

Conclusions and Results of the FractalComs Project: Exploring the Limits of Fractal Electrodynamics for the Future Telecommunication Technologies

*J.M. Rius⁽¹⁾, J.M. González-Arbesú⁽¹⁾, J. Romeu⁽¹⁾, Á. Cardama⁽¹⁾, A. Heldring⁽¹⁾,
E. Úbeda⁽¹⁾, J.R. Mosig⁽²⁾, E. Cabot⁽²⁾, R. Gómez⁽³⁾, A. Rubio⁽³⁾, M. Fernández
Pantoja⁽³⁾, M. Giona⁽⁴⁾, P. Burghignoli⁽⁴⁾, G. Buggeda⁽⁵⁾, M. Riera⁽⁵⁾, J. Parrón⁽⁶⁾*

*(1)Electromagnetics & Photonics Eng. Group, Polytechnic University of Catalonia (UPC),
c/ Jordi Girona 1-3, Mòdul D3, Campus Nord, 08034 Barcelona (Spain)
email: rius@tsc.upc.es, jmgonzalez@tsc.upc.es*

*(2)Lab. of Electromagnetics & Acoustics, Federal Polytechnic Institute of Lausanne (EPFL),
Lausanne (Switzerland)*

*(3)Dept. of Electromagnetics and Physics of Matter, University of Granada (UGR),
Granada (Spain)*

*(4)Interuniversity Research Center for Disordered Systems and Fractals in Chemical Engineering and Dept. of Electronic Engineering, “La Sapienza” University of Rome,
Rome (Italy)*

*(5)International Center for Numerical Methods in Engineering (CIMNE),
Barcelona (Spain)*

*(6)Dept. of Telecommunications and Systems Eng., Universitat Autònoma de Barcelona (UAB),
Barcelona (Spain)*

INTRODUCTION

The FractalComs Project [1] was a basic research activity developed by the FractalComs consortium during a two years period (2002-2003) and founded by the European Commission through its *Future and Emerging Technologies* program included in the *Information Society Technologies* priority of the 5th Framework Programme. The main goal of the Project was the basic research on Fractal Electrodynamics to ascertain the fundamental and technological performance limits of fractal-shaped miniature devices for their potential use in the future wireless telecommunication systems.

The FractalComs consortium had five European partners: the Electromagnetics & Photonics Engineering Group of the Polytechnic University of Catalonia (UPC, Spain), the Lab. of Electromagnetics and Acoustics of the Federal Polytechnic Institute of Lausanne (EPFL, Switzerland), the Dept. of Electromagnetics and Physics of Matter of the University of Granada (UGR, Spain), the Interuniversity Research Center for Disordered Systems and Fractals in Chemical Engineering and Dept. of Electronic Engineering of the “La Sapienza” University of Rome (Italy), and the International Center for Numerical Methods in Engineering (CIMNE). The multidisciplinary nature of Fractal Electrodynamics required the cooperation of experts from different fields, such as electromagnetic theory, fractal mathematics, design of microwave antennas and devices, and numerical modelling.

This paper briefly presents some of the main conclusions and results of the FractalComs Project.

UNDERSTANDING OF FRACTAL ELECTRODYNAMICS PHENOMENA

Based on the results of both numerical simulations and prototype measurements, and from the specific point of view of antenna miniaturization keeping reasonable bandwidth and efficiency, the following conclusions have been reached:

- Increasing the number of pre-fractal iterations means a reduction on resonant frequency, radiation efficiency and an increase on quality factor. The increase of **fractal dimension**, although making better space filling curves, builds larger monopoles with lower efficiencies and higher quality factors even for the first iterations. **Topology** has a stronger influence than fractal dimension on the behaviour of small 2D pre-fractal wire monopoles, in particular on the losses efficiency. Fig. 1 shows some of the printed monopoles used for the investigation on the influence of fractal dimension and topology on radiation efficiency and quality factor.

