A Self-Complementary 1.2 to 40 GHz Spiral Antenna with Impedance Matching

Petr Piksa, Miloš Mazánek

Dept. of Electromagnetic Field, Czech Technical University in Prague, Technická 2, 166 27 Praha, Czech Republic

piksap@fel.cvut.cz, mazanekm@fel.cvut.cz

Abstract. *This paper describes a design of the Self-Complementary Spiral Antenna (SCSA) which consists of a spiral antenna and wideband impedance transformer. The spiral antenna and the transformer are designed separately due to computing demands. New knowledge about current distribution on the spiral antenna and influence of higher numbers of wavelength in circumference is presented. The novel transition between feeding and radiating antenna structure are optimized in the frequency range 1.2 to 40 GHz. The meaning of the transition in the paper includes the impedance as well as the geometry transforming of the structure. The antenna is suitable for wideband illuminating of a parabolic reflector due to relatively constant phase center and radiation pattern with frequency.*

Keywords

Spiral antenna, ultra wide-band, UWB, circular polarization, planar, self-complementary structure, current distribution, transition, impedance transformer, impedance matching, s-parameters renormalizing.

1. Introduction

The spiral antenna is a self-complementary structure [1] that has the input impedance close to theoretical value of 60π however practical realizations [2] usually achieve less values of impedance. The antenna needs an impedance transformer for transforming nonsymmetrical 50 Ω to the symmetrically fed antenna impedance about 150 Ω.

2. Antenna Geometry and Properties

The whole antenna is placed inside a conductive cover, see Fig. 1, which is filled with a polyamide carbon absorber in order to attenuate the cross polarization component. Right-hand circular polarization is absorbed in the cover, whereas the left-hand circular polarization is transmitted in the opposite direction. The feeding of the antenna is connected to 2.92 mm coaxial connector and then it is converted through glass seal to microstrip line by axial transition. The spiral antenna is fed using the impedance transformer, which also fulfils a function of the geometry transition between nonsymmetrical and symmetrical lines.

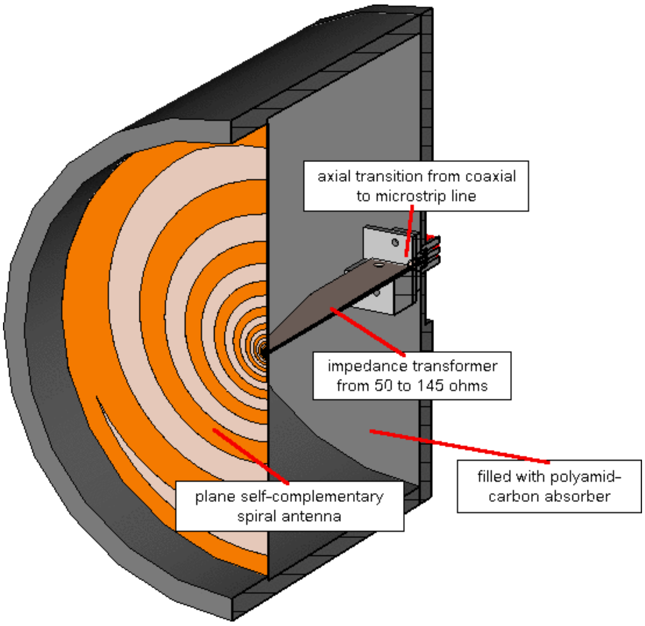


Fig. 1. Self-Complementary Spiral Antenna (SCSA)

2.1 The spiral antenna

The radiating part of the antenna is comprised of a spiral antenna. The spiral consists of two identical arms which are shifted by 180° with respect to each other. The shape of the spiral arm may be seen as a filling of two identical curves shifted by 90°. The whole spiral antenna is taken together from single curve rotated in four steps of 90°. The curve is described by the function [3]

$$r = r_0 \, e^{a(\phi+\varphi)} , \tag{1}$$

where r_0 is the starting distance at $\varphi=0°$, a determines the increasing rate of radius r, Φ is the variable angle and φ determines rotation of the curve. The outer curve is set up for $\varphi=0°$ and inner for $\varphi=90°$, see Fig. 2.

