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Pentagonal Microstrip Antenna Equivalent to a Circular Microstrip Antenna for GPS Operation Frequency

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Resumen. La antena pentagonal se diseña considerando su equivalencia en área a una antena de parche circular para la frecuencia de operación de GPS (Sistema de Posicionamiento Global, por sus siglas en inglés). La antena circular fue diseñada utilizando una simple ecuación de diseño, la cual requiere solamente de conocer la longitud de onda de grupo, la permitividad efectiva y la frecuencia de operación. Esta simple ecuación se recomienda para FR-4, para 1.57 GHz, entre otras frecuencias. Las simulaciones se realizan utilizando FEKO, un software basado en el Método de los Momentos (MoM). El bajo costo de la antena se basa en el material usado como substrato. El interés en la geometría pentagonal se debe a su relación con la razón dorada, un concepto matemático muy útil en ingeniería.

Abstract. The pentagonal antenna is designed as equivalent to a circular patch antenna for GPS (Global Positioning System) operation frequency. The circular antenna was designed with a simple design equation, which requires only knowing the group wavelength, the effective permittivity and the operation frequency. This equation is recommended for FR-4, among other frequencies, at the frequency used here. The simulations are realized using CADFEKO, software based on the Moment Method (MoM). The low cost of the antenna is based on the substrate material used. The interest in pentagonal geometry is due to its relationship with the golden ratio, a mathematical concept very useful for engineering.

Keywords: Patch antenna, circular polarization, FR-4, GPS.

1. Introduction

The circular patch antenna is one of the fundamental microstrip geometries. The methods used so far assumed an infinite size for the ground plane and substrate. The solutions are therefore approximated and lack of influence on the finite substrate and ground-plane dimensions [1]. The circular patch has a simple geometry and can operate on circular polarization. In this work, instead to use the common design equation [2]:

$$a=\frac{F}{\left\{1+\frac{2\times h}{\pi\times\varepsilon_r}\left[\ln\left(\frac{\pi\times F}{2\times h}\right)+1.7726\right]\right\}^{1/2}}. \quad (1)$$

with $F=8.791x10^9/\sqrt{\varepsilon_r}$, where h is the substrate thickness, ε_r is the dielectric permittivity and f_0 is the operation frequency; or the approximation used in [3]:

$$a=\frac{1.841}{k_0\sqrt{\varepsilon_r}} \quad \text{with} \quad k_0=\frac{2\times\pi}{\lambda_0} \quad (2)$$

We use a very simple and similar approach to the used equation for ring resonators (see Section 2). The simulations related with this purpose are provided in Section 2.

In Section 3, a pentagonal antenna designed to operate at the GPS operation frequency (1.57 GHz) and the corresponding simulations are presented. In Section 4, a comparison between pentagonal and circular patch antenna are discussed and finally, in Section 5 some concluding remarks are given.

2. Circular Patch Antenna

2.1 Design

As design equation, we use:

$$r=\frac{\lambda_g}{\pi}; \quad \text{with} \quad \lambda_g=\frac{c}{f_0\sqrt{\varepsilon_r}} \quad (3)$$

where r is the patch radius, λ_g is wavelength of group, and c is the speed of light in vacuum. Equation (3) is very similar to the used equation for ring resonators [4]:

$$r=\frac{\lambda_g}{2\times\pi} \quad (4)$$

The difference can be understood as a scaling of the radius into $r/2$.

The equivalence between Equations (1) and (2) has been demonstrated (Table 1), also in this work, where we found a maximal difference of 0.1%, for several substrates materials and frequencies of operation.

Table 1. (a) Comparison of sizes of the Circular Patch Antenna with Equation (1) and (2) (FR-4 Substrate).