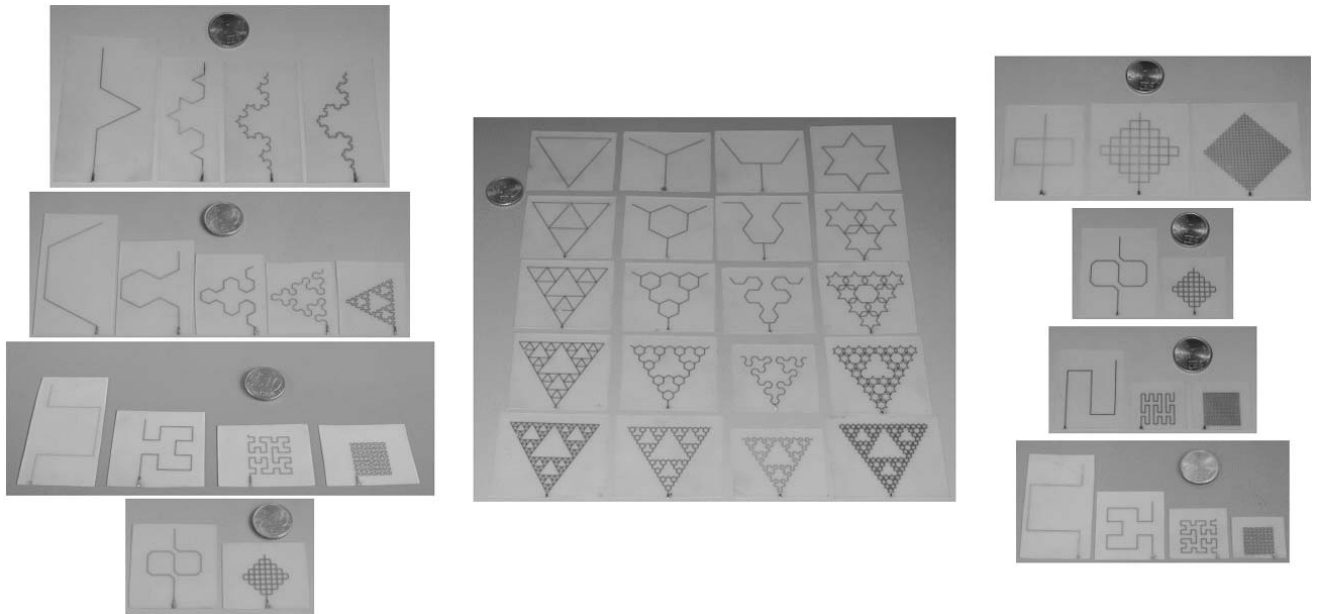


Fig. 1. Printed antennas used for the assessment of the influence of fractal dimension (left) and topology (centre and right) on the quality factor and radiation efficiency of antennas.

- As the **number of loops** inside the structure increases, efficiency and fractional bandwidth (inverse of quality factor) seem to increase with the order of the pre-fractal (number of IFS iterations). When there is **no loop**, each IFS iteration increases the length and bending of the wires, and as a consequence ohmic losses and the amount of stored energy on the surrounding of the antenna increases (this means lower radiation efficiencies and higher quality factors). When the number of IFS iterations increases beyond a certain threshold, the change in radiation patterns and input impedance of the antenna tend to zero. In other words, **there is no use in increasing the number of IFS iterations**. Convergence is usually achieved between 4 and 6 iterations. This value depends largely on the size, wire or strip width and topology of the antenna.
- The hypothesis of **electromagnetic coupling** –or shortcuts- between corners fully explains why the resonant frequency of pre-fractal antennas is much larger than what could be expected from the wire length only and why it stagnates as the number of IFS iterations increases. Fig 2 illustrates the “shortcut” effect.

