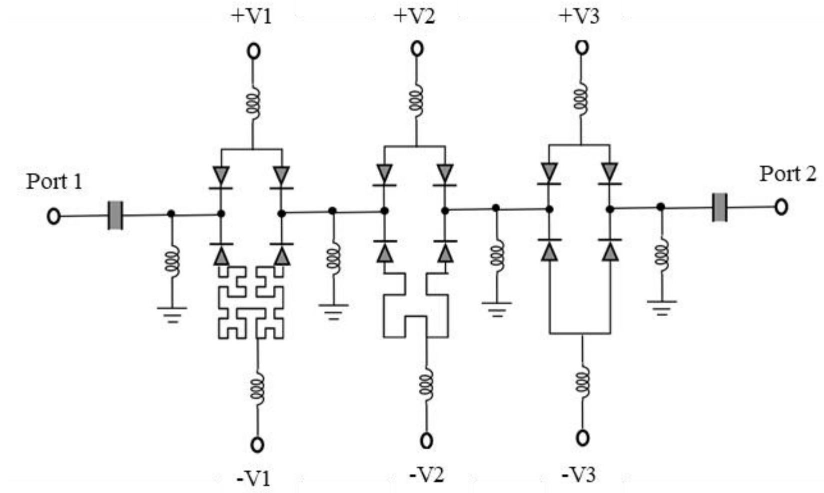

Fig. 3. Fractal phase shifter using PIN diodes.

B. Hilbert fractal-based phase shift

The device total size is defined by how the long delay lines are distributed in the printed circuit board. Hilbert's curve is known as a space-filling curve, in each iteration, the curve's length increases while the total area occupied by it remains the same [19]. Therefore, due to this space-filling property, all three bit lines occupy approximately the same area on the circuit board. Fig. 4 shows the proposed phase shifter design using Hilbert's fractal lines.

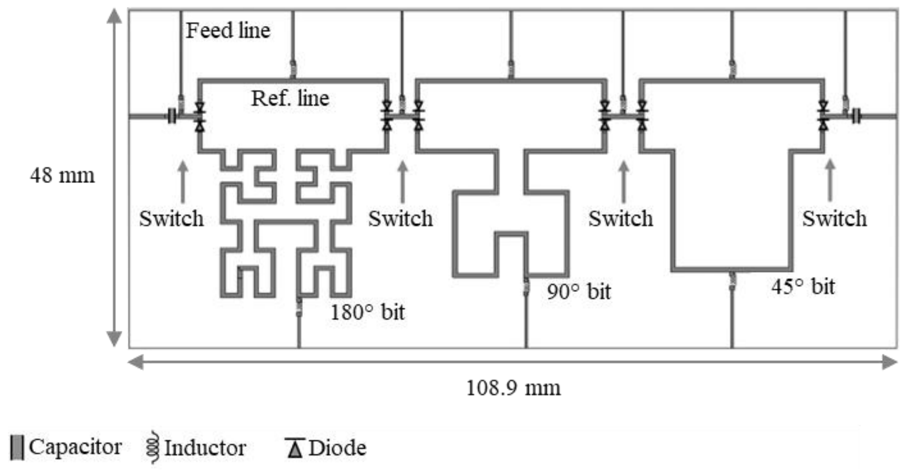

Fig. 4. Proposed fractal-based phase shifter.

The fractal phase shifter is patterned on a Rogers 3010 dielectric. The high dielectric constant of the Rogers 3010, 10.2, allows producing an even more compact design with a characteristic impedance of 50 Ohms and line widths of 0.6 mm.

III. RESULTS AND DISCUSSION

The phase shifter delay line lengths are defined and optimized through simulations using CST Microwave Studio and then fabricated using a CNC PCB prototyping machine. Fig. 5 shows the

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fabricated circuit.

