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Compact antenna array comprising fractal-shaped microstrip radiators

***Abstract**. A design method of antenna array consisting of eight microstrip patches modified with Sierpinski fractal curves has been presented and experimentally validated in this paper. Method proposed has enabled the achievement of considerable miniaturization of array length (26%), together with multi-band behavior of the antenna, which proves the attractiveness of presented design methodology and its ability to be implemented in more complex microstrip structures.*

***Streszczenie.** W pracy zaprezentowano metodykę projektowania ośmioelementowego szyku antenowego w technologii niesymetrycznej linii paskowej z wykorzystaniem promienników o brzegu zmodyfikowanym krzywą fraktalną w postaci krzyża Sierpińskiego. Zastosowanie nowego kształtu łat pozwoliło na gęstsze upakowanie elementów szyku prowadząc do jego 26% miniaturyzacji i poszerzenia pasma pracy. Wyniki eksperymentu wskazują na wielozakresową pracę zaproponowanego obwodu. (**Szyk antenowy z wykorzystaniem radiatorów o brzegu fraktalnym**).*

Keywords: fractal curves, Sierpinski, miniaturization, microstrip patch modification.
Słowa kluczowe: krzywe fraktalne, Sierpiński, miniaturyzacja, modyfikacja łaty mikropaskowej.

Introduction

For the past few years, considerable attention has been directed toward novel mobile devices, bringing forefront strong demands upon their multi-band and wideband properties. Due to a dynamic advancement in wireless communication industry, modern antenna components are continuously challenged with stringent requirements concerning their compact size, small weight, low profile, adequate beamforming or low cost of the production. Based on the simplicity of design and circuit implementation as well as their low cost, conventional microstrip patch antennas are found to be extremely useful in many nowadays wireless communication applications. However, such radiators suffer from narrow bandwidth and insufficient radiation pattern control [1]. Therefore, to overcome this limitation new antenna arrays enabling the achievement of modified radiation patterns as well as broadband or multi-band characteristics should be developed. It is noteworthy that high frequency circuits can be characterized by physical dimensions proportional to the operating frequency wavelength and, therefore, an application of antenna arrays becomes a serious obstacle in area-saving wireless communication designs. Efficient miniaturization of RF/microwave antenna circuits is a viable solution leading to a branch of novel mobile devices exhibiting adequate radiating properties.

To reduce the size of planar antenna circuits, numerous methods have been developed and reported throughout the years [2-7]. The implementation of various intentional defects in the patch metallization leads to a noticeable radiator minimization [2], however one can observe that such a technique decreases antenna resonant frequency and an additional antenna optimization is necessary. An alternative method of antenna size reduction is based on the application of a lumped element between ground plane and signal line metallization [3], however it is important to emphasize that such a solution adds complexity to the circuit. An interesting approach to antenna miniaturization involves the utilization of metamaterials [4, 5], however an artificial material construction leads to certain fabrication problems and its design process is a complex one. A viable solution to aforementioned limitations can be reached by means of fractal curve implementation efficiently shaping the geometry of the designed circuit. It has been reported, e.g. in [6, 7] that the application of space-filling fractal curves enables the achievement of considerable miniaturization, but also wideband or multi-band properties.

The following paper investigates a process of microstrip patch antenna miniaturization based on von Koch, Moore and Sierpinski fractal curves implementation [8]. Subsequently, a Sierpinski fractal-shaped patch antenna has been used to constitute eight-element linear antenna array.

Design of a microstrip patch antenna

A conventional microstrip patch antenna has been designed in IE3D E-M solver [9] on Taconic RF-30 substrate (ε_r = 3, h = 1.52 mm, tanδ = 0.0014) and designated for 11-GHz operating frequency. It has been taken into consideration that the adequate modification of microstrip patch edges using von Koch, Moore and Sierpinski fractal curves [8] should result from a trade-off between its electrical size and the geometric complexity of the design. The topology of a conventional microstrip patch antenna and its fractal-shaped counterparts are portrayed in Figure 1.