Frequency / Radius (cm)	400 MHz	900 MHz	1.5754 GHz	2.4 GHz	5.8 GHz
Equation (1)	10.9869	4.8831	2.7897	1.8312	0.7577
Equation (2)	10.9932	4.8859	2.7912	1.8322	0.7582

(b) Comparison of sizes of the Circular Patch Antenna with Equation (1) and (2) (Silicon Substrate)

Frequency / Radius (cm)	400 MHz	900 MHz	1.5754 GHz	2.4 GHz	5.8 GHz
Equation (1)	6.4248	2.8555	1.6313	1.0708	0.4431
Equation (2)	6.4278	2.8568	1.6320	1.0713	0.4433

(c) Comparison of sizes of the Circular Patch Antenna with Equation (1) and (2) (air medium)

Frequency / Radius (cm)	400 MHz	900 MHz	1.5754 GHz	2.4 GHz	5.8 GHz
Equation (1)	21.9618	9.7612	5.5766	3.6606	1.5148
Equation (2)	21.9865	9.7718	5.5824	3.6644	1.5163

On the other side, we also compared the results between Equations (1) and (3). The differences are from 8% up to 15% (Table 2).

The first difference corresponds to Silicon, showing a constant response in a wide frequency range. The last one corresponds to FR-4, for the case of high frequency (5.8 GHz), the difference was of 10%, while for the case of lower frequency (400 MHz) it was of 15%. In Air, the difference also remains approximately at a constant value (8.69%).

Table 2. (a) Comparison of sizes of the Circular Patch Antenna with Equation (1) and (3) (FR-4 Substrate)

Frequency / Radius (cm)	400 MHz	900 MHz	1.5754 GHz	2.4 GHz	5.8 GHz
Equation (1)	10.9869	4.8831	2.7897	1.8312	0.7577
Equation (3)	12.1204	5.3869	3.1070	2.0600	0.8779

(b) Comparison of sizes of the Circular Patch Antenna with Equation (1) and (3) (Silicon Substrate)

Frequency / Radius (cm)	400 MHz	900 MHz	1.5754 GHz	2.4 GHz	5.8 GHz
Equation (1)	6.4248	2.8555	1.6313	1.0708	0.4431
Equation (3)	6.9794	3.1020	1.8525	1.1632	0.4813

(c) Comparison of sizes of the Circular Patch Antenna with Equation (1) and (3) (air medium)

Frequency / Radius (cm)	400 MHz	900 MHz	1.5754 GHz	2.4 GHz	5.8 GHz
Equation (1)	21.9618	9.7612	5.5766	3.6606	1.5148
Equation (3)	23.8732	10.6103	6.0615	3.9789	1.6464

For the case of FR-4:

$$\lambda_g \approx \frac{\lambda_0}{2} \quad (5)$$

Then, Equation 3 can be replaced by:

$$r = \frac{\lambda_0}{2 \times \pi} \quad (6)$$

This equation is really simple for practical design. Using this expression, the difference was reduced to 8,64 % (Table 3). This value remains almost constant for all analyzed frequencies, but only is valid for FR-4.

Table 3. (a) Comparison of sizes of the Circular Patch Antenna with Equation (1) and (6) (FR-4 Substrate)

Frequency / Radius (cm)	400 MHz	900 MHz	1.5754 GHz	2.4 GHz	5.8 GHz
Equation (1)	10.9869	4.8831	2.7897	1.8312	0.7577
Equation (6)	11.9366	5.3052	3.0308	1.9894	0.8232

On the other side, the size of the square ground plane is given by [3]:

$$L_g = 6h + r \quad . \quad (7)$$

In order to demonstrate that our approximation, given in Equation (6), is useful, the design and simulation of a circular patch antenna for 1.5754 GHz (GPS signal frequency) were realized. The final sizes are shown in Table 4. The thickness of the FR-4 plate, used as substrate, is 1.6 mm.

Table 4. Sizes of the Circular Patch Antenna

Dimensions	Radius (m)	L_g(m)
Patch	0.0303	
Substrate		0.0399

For coaxial feeds, the location is usually selected to provide a good impedance match. In this case, this point is located near to the antenna center.

2.2 Simulation

The antenna was designed under the standard patch configuration for circular single-fed circularly polarized patch antennas. Our interest is to observe that the operation frequency remains very near to 1.57 GHz, as can be appreciated in Figure 1. The antenna gain was of 3.88 dB (Figure 2). The beam widths at phi=0 and phi=90 are of 100° and 95°, respectively (Figure 3 and 4), that means, almost a symmetrical radiation pattern. The back radiation in both cases was the same (-4.85 dB).