It is possible to consider the spiral as a combination of a current radiator with the current flow along its striplines and a slot radiator with the electric field between its striplines [6]. The spiral antenna has a circular left-hand polarization in one direction and right-hand in the opposite one. The impedance of the antenna is about 150 Ω feeding symmetrically. The gain is between 4 to 6 dBi.

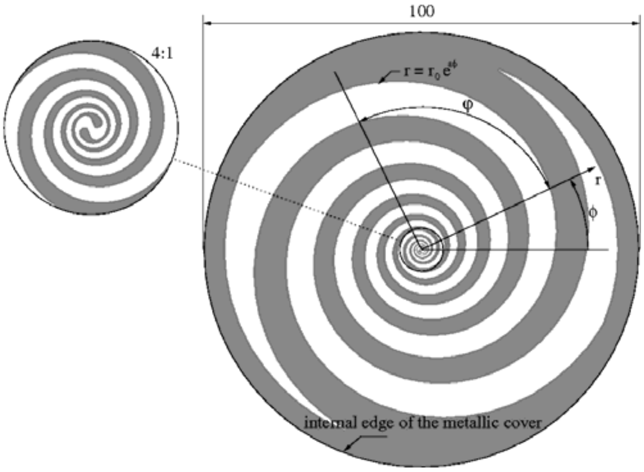


Fig. 2. The geometry of the plane self-complementary spiral antenna with detail of feeding.

2.2 Wideband Impedance Transformer

The impedance transformer is based on quarter-wave length impedance transformer theory. The two different impedances are connected with the quarter-wave length line with impedance, which is equal to the geometrical center of these impedances. The whole wideband transition is designed from small sections that keep the principle of the geometrical center of the impedances at boundaries given by

$$Z = \sqrt{Z_1 Z_2}\ , \tag{2}$$

where $Z_{1,2}$ are the impedances at boundaries.

The impedance distribution follows with an exponential distribution of impedance and it engages with uniformly distributed section reflection coefficients [4].

The wideband impedance transformer, see Fig. 3, is designed as a planar structure from composed planar transmission lines [5]. It transforms a nonsymmetrical 50 Ω to a symmetrical 65 Ω and to a symmetrical 145 Ω. The profile of the transformer, see Fig. 3, was optimized in order to reach maximal bandwidth, minimal losses and dimensions. The length of the transformer is 51.1 mm using substrate Rodgers RO4003 of permittivity 3.38 and height 0.508 mm.

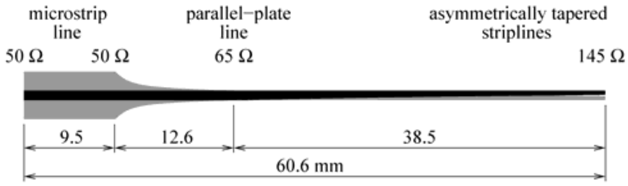


Fig. 3. The geometry of the planar impedance transformer from 50 Ω of microstrip line to 145 Ω of asymmetrically tapered striplines.

3. Modeling

The spiral antenna and the transformer were designed separately due to computing demands. They were modeled using IE3D from Zeland Software, Inc. [7], which simulates 2.5D (3D) structures using moment method in frequency domain very well.

Unfortunately it was not possible to include some discontinuities in the transition between the transformer and the spiral antenna in the modeling.

It should be mentioned, that there wasn't found out any influence of the cover on the input impedance of the antenna by modeling.

3.1 Spiral Antenna Structure

The profile of the spiral antenna was created in Matlab [8], afterwards imported to IE3D and meshed, see Fig. 4.