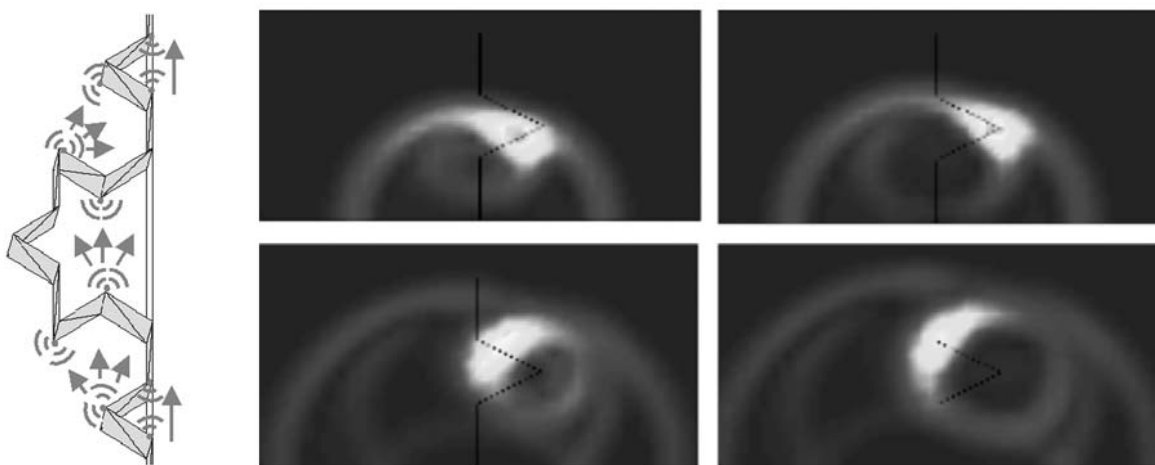


Fig. 2. The coupling between sharp angles at curve segment junctions in a Koch-2 pre-fractal monopole extrusion-strip is used to illustrate the shortcut effect (left). Near fields in the time domain in the vicinity of a Koch-1 pre-fractal monopole with a short-pulse excitation (right). The sharp angles of the pre-fractal curve become the centre of a spherical wave radiation, assessing the coupling or shortcut effect.

- It seems that the **high-gain localized modes** than have been previously observed in the Koch-island printed patch antenna are **not exclusive of pre-fractal** antennas.
- **Three-dimensional pre-fractal** design does not provide further improvements than planar design in the radiation performance of monopoles. In spite of the smaller electrical sizes attainable thanks to their increased space-filling capability, they have a more intricate topology and larger wires than their planar counterparts. Consequently, efficiency and Q factor for these 3D pre-fractals have unpractical values to real-world applications. Fig. 3 shows the geometry of a 3D Hilbert monopole of 1 to 3 iterations, and Table 1 their computed performances.

GUIDELINES FOR THE DESIGN OF SMALL ANTENNAS

Some guidelines for the design of small antennas have been derived as a result of the work in this project (the electromagnetic coupling hypothesis) and very recent work available in the literature:

- In order to reduce signal coupling –or shortcuts- between wire segment angles, the distance between those angles must be as large as possible, and the angles the larger possible.
- In order to reduce the signal coupling between the feeder and the wire segments, the most possible wire length must be perpendicular to the electric field radiated by the feeder.
- In order to reduce coupling between wire segments, parallel wire segments with opposite (anti-parallel) currents very close to each other must be avoided.

An example of wire antenna that closely follows these guidelines is a **two-arm square spiral**. The resonant frequency of a square spiral is inversely proportional to the wire length, while keeping the wire enclosed by a small square.

FUNDAMENTAL LIMITS

The fundamental Chu-McLean limit ([2], [3]) for the radiation quality factor of antennas holds for pre-fractal devices. Moreover, pre-fractals are not closer to this fundamental borderline than other standard designs. Fig. 4 shows measurement results for quality factor and radiation efficiency of some self-resonant planar pre-fractal monopoles versus meander line-loaded monopoles.

