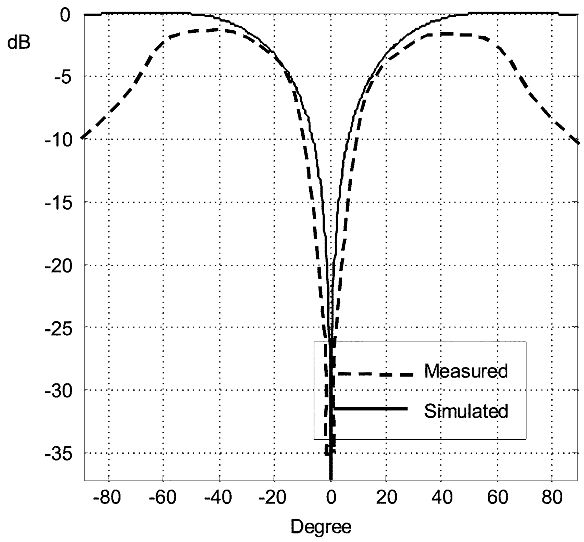

Fig. 7. Simulated (solid line) and measured (dashed line) radiation pattern at 985 MHz for the TM_{01} Mode of the designed antenna.

modes are very well matched. If we compare the experimental values with the calculated ones we can see a shift towards the higher frequencies in the measured ones. This can be due to the fact that the cavity model is a theoretical one with assumptions and approximations like the ideal magnetic boundary condition or the infinite size of the ground plane.

Finally, the radiation patterns for both the TM_{11} and TM_{01} of this antenna have been calculated and measured. Fig. 6 shows a comparison of the experimental (dashed line) and calculated (solid line) radiation pattern for mode TM_{11}. On the other hand, in Fig. 7 we can find the same comparison for TM_{01} Mode radiation pattern.

The small differences between the measured and simulated radiation patterns come from the finite ground plane size (because the cavity model assumes infinite ground plane) and also from the effect of the feeding probe (the model does not take into account it for calculating the radiation patterns). The finiteness of the ground plane especially affects to the radiation pattern in the azimuthal direction ($\theta = 90^\circ$). For this reason, the larger difference between measurements and simulations appears at this angle. The feeding probe causes an asymmetry in the radiation pattern that is especially important in the E-plane for TM_{11} mode.

IV. Conclusion

The cavity model has been applied to analyze the short circuited ring antenna. Expressions for the resonant frequency, input impedance and radiated field have been provided. A particular study has been performed on TM_{01} mode which is the fundamental mode for this geometry. All the theoretical expressions have been applied for the first time to this mode.

Also, experimental results have been obtained. These results are in good agreement with the theoretical developments for both radiation pattern and input impedance. Particularly, the usefulness of this geometry to design "monopolar" printed antennas has been pointed out.

The advantages of ring geometries from the point of view of antenna performances have been discussed. Finally, some advantages of this geometry from a practical point of view, such as to have two different radiation patterns at close frequencies, have been presented.

References

[1] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*. Norwood, MA: Artech House, 2001.
[2] C. Martín-Pascual, E. Rajo-Iglesias, and V. González-Posadas, "Invited Tutorial: 'Patches: the most versatile radiator ?'," in *IASTED Int. Conf. Advanced in Communications*, Rhodas, Greece, Jul. 3-6, 2001.
[3] I. J. Bahl and P. Bhartia, *Microstrip Antennas*. Norwood, MA: Artech House, 1980.
[4] M. D. Deshpande and M. C. Bailey, "Input impedance of microstrip antenas," *IEEE Trans. Antennas Propag.*, vol. AP-30, no. 4, pp. 645–650, Jul. 1982.
[5] W. F. Richards, Y. T. Lo, and D. D. Harrison, "An improved theory for microstrip antennas," *IEEE Trans. Microw. Theory Tech.*, vol. 29, no. 1, pp. 38–46, 1981.
[6] D. R. Jackson, J. T. Williams, A. K. Bhattacharyya, R.L. Smith, S. J. Buchheit, and S. A. Long, "Microstrip patch design that do not excite surface waves," *IEEE Trans. Antennas Propag.*, vol. 41, no. 8, pp. 1026–1037, Aug. 1993.
[7] Y. Lin and L. Shafai, "Properties of centrally shorted circular patch microstrip antennas," in *IEEE Antennas and Propagation Symp.*, Syracuse, NY, 1988, pp. 700–703.
[8] Y. Lin and L. Shafai, "Characteristics of concentrically shorted circular patch microstrip antennas," *Proc. Inst. Elect. Eng.*, vol. 137, no. 1, pp. 18–24, 1990.
[9] Q. García, "Contribución al Estudio de las Antenas Autodiplexadas," Ph.D. dissertation, University of Sevilla, , Spain, May 1996, Ch. 3.
[10] M. V. Schneider, "Microstrip lines for microwave integrated circuits," *Bell Syst. Tech. J.*, pp. 1421–1444, 1969.
[11] Y. S. Wu and F. J. Rosenbaum, "Mode chart for microstrip ring resonators," *IEEE Trans. Microw. Theory Tech.*, vol. 21, pp. 487–489, 1973.
[12] K. F. Lee and J. S. Dahele, "Characteristics of annular ring microstrip antenna," *Electron. Lett.*, vol. 28, no. 24-10, pp. 1051–1052, 1982.

