Conclusion: In single-fed microstrip antennas the narrow CPBW arises mainly from the difficulty of maintaining the proper excitation conditions and hence polarisation purity over a wide bandwidth. In this Letter, it has been made clear that the trade-off between good axial ratio and impedance bandwidth usually limits the designer in single-fed CP schemes, where techniques for achieving wideband polarisation techniques as well as wideband impedance features are important.

In summary, a new CP single-fed dual-band microstrip antenna has been described. The new geometry of the microstrip patch antenna has proven to be a flexible and CP dual-band element. This is particularly important for mobile communications systems where small size, light weight, low profile and low cost are often demanded in portable or pocket-sized equipment and vehicles. It is especially relevant when a flush-mounted or built-in antenna is required. It can also be applied to satellite systems where two channels are needed to receive/transmit the telecommand and telemetry signals (GPS receivers) or in a hand-held message communication terminal (HCMT).

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Multiband properties of a fractal tree antenna generated by electrochemical deposition

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Indexing terms: Fractals, Antennas, Electrochemistry

Experimental results on a fractal tree-like antenna are reported. The fractal structure is generated by electrochemical deposition. The antenna presents a multiband behaviour with a denser band distribution than the previously reported Sierpinski fractal antenna. The matched frequencies are related to the length distribution over the fractal shape.

Introduction: Fractal electrodynamics is a quite novel research area which relates fractals and electromagnetics. Jaggard *et al.* have recently described [1] the scattering and diffraction properties of some fractal bodies. Such fractal structures present some special features, not shared by common Euclidean shapes, which can be of interest when designing antennas. First, they have a complex, convoluted form that can properly enhance radiation [2, 3]. Secondly, fractals are usually self-similar structures, which means that several copies of the main shape are found at several scales within the fractal body. This property can be used to design multi-

frequency antennas [4] and arrays as was suggested by Puente *et al.* [5]. The Sierpinski antenna [6] was the first reported example of a fractal multiband antenna from both the input impedance and radiation patterns points of view.

Fig. 1 Fractal tree antenna and two blow-ups around feeding point

- (i) fractal tree antenna
(ii) blow-up of fractal structure

Here the authors introduce a novel approach to the design of fractal multifrequency antennas. The aim was to test a random fractal shape (Fig. 1) which had a denser distribution of sizes than the distribution featured by the Sierpinski antenna (log period = 2). It could be expected from such a multiple-scale structure that there could be a denser spectral behaviour as well, i.e. a more compact distribution of bands or even broadband behaviour.

Antenna generation and morphology: A monopole configuration on an 80 × 80cm square conductor ground plane was chosen to test the structure (Fig. 1). The fractal shape was obtained by means of a quasi-two-dimensional electrodeposition experiment. A deposit was grown from a thin layer of an aqueous electrolyte containing the metal ion to be deposited sandwiched between two glass plates. The nature and morphology of this kind of deposit range from fractal shapes to well-ordered dendrites, depending on the experimental conditions [7]. In this particular case, the electrochemical cell was formed by two glass plates (11 cm × 11cm × 5mm) separated by two copper wires of 100μm diameter. The electrode configuration consisted of a point-like cathode located 8cm from the centre of an 11cm long anode, parallel to a plate side. The electrolyte solution was a non-deaerated aqueous 0.05M copper sulphate solution prepared with ultra pure water supplied by a Millipore-Milli Q system and Merck quality p.a. copper sulphate. The electrodeposits were grown under a voltage of 12V between electrodes.

Once the aggregation process had been completed, an image of the deposit was taken with a CCD camera. The image was printed over a Cuclad 250 dielectric substrate ($\epsilon_r = 2.5$, $h = 1.588$ mm) using standard printed circuit techniques.

Fig. 2 Distribution of lengths over fractal tree (horizontal axis transformed to associated frequency)

- a Input reflection coefficient
b Resistance
c Reactance
d Of fractal tree monopole of same size
— monopole
— fractal tree

The fractal dimension (D) [8] of this structure was computed by means of MFRAC software [9] leading to a value of $D = 1.71$. It is interesting to notice the statistical self-similarity [8] of the tree as shown in the blow-up in Fig. 1. We can expand an inner region around the feeding point and still keep a similar shape to the overall tree. An expansion by a factor of a 7 still holds the main features of the structure and if the contribution of the smaller parts of the body to the radiation process at longer wavelengths is neglected, similar electromagnetic behaviour might be expected at a frequency 7 times larger than the smaller one.

Experimental results: The antenna input reflection coefficient (Γ_{in}) relative to 50Ω was measured from 900MHz to 8GHz using an HP8510B. The resistance and reactance of the input impedance along with Γ_{in} are shown in plots *b*, *c* and *d* of Fig. 2. The same parameters corresponding to a monopole of the same size (7.8cm) are also plotted in dash-dotted lines for comparison. The fractal tree clearly displays a rich spectral structure with many resonant frequencies and is well matched (VSWR < 2) to 50Ω at as many as 15 bands within the measured frequency range. The position of these bands can be related to the distribution of lengths over the fractal pattern as shown in the histogram of Fig. 2a. In such a histogram, the distribution of lengths was converted to frequency by assuming that each segment on the structure resonated at a wavelength four times its length. On the other hand, frequency independent behaviour cannot be stated for the fractal tree, but in general the tree is better matched than the monopole in the whole range because both the reactance and the resistance of the fractal keep a smaller deviation from 0 and 50Ω , respectively.

Fig. 3 Main cuts ($\phi = 0^\circ$) of radiation pattern at 15 matched bands
All plots are normalised (30dB dynamic range)

Fig. 4 Main cuts ($\phi = 90^\circ$) of radiation pattern at 15 matched bands
All plots are normalised (30dB dynamic range)

The radiation patterns were measured in an anechoic chamber at the 15 bands. The main cuts $\phi = 0^\circ$ and $\phi = 90^\circ$ for the E_0 component are shown in Figs. 3 and 4, respectively. It can be seen that the $\phi = 0^\circ$ cuts hold a notable degree of similarity among them,

up to 5GHz. Although the patterns at 4.94, 5.44 and 7.58GHz still keep a similar shape to the patterns at lower frequencies, they show a 10dB dip at $\theta = 60^\circ$. Conversely, the patterns of the $\phi = 90^\circ$ cut seem to randomly tilt from left to right through the bands, although the number of lobes are not significantly increased at larger frequencies. Such random behaviour can be related to the randomness of the fractal structure itself; the tree is not symmetrical with respect to the XZ plane and the active region extends to a different branch configuration when a contraction or expansion is produced at the highest frequencies. That behaviour was not held by the other cut due to the symmetry of the antenna with respect to the YZ plane. The randomness also becomes apparent from the polarisation point of view, since it is not held constant through the bands. A difference on the axial ratio as large as 25dB was measured among different bands.

Conclusions: The radiation properties of a random fractal aggregate generated by electrochemical deposition has been tested in a monopole configuration. The rich distribution of scales within the structure is clearly translated into multifrequency behaviour from the input reflection coefficient point of view. The distribution of frequencies has been shown to be related to the distribution of lengths over the antenna. In general, the radiation patterns are held to be similar through the bands, although the $\phi = 90^\circ$ patterns fluctuate from left to right in a random manner due to the XZ asymmetry of the fractal shape. The polarisation axial ratio also presents significant random behaviour. Alternative symmetrical or deterministic regular configurations might be suggested if further investigation on fractal tree antennas is carried out.

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