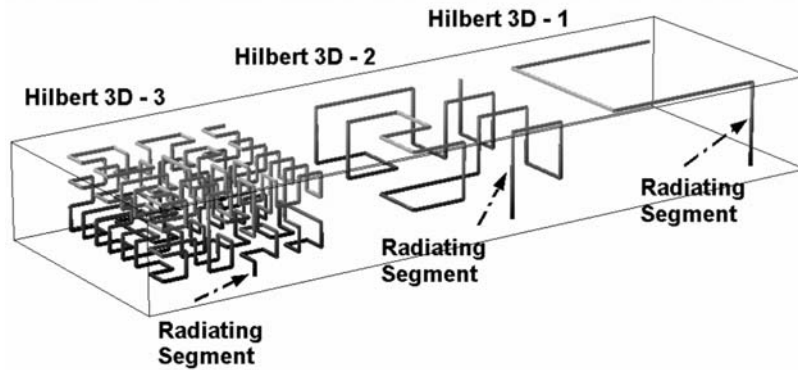


Fig. 3. Simulated 3D antennas in a monopole configuration. The main contribution to radiation seems to proceed from the first segment of the monopole.

Table 1. Computed performance of a 3D Hilbert pre-fractal monopole of 1 to 3 iterations.

Antenna	Total Wire Length (cm)	Electric Size at Resonance, ka	Resonant Frequency (MHz)	Radiation Resistance at Resonance (Ohms)	Input Resistance at Resonance (Ohms)	Efficiency (%)	Quality Factor	Fundamental Limit, Q
Hilbert 3D-1	61,78	0,71	127,5	2,47	3,24	76,6	126	4
Hilbert 3D-2	184,99	0,25	51,4	0,16	1,67	9,4	2091	70
Hilbert 3D-3	642,61	0,10	21,0	0,01	3,07	0,5	31966	1088

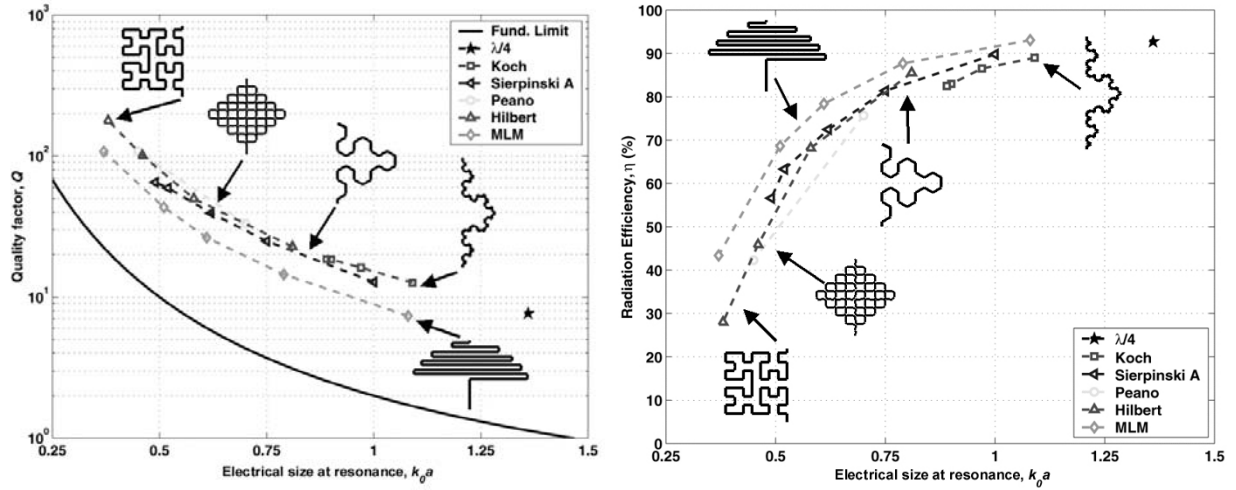


Fig. 4. Quality factor (left) and radiation efficiency (right) versus the electrical size at self-resonance $k_0 a$ of some planar pre-fractal monopoles compared with a meander line-loaded design.

- A multi-objective optimisation technique based on Genetic Algorithms (GA) assessed the existence of practical limits more restrictive than the fundamental limit predicted by Chu and reexamined by McLean. Both, conventional and pre-fractal geometries are near this practical limit that has been found for planar self-resonant wire monopoles.
- Recently, Thiele, Detweiler and Penno [4] published a more realistic limit that holds for antennas with sinusoidal current distribution. The practical limit found in the project agrees pretty well with this new realistic limit. In Fig. 5 the limits by Thiele, Detweiler and Penno is compared with the restrictive limits from the optimisation using GA.