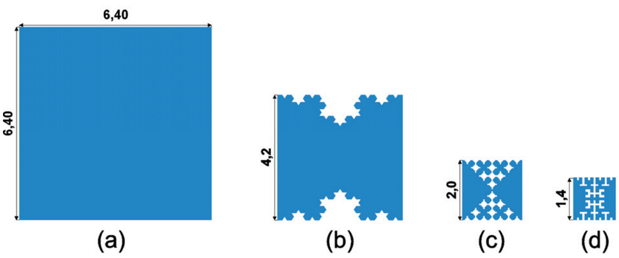

Fig.1. Layout of proposed microstrip patches: (a) reference structure; structures modified with 3rd iteration: (b) von Koch fractal curve (35% miniaturization); (c) Sierpinski fractal curve (69% miniaturization); (d) Moore fractal curve (78% miniaturization)

As presented in Figure 1, an adequate modification of the conventional patch topology results in various compact patch antenna designs maintaining the same electrical size. Their fundamental parameters have been collected in Table 1, where the bandwidth (BW) has been determined for $S_{11} \leq$ -10 dB.

The analysis of the data collected in Table 1 leads to a conclusion that the considerable miniaturization comes at a price of key parameters degradation. However, it is valuable to find an optimal solution that presents maximal miniaturization and, simultaneously, minimal parameter degradation.

Table 1. Collection of key parameters (BW - bandwidth, M - miniaturization, D - directivity, G - gain, E - efficiency) corresponding to the reference patch and miniaturized (Koch, Sierpinski and Moore) microstrip antennas

Design	BW [%]	M [%]	D [dBi]	G [dBi]	E [%]
Fig. 1a (reference)	6.9	0	7.01	5.45	68.7
Fig. 1b (Koch)	3.73	35	6.89	5.19	67.6
Fig. 1c (Sierpinski)	1.03	69	6.69	4.46	59.8
Fig. 1d (Moore)	0.75	78	6.7	3.94	58

Design of an antenna array

A Sierpinski fractal-shaped patch antenna (see Fig. 1c) presents the greatest scale of size reduction among investigated structures under condition of the minimal degradation of parameters collected in Table 1. In order to improve transmission characteristics of the radiator under consideration, a concept of antenna array has been proposed. A Sierpinski fractal-shaped patch has been chosen to constitute a linear eight-element antenna array fed by aperture coupling (see Fig. 2b). An antenna array consisting of conventional microstrip patches has been also designed for comparison purposes (see Fig. 2a).

The main advantage of Sierpinski fractal curve-based antenna array is the improvement of the bandwidth with the reduction of the distance between adjacent radiators (see Tab. 2) as well as a considerable length miniaturization (26%). The collection of key parameters of both classic and miniaturized linear antenna array has been presented in Table 2. Moreover, one can observe that the variation of the distance between adjacent radiators has a minor impact on the radiation characteristics depicted in Figure 3.

Table 2. Collection of key parameters (d - distance between adjacent radiators, BW - bandwidth, D - directivity, G - gain, E - efficiency) corresponding to the classic antenna array (C) and the antenna array comprising fractal-shaped radiators (F)

	C	F	C	F	C	F
d [mm]	9.6		3.5		1.5	
BW [%]	13.2	1.55	11.45	3.1	4.42	3.77
BW [MHz]	1460	171	1260	348	488	415
D [dBi]	14.51	14.25	12.66	12.62	11.75	11.73
G [dBi]	12.57	11.86	10.91	10.46	9.89	9.68
E [%]	63.9	57.7	66.7	60.6	65.7	62.4