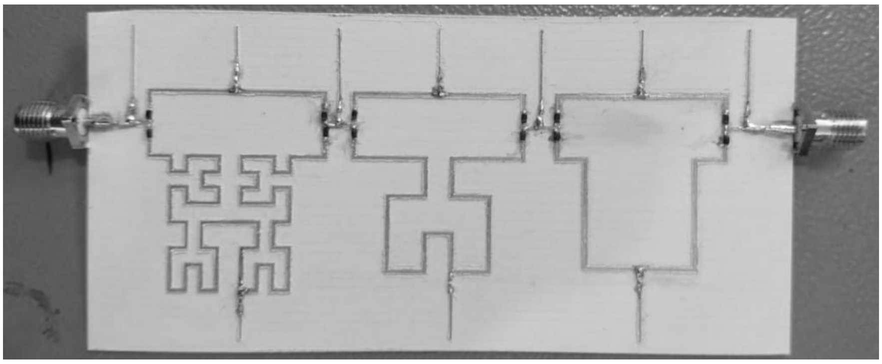

Fig. 5. Fabricated fractal-based phase shifter.

In the numerical analysis, the boundary conditions were configured as "open add space". This boundary condition simulates the experiment's environment where the device is surrounded by air. The simulated results for the phase shift showed that, as expected, the shift is linear with respect to frequency. At 450 MHz the phase shifts are 45.2, 90.9 and 181.5 degrees were obtained by selecting a bit at a given time.

The measurements were performed using the Agilent Technologies N9952A network analyzer, together with the calibration kit model 85033E, from the same manufacturer. Results for magnitude and phase of the scattering parameters were measured, but before the measurement process, the analyzer was properly calibrated by the SOLT (Short-Open-Load-Through) method in the frequency range from 430 MHz to 470 MHz, and the central frequency of 450 MHz.

The measured phase shifts for the 3 bits are 46.5, 89.5 and 139.3 degrees at the central frequency. In two of the three bits of the device, the shift was close to those estimated, with an error of 1.1 degrees for the first bit (45 degrees) and 1.4 degrees for the second bit (90 degrees). For the third bit (180 degrees) there is a 42.2 degrees error compared to the simulated results. Fig. 6 shows the comparison between the simulated and measured results for the phase shifter. Additionally, it is possible to notice that there was a variation in the slope of the curve, showing that for values further away from the central frequency of the device, the phase shift values differed from the simulation results.

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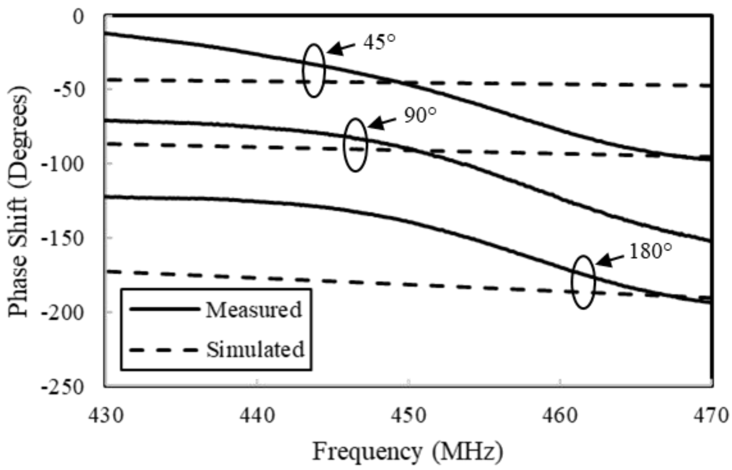

Fig. 6. Simulated and measured phase shift versus frequency.

The difference between the measured and simulated phase shifts in one of the bits may have occurred due to some resonance in the phase shift geometry; this is a known problem in switched line phase shifters [2]. One of the possible causes to explain the differences between the measured and simulated results is the dimension of the SMD components. In the simulation process, the discrete components are modeled as an infinitesimal line, where real physical dimensions of the components are not taken into account. Another cause would be the process of soldering the SMDs to the structure. Both cases introduce capacitances and inductances to the microstrip lines, producing differences between measured and simulated results.