GA Design of Small Thin-Wire Antennas: Comparison With Sierpinsky-Type Prefractal Antennas

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***Abstract*—A new set of genetically generated electrically small thin-wire antennas with a better performance than that of several families of Sierpinsky prefractal monopoles of the same electrical size at resonance is presented.**

I. Introduction

As is well-known, electrically small antennas are inherently highly reactive and inefficient radiators and they present a very narrow bandwidth when they are tuned to resonance. Hence, in designing these

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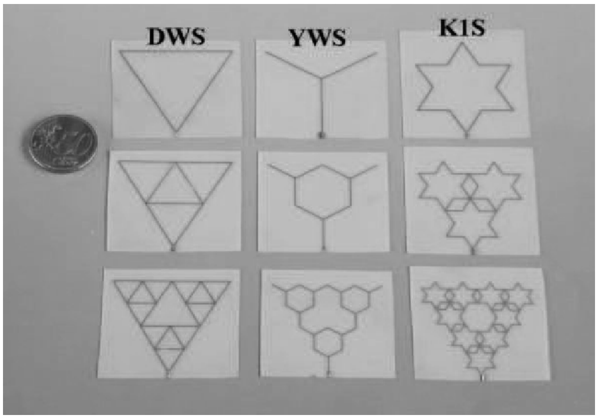

Fig. 1 From left to right, three iterations of: Delta wire Sierpinski, Y Wire Sierpinski, and Koch-Sierpinski.

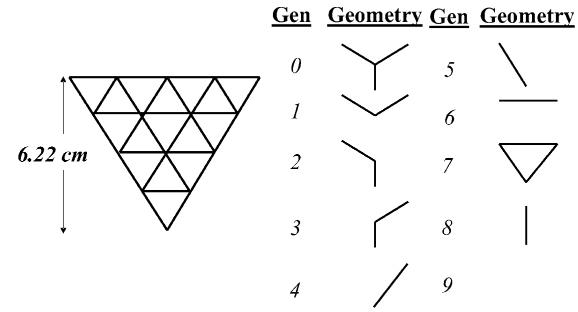

Fig. 2 Area to be filled and basic elements to replace the subtriangles (rotated if necessary). The equilateral triangle has the same height, $h = 6.22$ cm, than the Sierpinski antennas in Fig. 1.

kinds of antennas, it is necessary to seek a compromise between parameters such as resonance frequency, bandwidth and efficiency. In a previous work [1] a multiobjective genetic algorithm (GA) in conjunction with the numerical electromagnetic code (NEC) [2] was applied to the optimization of electrically small wire antennas in search of such a compromise. In [1], our aim was twofold: to find GA designs optimized in terms of several parameters and to compare their performance with that of prefractal-shaped antennas which, due to their intricate and convoluted configurations, have been considered in the literature as good small antennas. As a result, for a given overall wire length and antenna size, it was shown that genetically optimized antennas with either zigzag or meander geometries behaved better than genetically optimized prefractal antennas with generalized Koch-type geometries. Therefore, it was always possible to find designs with better performance than that of Koch-type prefractals. In this paper, we extend the work in [1] (valid only for the particular case of generalized Koch-type prefractal) to other prefractal shapes.