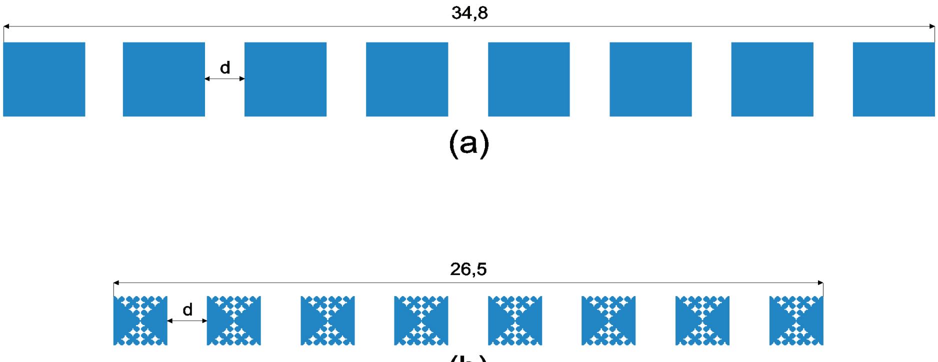

Fig.2. Layout of proposed antenna arrays (d = 1.5 mm): (a) array composed of classic square patches; (b) array constituted by radiators modified with Sierpinski fractal curves

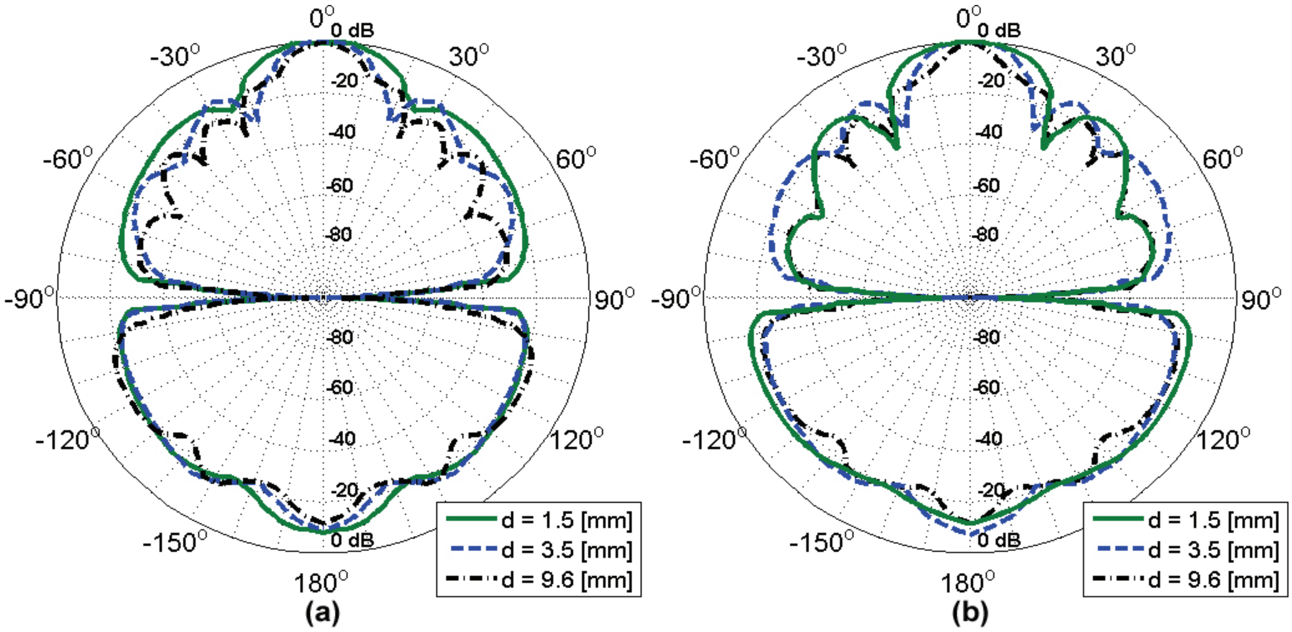

Fig.3. Eight-element antenna array radiation pattern: (a) patches modified with Sierpinski fractal curves; (b) classic patches