The transmission coefficient (TC) also presented a significant difference between the measured and simulated. The Fig. 7 shows the measured and simulated results. While the simulated results present a TC of -6 dB, the measured one presents a TC ranging from -7.8 to -14 dB. Also here, differences could have been caused by the losses and resonant behavior introduced by soldering.

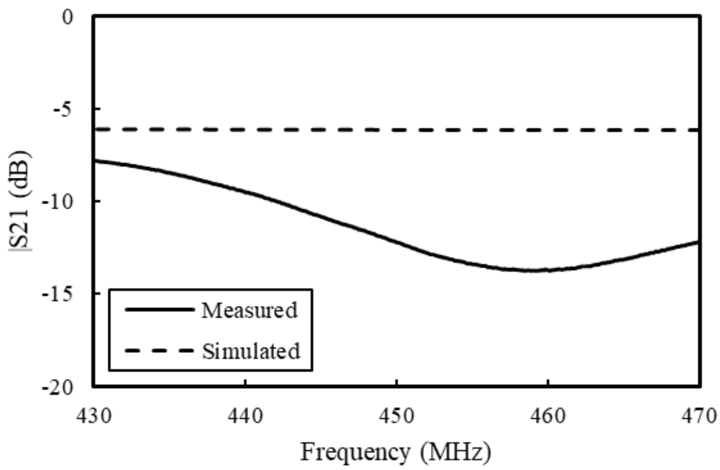

Fig. 7. Simulated and measured $|S_{21}|$ for its 0 degrees phase shift.

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Table I shows a comparison of this work with some other phase shifters presented in the literature. In [20], a 4-bit phase shift with only simulated results has low phase error at the center frequency of 2.45 GHz, but with a large circuit size. In [21], he presents a low-cost 4-bit reciprocal phase shifter in the 2.45 GHz ISM band with COTS components, which manages to reduce the size of the structure, but generates an increase in the phase error of 4.1°. In [22], a new method for phase shift design is presented using discrete components in high-pass, low-pass, band-pass and all-pass networks (APNs) in a frequency range of 530 to 1090 MHz, which is similar to the frequency range of the phase shifter proposed here.

TABLE I. COMPARISON OF PIN DIODE SWITCHED PHASE SHIFTERS.

Comparison	This paper (simulated)	This paper (measured)	[20]	[21]	[22]
Area / λ [cm]	78	78	400	212	N/A
Freq. Range [MHz]	430-470	430-470	2300-2600	2300-2600	530-1090
Phase error [º/MHz]	0.46*	2.6*	0.6	0.01	> 5,9
Resolution (bits)	3	3	4	4	4
IL** range [dB]	6	7.8-14	< 4	< 8.8	2.5

* Simulated result at the 180º bit.
** Insertion loss.

One of the significant advantages that we can observe in the device proposed here is that it has the smallest area/wavelength ratio, that is, it occupies a smaller area per wavelength than the other phase shifters in Table I. This indicates that Hilbert fractal geometry can be used to design more compact phase shifters.

IV. CONCLUSION

The design, simulation, and measurements of a 3-bit switched-line microstrip phase shifter are described in this work, with an operating frequency range from 430 MHz to 470 MHz. The proposed design miniaturization is obtained from the use of delay lines with different lengths confined in a fixed area. Measured and simulated insertion loss for the reference state were presented and they were in good agreement. Considering the frequency response at 450 MHz, the measured results for the phase shift are in agreement with the simulation results, showing a difference of less than 3.5% for the 45 and 90 degrees phases referring to bits 2 and 3 of the device. The third bit (180 degrees) presented the largest difference of 42.2 degrees between the measured and simulated results. Variations between the measured and simulated results could be related to the soldering of discrete components. At the designed frequency, the manufactured device presented a satisfactory performance close to the projected one. Furthermore, in comparison with other works, it was demonstrated that the use of the proposed fractal geometry can result in a greater degree of miniaturization of the device. The next steps will involve improving the welding process and designing a four-bit phase shifter.

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