Further, numerical experiments and measurements using other prefractal wire monopole antennas such as those with Peano and Hilbert geometries [3], [4] confirmed the superior performance of genetically optimized zigzag and meander antennas (see [5] for specific details). One common feature of all these antennas is that they do not include in their geometry any closed-loop shapes. Nevertheless, for other prefractal families of wire antennas which do include closed-loop shapes in their geometry, such as the Delta, Y, and Koch- and Sierpinsky-types (see Fig. 1), improvement was not possible using zig-zag or meander designs.

Subsequently, the option of including closed loops in the GA code was allowed when seeking the best possible structure instead of the restriction to exclusively zigzag and meander geometries. The result was that the new set of genetically optimized antennas performed better than all the prefractal antennas plotted in Fig. 1. In this paper these results are presented and discussed.

II. Genetically Optimized Antennas Including Loops

With a procedure similar to the one described in [1], a multiobjective (Pareto) GA code [6] was used to design genetically optimized small monopole antennas, seeking better performance than that of the prefractal antennas shown in Fig. 1. Initially, the space to be filled by the GA antennas was restricted to a half circle having a radius equal to the height of the monopoles depicted in Fig. 1 and, as in [1], zigzag and meander-type geometries were considered. However, it was found that the GA designs did not outperform the radiation characteristics of the prefractal shapes. These results were shown in [5] and, for the sake of brevity, will not be repeated here. Thus, instead of limiting the search to only zigzag and meander geometries, the possibility of generating structures including closed-loop was allowed. This new family was formed by filling an equilateral triangle of height $h = 6.22$ cm using the basic elements depicted on the right side of Fig. 2. For this, the main triangle was subdivided into 16 equilateral subtriangles, which were randomly replaced by one of the basic shapes (rotated if necessary).

To generate the genetically optimized antennas a set of monopole antennas, which constituted the initial generation, were randomly formed and encoded into chromosomes using fixed-point decimal coding [6]. The population was composed of 20 chromosomes, each comprising a set of $N = 16$ genes which represent coded versions of the individual characteristics. Fig. 2 indicates the genes associated with each of the basic shapes utilized. The antennas were made of 0.1 mm radius copper wires, and fed at their base. Their efficiency, input impedance, and resonance frequency were calculated applying the frequency-domain method-of-moments-based NEC code. As our aim was to evolve towards small individuals with the lowest possible Q factor and the highest possible efficiency, e, the three following fitness functions were evaluated for each individual:

$$\begin{aligned} F^1 &= 1 - \frac{f_r}{f_r^s} \\ F^2 &= e \\ F^3 &= \frac{1}{Q} \end{aligned} \tag{1}$$

where f_r is the resonance frequency corresponding to any generated antenna and f_r^s is the first resonance frequency of a straight monopole of length 1 cm (this length was chosen to be smaller than the height of a subtriangle in Fig. 2 so that F^1 is always smaller than 1).

After applying the GA operators [6] of the tournament method, one-point crossover and a Gaussian-probability-distribution mutation, the multiobjective GA procedure renders a 3-D graph of $k_0 a$, e, and Q corresponding to each individual after each generation, where k_0 is the wavenumber corresponding to f_r; $a = 7.18$ cm is the radius of the minimum hemisphere enclosing the monopole antenna. The envelope of this graph evolves to an optimal set of solutions called the Pareto front [6], [7], from which the designer can choose the individual that best fits the design requirements. The procedure is applied by means of domination schemes using triangular sharing functions to guarantee diversity in the final set of optimal solutions. The specific GA adopted in this work employs both a crossover operator and a mutation operator with probabilities of 80% and 5%, respectively.