TECHNOLOGICAL LIMITATIONS

Two issues have been considered: the limitations related with the modelling and numerical analysis of highly iterated pre-fractals, and the limitation related to their manufacturing. Concerning these two issues the following conclusions have been reached:

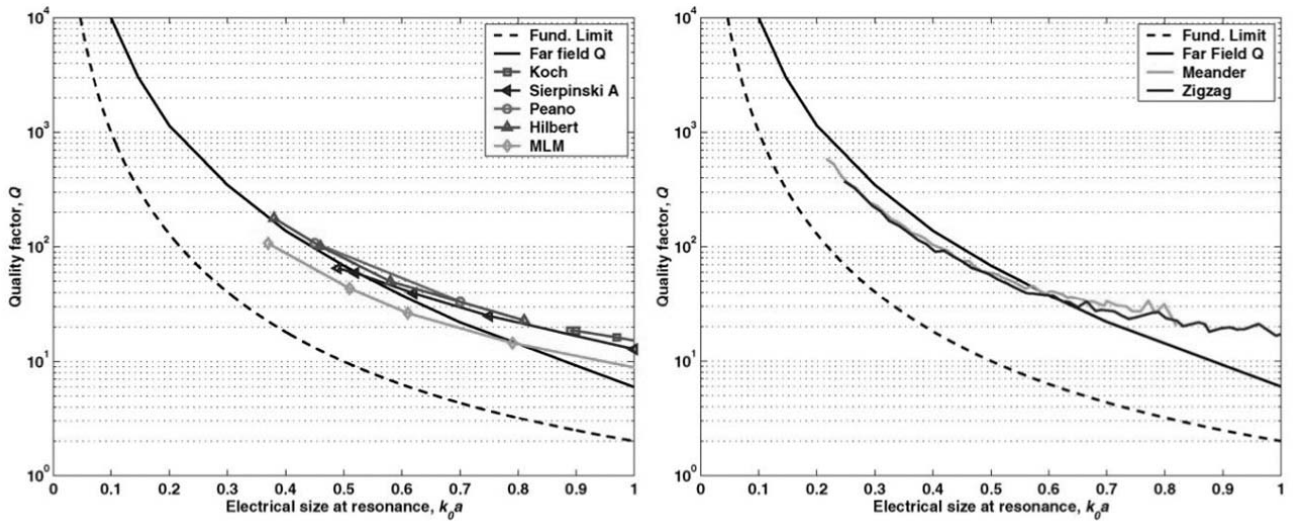


Fig. 5. Quality factor versus electrical size at self-resonance of planar pre-fractal antennas (left) and optimised GA meander and zigzag designs (right) compared with the realistic limit of Thiele, Detweiler and Penno.

- The best way to accurately model highly iterated pre-fractal curves is by an extrusion-strip model rather than a planar strip or a thin wire, as shown in Fig. 6.
- Thin-wire models with reduced kernel are still useful for analysing low-order pre-fractals. Consequently, NEC and the time-domain DOTIG code are helpful tools for the simulation of such geometries.
- In order to analyse highly iterated pre-fractals with the thin-wire EFIE, a new formulation has been developed to achieve a very fast evaluation of the full kernel. The new formulation is valid for any ratio of the wire segment length to the wire radius, and can be applied to highly iterated pre-fractals discretized in very short wire segments. The main advantage of the new thin-wire full kernel approach over the 2-D extrusion-strip formulation is that computation time is very small, since the 1-D discretization requires, for instance, only 4096 unknowns while the 2-D mesh has 22,524 unknowns to model a 5-iteration Koch antenna.
- Due to the non-zero width of the pre-fractal curve, technological manufacturing limitations make impossible the construction of highly iterated pre-fractals for reduced overall dimensions. Fig. 7 shows the maximum attainable iteration for a Koch pre-fractal versus a given ratio width w of the pre-fractal over the size S of the curve. Circles and triangles show the highest iterations found in literature that have been simulated and fabricated, respectively.