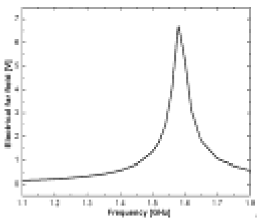

Figure 1. Electrical far field.

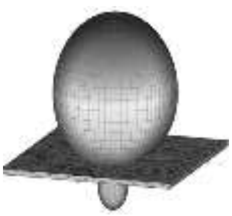

Figure 2. Patch antenna gain.

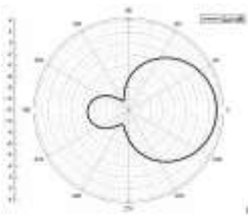

Figure 3. Beam width of patch antenna, at phi=0.

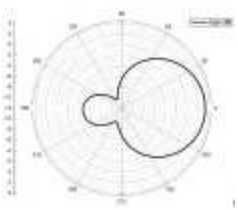

Figure 4. Beam width of patch antenna, at phi=90.

3. Pentagonal antenna

3.1 Design

Pentagonal geometry is one of the various shapes for microstrip antennas capable of circular polarization operation that has been reported in the literature [5]. The pentagonal antenna sizes calculation was made considering the invariance of the electrostatic energy below the pentagonal and circular patches, as it was realized in [6], for rectangular and circular ones, keeping constant areas.

The relationship between the circle patch (r_1) to the circle (r_2), where the pentagon patch is inscribed, in order to obtain equivalent areas is given by:

$$r_2^2 = \frac{\Pi r_1^2}{2.37} . \qquad (8)$$

Considering the radius length of the circle equal to 3.02 cm, the corresponding length of each side of the pentagon is 4.05 cm, and the apothem is equal to 2.79 cm, considering the cosines law and the Pythagoras theorem, respectively.

On the other hand, we also analyzed the case where the pentagon is inscribed, into a circle with a radius equal to the patch antenna. The simulations were also realized, considering a rectangular ground plane separated from the edges of the pentagon in a length equal to 3*h*.

3.2 Simulation

Both cases of pentagonal patch were analyzed, the first one where the pentagonal patch is inscribed into a circle with a radius equal to the circular patch antenna, and the last one keeping the patches areas equivalents. As the last one give us better results, considering the symmetry of the electric far field around the operation frequency, we only present this case in this section. Again, the operation frequency remains very near to 1.57 GHz (Figure 5), at 1.58 GHz. The antenna gain is of 3.43 dB (Figure 6), a little bit smaller than in the circular case.

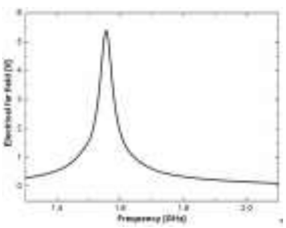

Figure 5. Electrical far field.

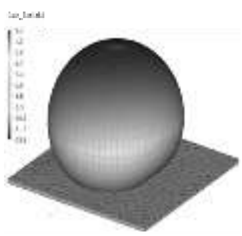

Figure 6. Patch antenna gain.

The beam widths at phi=0 and phi=90 are of 80° and 95°, respectively (Figure 7 and 8), showing a deviation of symmetry on the radiation pattern.

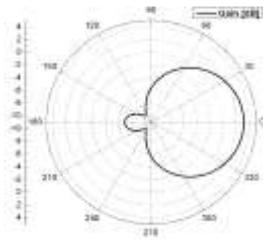

Figure 7. Beam width of patch antenna, at phi=0.

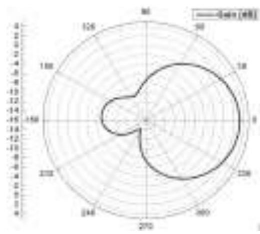

Figure 8. Beam width of patch antenna, at phi=90.

Finally in Figure 9, the return loss is presented considering a load of 50 Ω. As can be appreciated the corresponding bandwidth is of 650 MHz and the peak is obtained at 1.55 GHz, very near to the design operation frequency.