Fig. 3 plots two projections of the Pareto surface corresponding to the results after 7000 generations. To compare the characteristics of

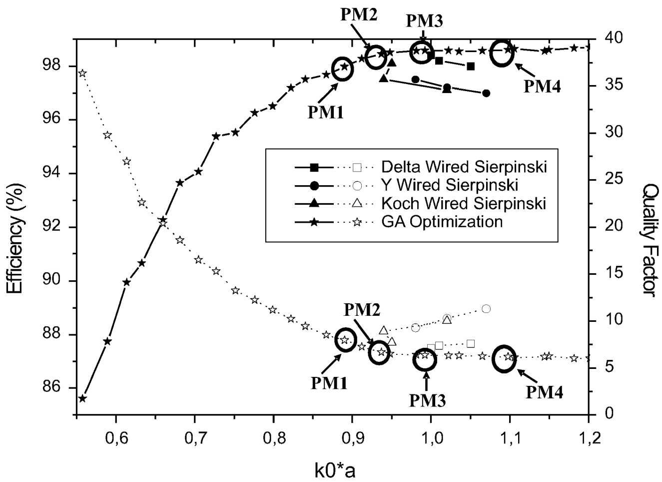

Fig. 3 Efficiency (solid line) and Q factor (dashed line) of the individuals designed with GA and of the prefractal antennas in Fig. 1. The filled symbols represent the efficiency while the non-filled symbols represent the Q factor.

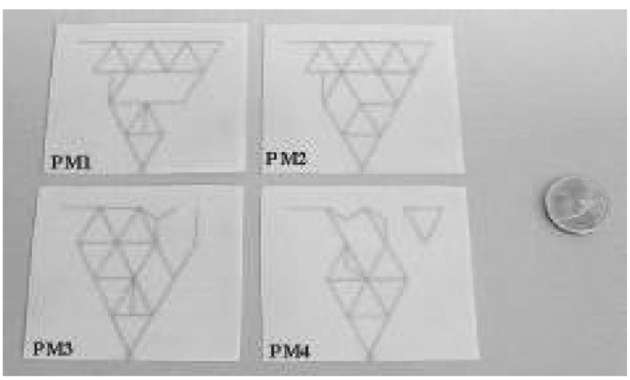

Fig. 4 Example of several optimized GA antennas.

the same set of specific individuals, we first projected the Pareto surface onto the efficiency-Q plane, then selected the individuals with the lowest Q and plotted both their efficiency and their Q factor versus their electrical size (see Fig. 3). The solid curve represents efficiency while the dashed line represents Q. Note that there is now consistently a GA design with a better performance, higher efficiency and lower Q, than that of any prefractal Sierpinsky antenna of the same electrical size at resonance.

Among all the GA-designed antennas, the four shown in Fig. 4 have been selected to construct and compare with the prefractal Sierpinski antennas of Fig. 1. Note that the Sierpinski antennas are considered only up to the third iteration, so that the maximum wire length of the GA individuals coincides with that of the prefractal monopoles, and the comparison is made under the same conditions. To facilitate the measurements, all the antennas were scaled from their original height to have the same size (56.9 mm high). The antennas have been printed on a 0.25 mm thick FR4 fiberglass substrate (permittivity 4.2 and loss tangent 0.02) using standard techniques for printed circuit-board manufacturing. They were made 0.3 mm wide with 35 μm etch strips. The dimensions of the strip were chosen so that the actual geometry where the current flowed in the strip had the same surface area in cross section as that in the original wire [8]. Once constructed, the antennas were mounted on a 3 mm thick ground plane of 80 cm $\times$ 80 cm and fed through their base with a SMA connector. The antennas were raised 2.2 mm (the length of the connector central pin) from the ground plane.

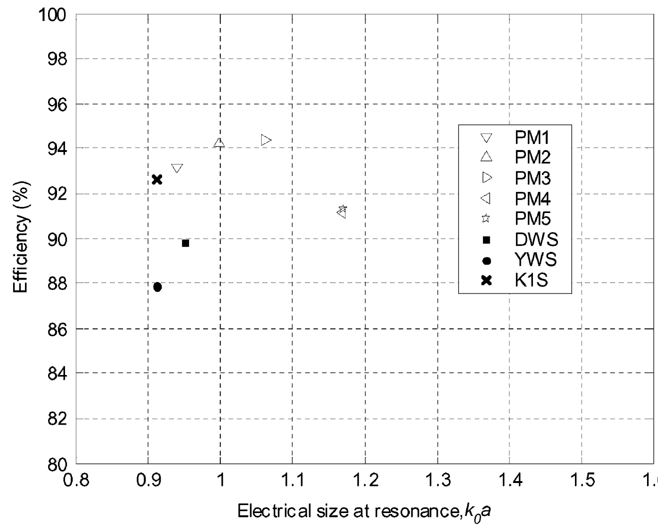

Fig. 5 Measured efficiency of the antennas in Fig. 4 and in Fig. 1.