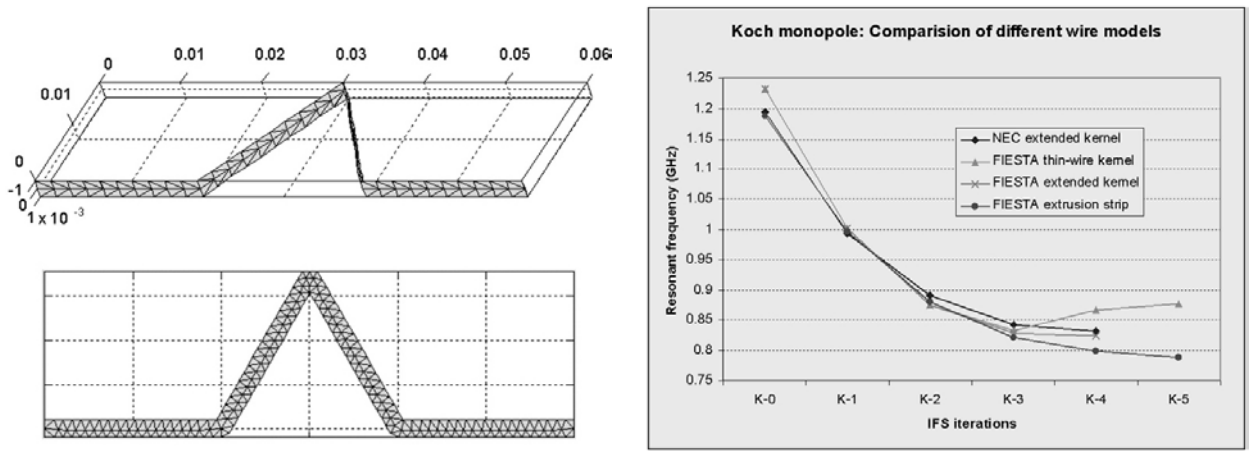


Fig. 6. Koch-1 pre-fractal antenna discretized in triangular patches using an extrusion-strip model and a planar-strip (left). Resonant frequency of a 6 cm-height Koch monopole of 1 to 5 iterations, computed using different formulations of the EFIE (right). Only the surface formulation with an extrusion-strip mesh shows the expected behaviour for a pre-fractal structure. The thin-wire approximation fails for highly iterated structures.