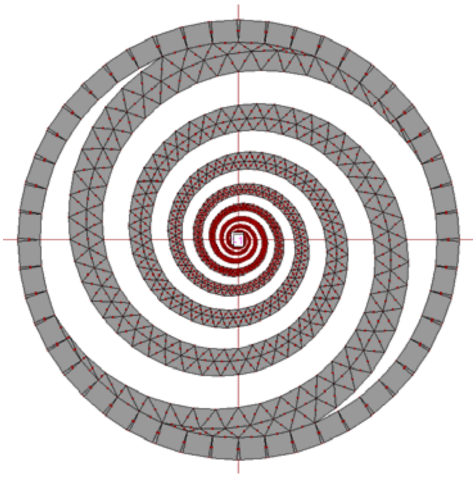


Fig. 4. Designed structure showed in simulation software IE3D from Zeland.

Now let us define "equivalent value of impedance" as an optimal impedance matching over the whole frequency band.

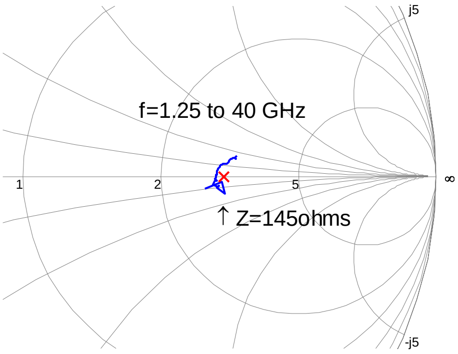


Fig. 5. Searching of the "equivalent value of impedance" of the spiral antenna above.

The equivalent value of the impedance can be found by an iteration method using the method of minimal square and renormalization of the reflection coefficient. The equivalent value 145 Ω of this particular spiral antenna was achieved by modeling, see Fig.5.

Some parametric analyses of the spiral antenna are depicted in Fig. 6 to Fig. 9, the parameters *a* and *φ* (as *phi0*) are explained in chap. 2.1:

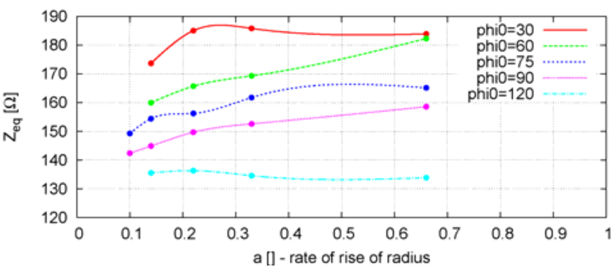


Fig. 6. "Equivalent value of impedance" versus *a* (rate of rise of radius of the spiral in eqn. 1).

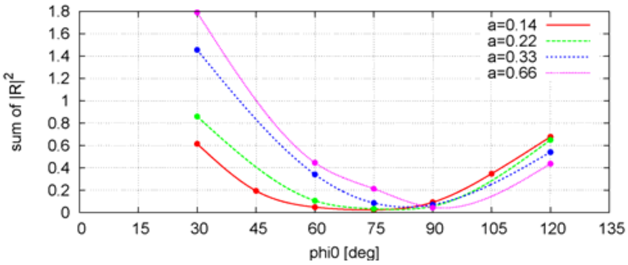


Fig. 7. Error function of the frequency independence of impedance versus angle φ (thickness of the spiral in eqn. 1).

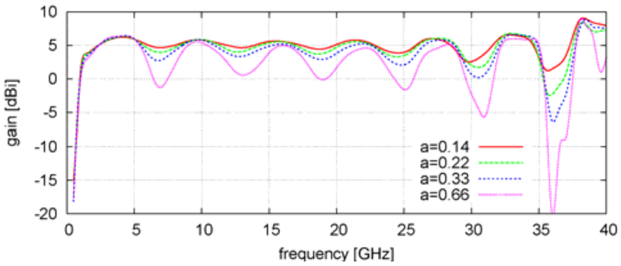


Fig. 8. Gain as a function of frequency.