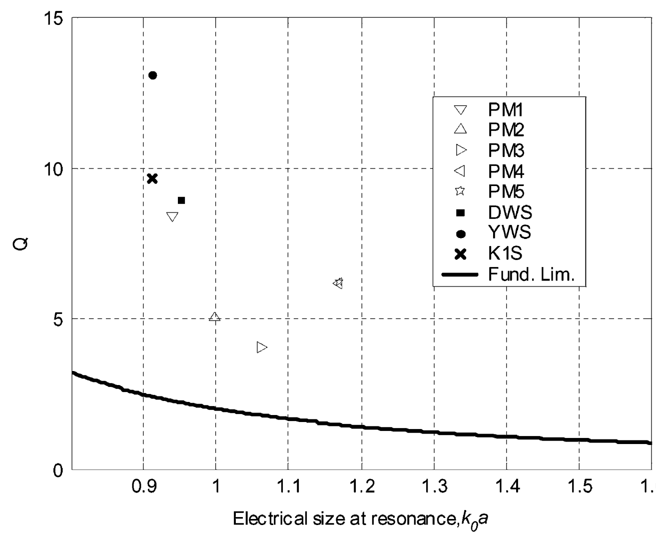

Fig. 6 Measured Q factor of the antennas in Fig. 4 and in Fig. 1.

Radiation efficiency of the antennas was measured at resonance with the Wheeler cap method based on the measurement of the input resistance of the antenna when radiating in its usual environment and when surrounded by a metal shield [9]. A cylindrical metal bowl was used as a cap, its size being enough to fulfill the radian length criterion for the minimum spacing between the antennas and the cap walls. The resonance frequencies of the cap were also checked to be out of the frequency range of the antennas being tested [10]. Once the radiation resistance at resonance and the input reactance in a frequency range around the resonance were known, the quality factor without losses was also estimated using the relationship in [11]. The input resistance and the reactance of the antennas, with and without the cap, were measured with a calibrated vector network analyzer inside an anechoic chamber. The shift between the reference (calibration) plane and the ground plane was compensated for using the electrical delay of the analyzer.

Figs. 5 and 6 show, respectively, the values of efficiency and Q measured for the GA designed antennas and for those shown in Fig 1, confirming that the non-fractal antennas perform better than do the fractal

TABLE I

Antenna	Rinput (Ω)
PM1	17.60
PM2	21.03
PM3	22.07
PM4	21.74
PM5	21.82
DWS	15.87
YWS	13.88
K1S	13.80

designs. In Fig 5, the fundamental limit for the Q factor [11] was included as a reference. Figs. 5 and 6 also include the results corresponding to a monopole, named PM5, built by removing from the PM4 antenna the detached triangle located in its upper right corner. It can be seen that PM4 and PM5 elements behave identically. Measured efficiencies, quality factors, and electrical sizes at resonance agree reasonably well with the expected values from simulations plotted in Fig 3, and both reveal the GA capability of designing monopoles with slightly better performance than prefractals for almost the same electrical sizes. The slight differences between simulations and measurements are due to the scaling factor used in order to have antennas with the same height as well as the presence of a substrate that supports the strips [12]. Both shift the resonance frequencies towards lower frequencies from the expected values and add losses to the antennas. In addition, the antennas are modeled with NEC using wires while the manufactured ones are strips over a substrate. PM4 and PM5 have less measured efficiency than the others presumably because PM4 and PM5 have resonance frequencies higher than the other antennas and, when using the Wheeler cap method for the determination of the radiation efficiency, they are slightly closer to the first resonance frequency of the cavity. Although those resonance frequencies are not severely affected, the measured ohmic losses of both antennas slightly increase over the expected value (but due to the losses in the cavity, not on the antennas). This slight increase in the ohmic losses of the cavity translates as reduced efficiency of both antennas.

Finally, the input resistance of the monopoles, though not considered during the optimization process, was measured in the final designs and the results are presented in Table I showing values ranging from $13 - 20\ \Omega$.