Experimental results

The linear antenna array comprising fractal-shaped radiators proposed in the previous section has been experimentally validated. The prototype has been fabricated on Taconic RF-30 substrate and measured. Figure 4 presents a comparison between simulated and measured results (reflection coefficient S_{11}) of the miniaturized antenna array. One may notice that the application of miniaturized radiators enabled the achievement of 26% of antenna array length reduction. Moreover, as a result of fractal curve implementation in the process of radiator edge modification, additional resonant frequencies have emerged (9.75 GHz and 12.75 GHz) leading to a multi-band behavior.

The measured elevation characteristics of the miniaturized antenna array portrayed in Figure 5 are in good accordance with the theoretical (simulated) results. The measured results indicate that the main lobe has been broaden by 10˚, while the fabrication inaccuracy of the feeding system (see Fig. 4) can be accounted for the asymmetry observed in the radiation pattern presented in Figure 5.

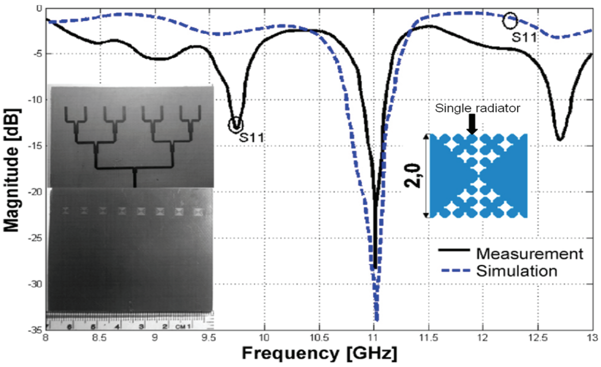

Fig.4. Reflection coefficient S_{11} of proposed antenna array consisting of 3rd iteration Sierpinski fractal-shaped patches

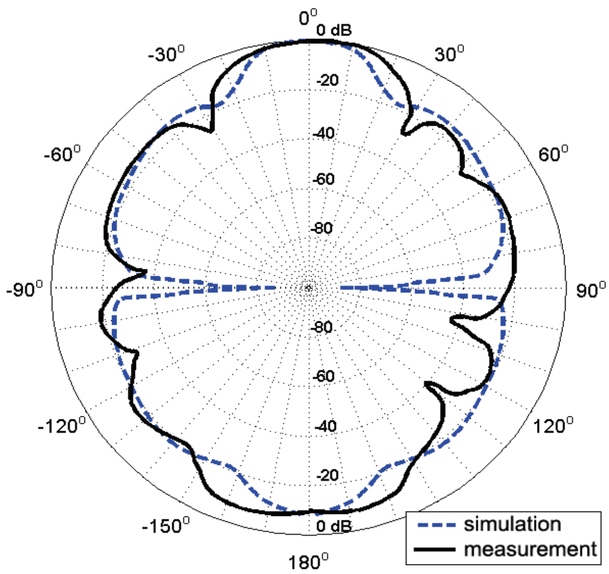

Fig.5. Comparison of radiation pattern of measured and simulated antenna array composed of Sierpinski fractal-shaped patches

Conclusions

The following article demonstrates a miniaturization technique dedicated to antenna arrays that involves the implementation of fractal curves in the process of radiator geometry modification. The investigation indicates that the selection of the adequate fractal curve and its properties (iteration, shape, dimensions etc.) is a trade-off between the scale of radiator size reduction and the degradation of its radiation parameters. To illustrate the possibilities of the approach a 3rd iteration Sierpinski fractal-shaped radiator has been chosen to construct an eight-element linear antenna array prototype. The measured results indicate that the application of the technique proposed has enabled the achievement of 26% of antenna array length reduction and additionally led to a multi-band behavior. Summarizing, the method presented is a universal and a promising tool adequate to design innovative layouts of RF/microwave components.

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