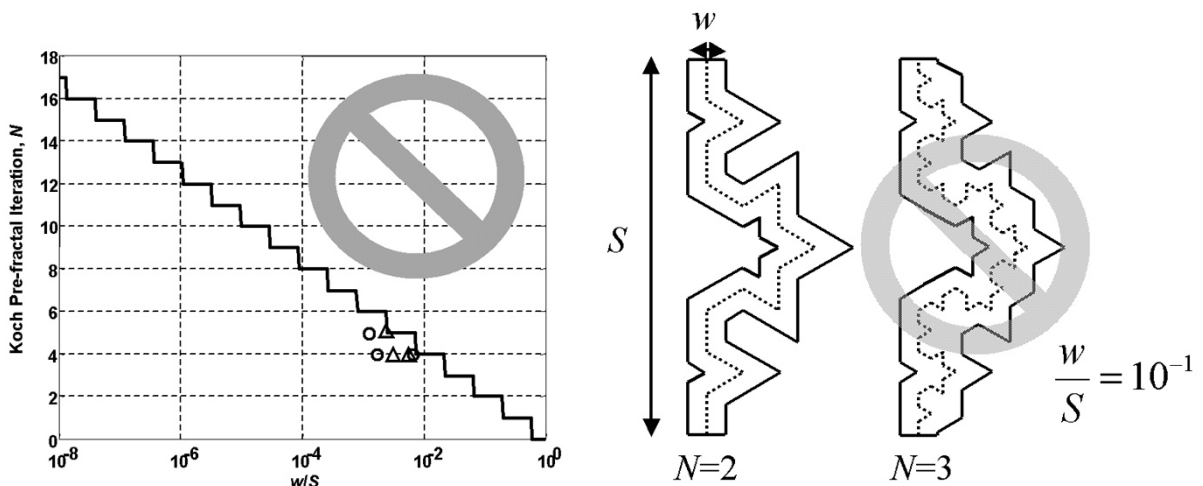


Fig. 7. Maximum attainable Koch pre-fractal given a w/S ratio (left). Circles and triangles show the highest iterations found in literature that have been simulated and fabricated, respectively. Graphical example to illustrate what is considered a correct and an incorrect Koch pre-fractal design for a given w/S ratio (right). Koch-2 is a valid design when the w/S ratio is 10^{-3} . Dotted lines show the ideal zero-width Koch pre-fractal curve.

CONCLUSION

The objectives of the FractalComs Project have been fulfilled, increasing the understanding of the behaviour of electromagnetic fields and electric currents in fractal domains, exploring the capability of fractal-shaped devices to reach the fundamental miniaturization limit (never reached by Euclidean-shaped devices), developing software tools for computer simulation of fractal-shaped devices performance, and exploring the impact of technological limitations on the performance of fractal-shaped microwave devices (minimum detail size and loss efficiency).

Besides the objectives initially set for this basic research project, new approaches have been investigated related to the following technological application of pre-fractals: **Superconductor pre-fractal resonators for miniature filters** (that reveal a good trade off between quality factor and reduced dimensions, Fig. 8), self- and quasi-self complementary pre-fractal antennas (as potential candidates to fabricate wideband antennas, Fig. 9), GA optimised highly convoluted miniature antennas, and H-trees (resulting antennas may have miniature size and broadband properties, Fig. 10) and Capillary filters (built from the parallel-connection of blocks, Fig. 11).

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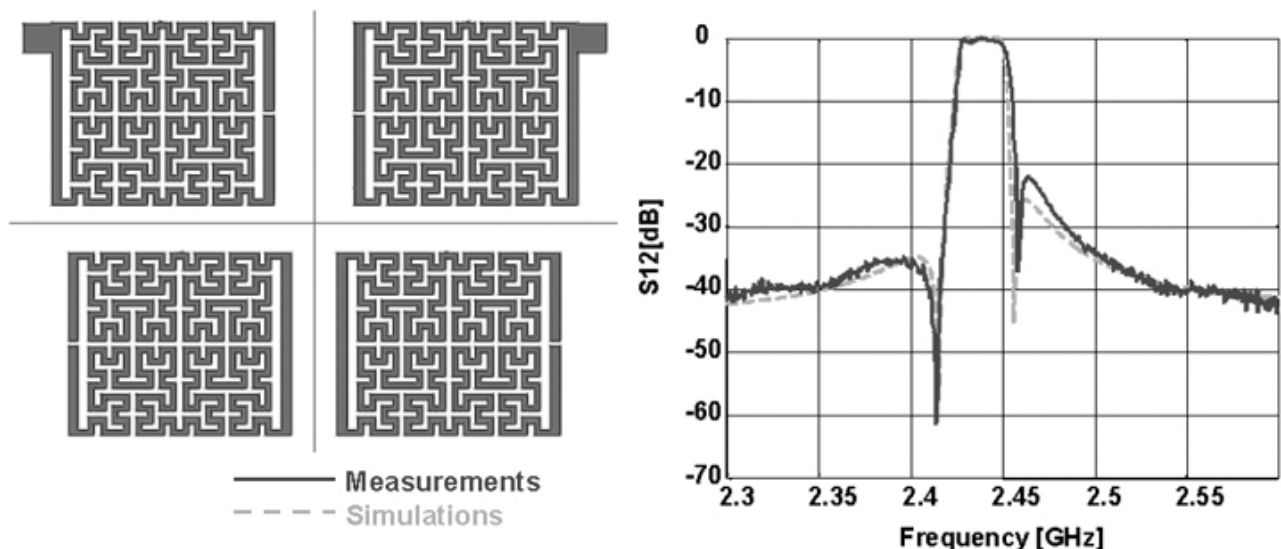


Fig. 8. Cascade-quadruplet quasi-elliptical superconductor filter: geometry (left), and frequency response simulated and measured in liquid nitrogen (right).