III. Conclussion

A multiobjective genetic algorithm has been applied to generate a new family of electrically small, thin wire antennas that perform better than do several families of prefractal Sierpinsky antennas in terms of resonance frequency, efficiency, and Q factor. For this aim it was necessary to allow the GA procedure to take into account geometries which also include closed-loop shapes instead of only seeking for zigzag and meander designs. Measurements confirmed the numerical results obtained.

References

[1] M. F. Pantoja, F. G. Ruiz, A. R. Bretones, R. G. Martín, J. González-Arbesú, J. Romeu, and J. M. Rius, "GA design of wire prefractal antennas and comparison with other Euclidean geometries," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 238–241, 2003.

[2] G. J. Burke and A. J. Poggio, Numerical electromagnetics code (NEC) - method of moments, Lawrence Livermore National Laboratory, Rep. UCID-18834, 1981.

[3] *Exploring the limits of fractal electrodinamics for future telecommunication technologies*, European project, {IST}-2001-33055 [Online]. Available: http://www.tsc.upc.es/fractalcoms/, Fractalcoms Web Site

[4] J. González-Arbesú and J. Romeu, "Experiences on monopoles with the same fractal dimension and different topology," in *Proc. IEEE APS-URSI Int. Symp.*, Columbus, OH, 2003, vol. 2, pp. 218–221.

[5] J. González-Arbesú, J. Romeu, J. Rius, M. Fernández-Pantoja, A. Rubio-Bretones, and R. Gómez-Martín, "Are prefractal monopoles optimum miniature antennas?," in *Proc. IEEE APS-URSI Int. Symp.*, Columbus, OH, 2003, pp. 17.8–17.8.

[6] T. Back, D. Fogel, and Z. Michalewicz, *Handbook of evolutionary computation*. Bristol, U.K.: IOP Publishing, 1997.

[7] C. A. Coello, "Constraint-handling using an evolutionary multiobjective optimization technique," in *Proc. Genetic and Evolutionary Computation Conf. (GECCO99)*, Orlando, FL, 1999, pp. 117–118C. A. Coello.

[8] B. Popovic and A. Nesic, "Generalization of the concept of equivalent radius of thin cylindrical antennas," *Proc. Inst. Elect. Eng.*, vol. 131, pt. H, pp. 153–158, 1984.

[9] H. Wheeler, "The radiansphere around a small antenna," *Proc. IRE*, pp. 1325–1331, Aug. 1959.

[10] B. A. Austin, "Resonant mode limitations with the wheeler method of radiation efficiency measurement," in *Inst. Elect. Eng. Colloquium on Advances in the Direct Measurement of Antenna Radiation Characteristics in Indoor Environments*, 1989, pp. 7/1–7/4.

[11] L. J. Chu, "Physical limitations on omni-directional antennas," *J. Appl. Phys.*, vol. 19, pp. 1163–1175, Dec. 1948.

[12] A. R. Bretones, R. Martín, and I. S. García, "Time-domain analysis of magnetic and/or dielectric coated wire antennas and scaterers," *IEEE Trans. Antennas Propag*, vol. 43, pp. 591–596, Jun. 1995.

Bandwidth Enhancement of Small Dielectric Resonator Loaded Patch Antenna

K. Y. Hui and K. M. Luk

***Abstract*—A coaxial-fed rectangular dielectric resonator antenna loaded by a folded metallic patch is studied. By introducing a foam layer between the metallic patch and the dielectric resonator, the impedance bandwidth of the antenna is increased from 2.2% to 6.3% (10-dB bandwidth). The proposed antenna has a maximum gain of 5 dBi. Good agreement between the simulation and measurement results are found.**

***Index Terms*—Dielectric resonator antennas, patch antennas.**

I. Introduction

Both the microstrip patch antennas and the dielectric resonator antennas (DRAs) are very attractive to designers for modern communication systems. These antennas share many advantages such as low profile, light weight and ease of manufacture. A new kind of small antenna based on a combination of the two conventional antennas mentioned above has also received much attention as a research topic in recent years. The literature shows that dimensions of the merger are reduced significantly but it inherits a substantial reduction in bandwidth [1]. Methods for bandwidth enhancement of DRAs have received intense

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