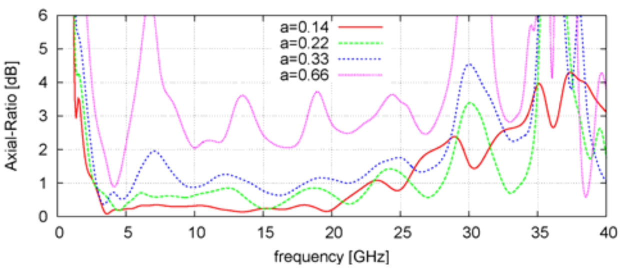
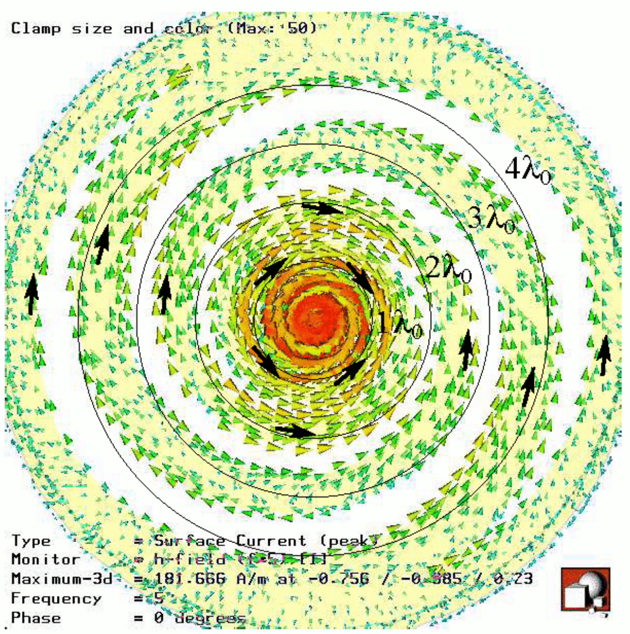


Fig. 9. AR as a function of frequency.

In addition, the equivalent value and error function of frequency independence of input impedance are slightly depending on parameter *a*, as well the gain and axial ratio on parameter *φ*.