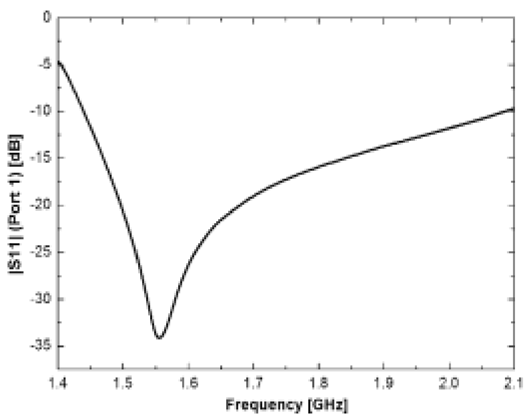

Figure 9. Return loss of the pentagonal antenna.

4. Comparison

The simulations of the gains of two cases where realized: 1) where the pentagonal radiating patch keeping equivalent the radius where it is inscribed and the circular patch, and 2) where the circular and pentagonal patches have equivalent areas. The first case shows severe asymmetries in shape of the electric far field near to the operation frequency, and a smaller gain compared to the case of equivalent areas (Figure 10). Considering the pentagonal antenna of bigger gain, a comparison between the pentagonal case and the circular one was realized (Figure 11).

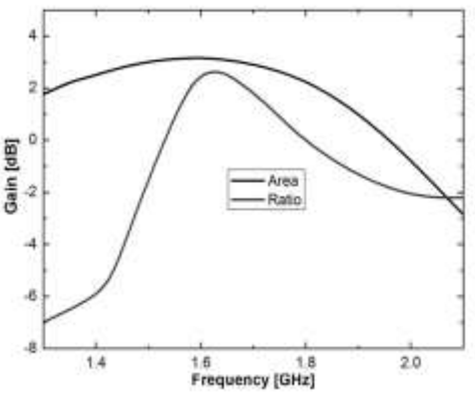

Figure 10. Gain of pentagonal antennas. In red, keeping an equivalent radio between the circular patch and the circle where the pentagonal patch is inscribed, and in black, keeping equivalent areas between the circle and the pentagonal patches.

As can be observed, in Figure 11, the pentagonal case shows a more defined symmetric curve considering at the center to the operation frequency, the same happen with the return loss and it is also almost imperceptible in the case of the electric far field. These facts constitute the main advantages of the pentagonal one, because the rest of the characteristics exhibit bigger symmetry in the case of the circular case.

Other advantage is the easier fabrication of straight sides instead of curves, which is even more economic for reducing costs of a complete GPS system.

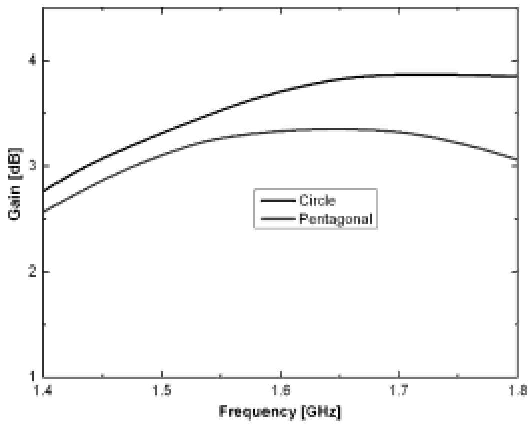

Figure 11. Gain of the pentagonal antenna (red) and of the circular one (black).

5. Conclusions

The approximation of the circular antenna design equation was enough ideal to obtain a circular patch antenna at GPS frequency with a satisfactory behavior, but for commercial purposes the substrate must be changed in order to obtain a bigger and competitive patch antenna gain.

As future work, it will be made prototypes with the sizes given by Equations (1) and (3), in order to observe its experimental behavior and corroborate the result obtained in the corresponding simulation.

The asymmetries on the response of the pentagonal antenna could be reduced implementing a circular substrate instead of the rectangular one. The purposed solution here demonstrates that different strategies can be realized with the aim to reducing global costs.

The location of the feed point also affects to the gain value, which increases as it is separated from the origin, as a consequence of the adjusting on impedance.

Additionally, on the base of the pentagonal antenna, the implementation of a dual antenna is under analysis. This has the purpose to show the high applicability of the pentagonal geometry for diverse uses.

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