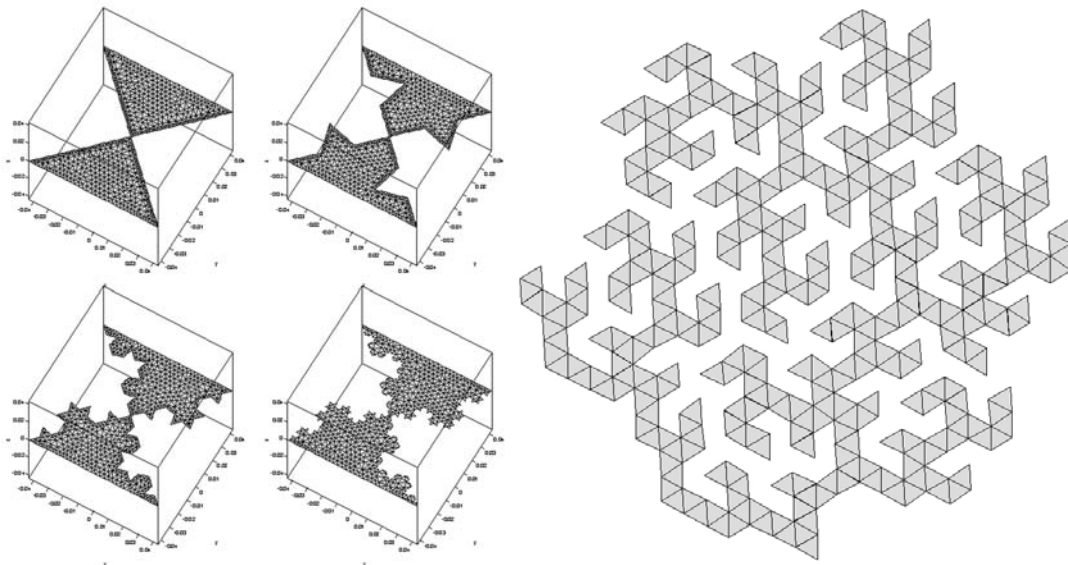


Fig. 9. Self-complementary antennas with pre-fractal shape: the first iterations of Koch-tie dipole (left). Quasi-self complementary design: the Gosper Island of 3rd iteration (right).

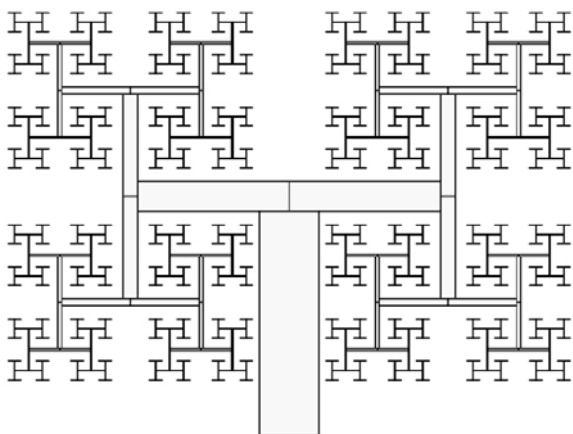


Fig. 10. Thick-stemmed H-tree.

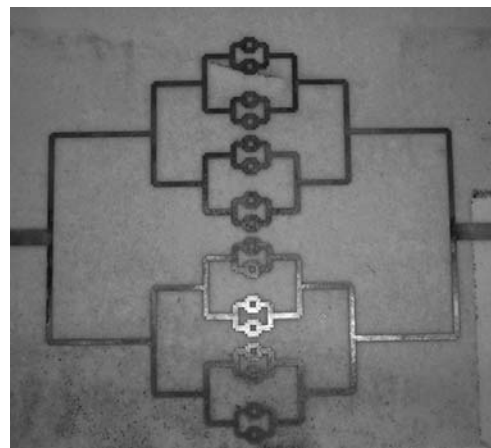


Fig. 11. Two port capillar.