From a point of view of power budget, nearly all energy is radiated by first resonance in circumference that is equal to one wavelength, see Fig. 10. Rippling character of gain is caused then by summarizing of higher numbers of wavelength in circumference. These also depreciate stability of the antenna phase center, thus the position of phase center continuously oscillates along the axis of spiral.



```
Type          = Surface Current (peak)
Monitor       = h-field (f=5) [1]
Maximum-3d    = 181.666 A/m at -0.756 / -0.885 / 0.23
Frequency     = 5
Phase         = 0 degrees
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Fig. 10. Current distribution on the spiral antenna at frequency 5 GHz, modeled using CST Microwave Studio.

3.2 Impedance Transformer

Firstly let us show some differences in variety of impedance distributions.

Effective permittivity of the transformer is obtained from comparison of IE3D model and analytical results of reflection coefficient. Effective permittivity is about 3.72. The example of analyzed structure consists of 8 sections of transmission lines.

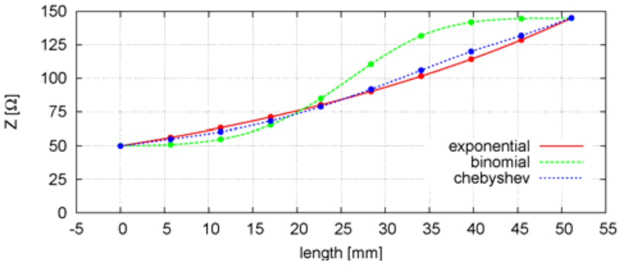


Fig. 11. Comparison of exponential, binomial and Chebyshev impedance distribution for 8 sections of transmission lines.

The exponential distribution of impedance represents the simplest way to design a minimal length of the transformer, see Fig. 11 and Fig. 12.

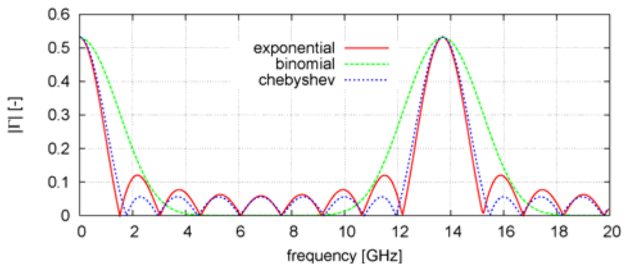


Fig. 12. Comparison of the reflection coefficient for exponential, binomial and Chebyshev impedance distribution for 8 sections of transmission lines.

The impedance of all planar transmission lines was full-wave modeled using IE3D and post-analyzed using renormalization of scattering parameters.

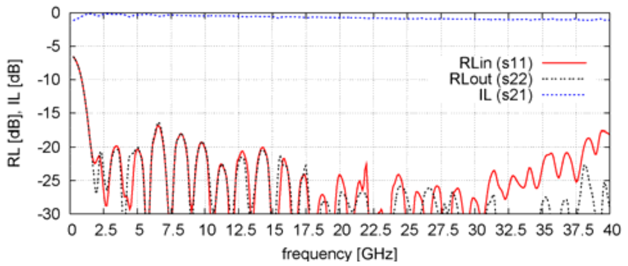


Fig. 13. Impedance matching and insertion loss of the impedance transformer

The parameters of the new transition structure are obtained only by modeling. Due to their normalization to the input and output characteristic impedance of 50 Ω, parameters should be renormalized to the input characteristic impedances of 50 Ω and output of 145 Ω. The resulting parameters of the transition are shown in Fig. 13.

3.3 SCSA Scattering Parameter Results

Due to the influence of impedance matching of the spiral antenna, the resulting parameters of the antenna should be taken as a matrix cascade of scattering parameters. Firstly the scattering parameters of the impedance transformer are renormalized to the input and output characteristic impedance of 50 Ω. The studied parameters of the spiral antenna are impedance matching and gain. These parameters could be considered as scattering parameters with the input characteristic impedance of 145 Ω and output of 376 Ω. The antenna scattering matrix is renormalized to the input and output characteristic impedance of 50 Ω. Next step is to convert both scattering matrixes to transmission T matrixes and to multiply them. Finally the resulting transmission matrix is converted back to scattering matrix and it is renormalized to the input characteristic impedance of 50 Ω and output of 376 Ω. The final results of impedance matching and gain of the antenna with the new transition are shown in Fig. 14 and Fig. 15.

Matrix formula for renormalizing of scattering parameters consists of two parts:

$$\mathbf{N} = (\mathbf{S} - \mathbf{\Gamma})(\mathbf{E} - \mathbf{\Gamma S})^{-1} \tag{3}$$

$$S'_{n,m} = N_{n,m} \sqrt{\frac{Z_m Z_{0m}}{Z_n Z_{0n}}} \frac{Z_n + Z_{0n}}{Z_m + Z_{0m}}, \tag{4}$$

where **S** is original matrix of scattering parameters and **S’** is renormalized matrix, **Γ** is matrix of reflection coefficients on diagonal between normalizing and characteristic port impedance and **E** is identity matrix. This formula was taken from documentation of Qucs program [9] and corrected by the author.

4. Measurement

Impedance matching was measured on vector analyzer E8364A from Agilent Technologies, see Fig. 14.

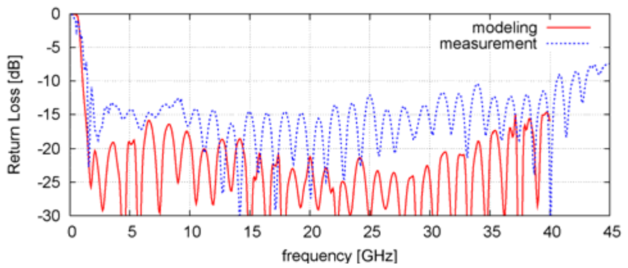


Fig. 14. Impedance matching of the Self-Complementary Spiral Antenna with impedance transformer

Radiating parameters of the antenna was measured up to 40 GHz in the anechoic chamber. The measured gain in comparison with modeling is in Fig. 15.

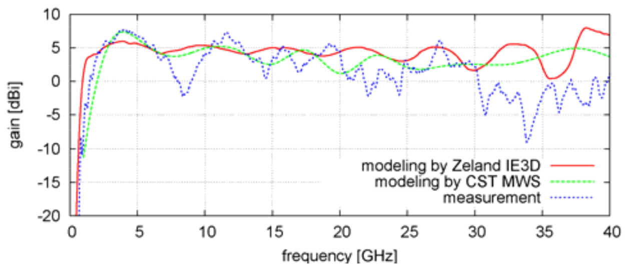


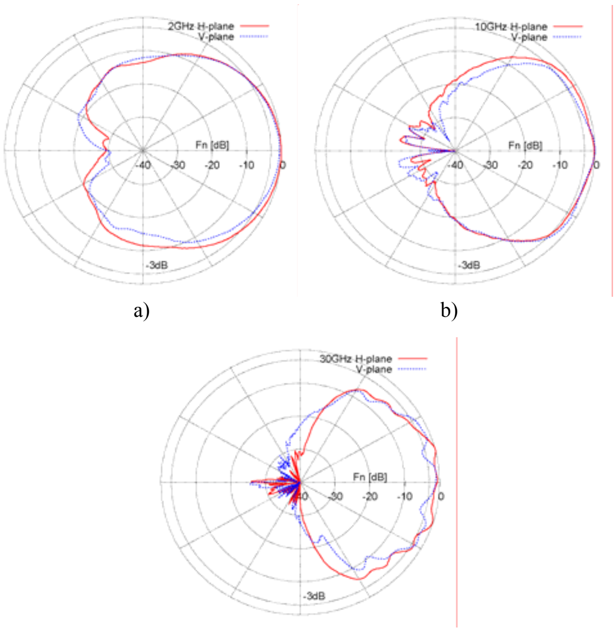
Fig. 15. Gain of the Self-Complementary Spiral Antenna with impedance transformer.

Relatively constant radiation pattern with frequency can be seen in Fig. 16. The components of the antenna are in Fig. 17.

5. Conclusions

The spiral antenna and the impedance and geometry transition were modeled using IE3D from Zeland Software, Inc. with manually made mesh structure due to computing demands. The antenna was designed as a planar structure.

The profile of the transformer was optimized in order to reach maximal bandwidth, minimal losses and dimensions. The impedance distribution of the transformer was improved with respect to the transmission design method. The transmission design method is the simplest way to design a minimal length of the transformer.



a) b)

c)

Fig. 16. Measured normalized radiation pattern in [dB] at frequencies a) 2 GHz, b) 10 GHz, c) 30 GHz.

The modeled results were confirmed by measurements. At larger structure of the spiral antenna with coaxial feeding the agreement between modeling and measurement of the input impedance was verified.

Fig. 17. Components of the SCSA antenna.

Acknowledgements

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[7] http://www.zeland.com

[8] http://www.mathworks.com

[9] http://qucs.sourceforge.net/docs.html - Technical documentation.

About Authors

Petr PIKSA was born in Děčín in 1977. He received his M.Sc. degree from the Czech Technical University in Prague, in 2002. Now he is working toward his Ph.D. degree in radio electronics. His interest is in planar wideband antennas and transitions. He was a visiting student researcher at the Cork Institute of Technology, in 2004/2005. His research at CIT was focused on design of antennas for UWB and development of Linux embedded system for WiFi connection of mesh network.

Miloš MAZÁNEK graduated from the Czech Technical University in Prague in 1974. He joined the Department of Electromagnetic Field, where he has been the head of the department since 1997. He is a member of IEEE, the head of Radioengineering Society and Radioengineering journal executive editor. His research interests are in the field of microwave radiometry, antennas, propagation of electromagnetic waves, and electromagnetic compatibility.