Chapter 1

Compact Antennas — An overview

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Additional information is available at the end of the chapter

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1. Introduction

Antenna size reduction is restricted by fundamental physical limits [1-3], in terms of trade-off between radiation performances and impedance bandwidth. Miniaturization of devices leads to the reduction of antennas which becomes one of the most important challenges [4]. Limitations in terms of bandwidth and efficiency suggest an analysis with respect to fundamental limits [5]. Although interests are often focused on the impedance bandwidth, many studies deal with the radiation quality factor Q. Some papers [6] have been concluded that the impedance bandwidth BW equals 1/Q. The minimum Q value reachable by an infinitesimal electric dipole, or similarly by the azimuthally symmetric TM_{10} spherical mode, has been investigated thoroughly.

Hansen and Best [7] have shown that the lower bound on Q, deriving from Chu's analysis, is depending on the expense of efficiency as shown by the equation:

$$Q_{lb} = \eta\left(\frac{1}{(ka)^3} + \frac{1}{ka}\right)$$

where a is the minimum radius of the sphere enclosing the antenna and k is the wave number (k=2π/λ).

The Figure 1 shows that it is very difficult to have a wide bandwidth (low Q-factor), while reaching a good efficiency for miniature antennas (k.a around 0.2). Thus, the miniaturization of antennas implies them to suffer of both limited efficiency and low bandwidth.

Since many years the scientific literature addresses some approaches concerning miniaturization techniques. The goal is to decrease the electrical size of the radiating element. This chapter will draw up a survey of compact antennas in practical settings and the most common miniaturization techniques listed below:

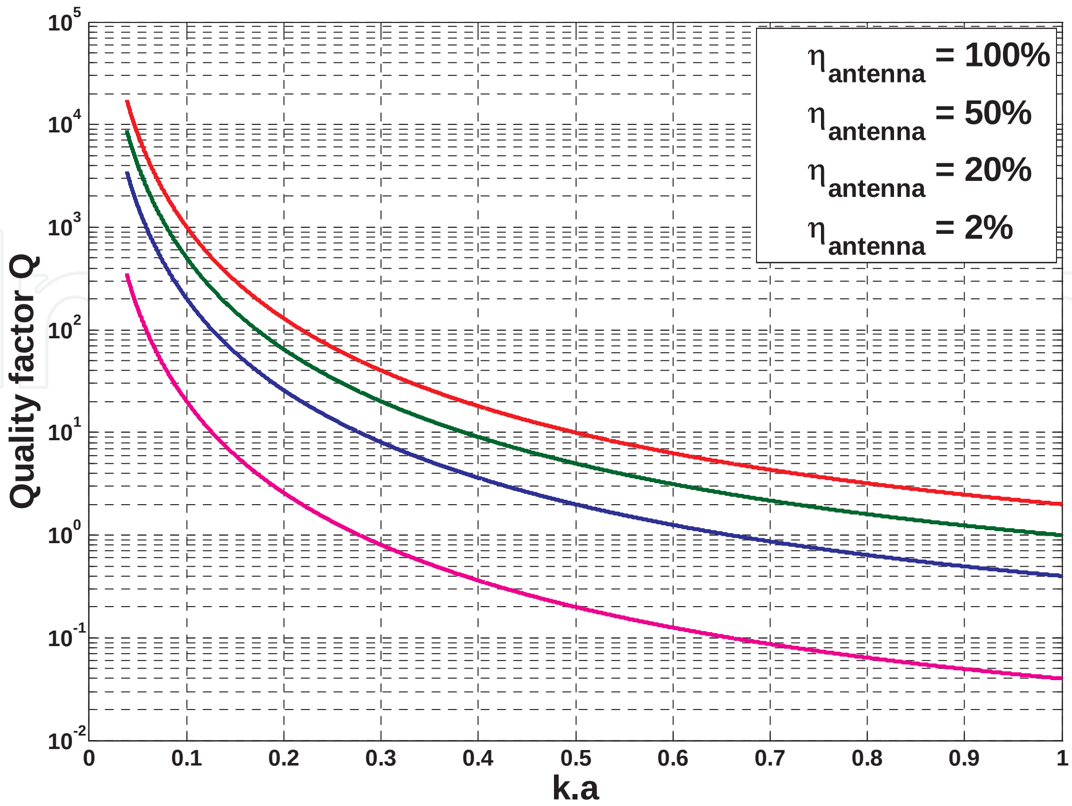

Figure 1. Quality factor according to the antenna dimensions and efficiencies

- Folded configurations [8-10]
- Surface etching techniques [11-14]
- Shorting walls or pins [15-16]
- The use of high dielectric constant materials or magneto-dielectric materials [17-22].
- Loading the radiating element with active components [23-26].
- Creation of hybrid modes with particular boundary conditions in dielectric resonator antennas. It allows choosing their resonance frequencies (for multiband or wide impedance bandwidth) [27].

We will start this chapter by detailing wire antennas. Indeed, after explaining the classical dipole antenna, we will show how to miniaturize this kind of antennas based on shape design such as bending, folding and meandering. The second part will detail planar antennas. We will see the impact of materials properties under the patch antenna hat, i.e. dielectric or magneto-dielectric materials. Then, planar miniature antennas will be shown, e.g. Planar Inverted F Antenna (PIFA) and monopolar wirepatch antenna. The third part will exhibit Dielectric Resonator Antennas and how to use this kind of antennas for low frequency band application while having compact sizes. Finally, the last part will summary all the antennas presented in this chapter, while showing their main settings.

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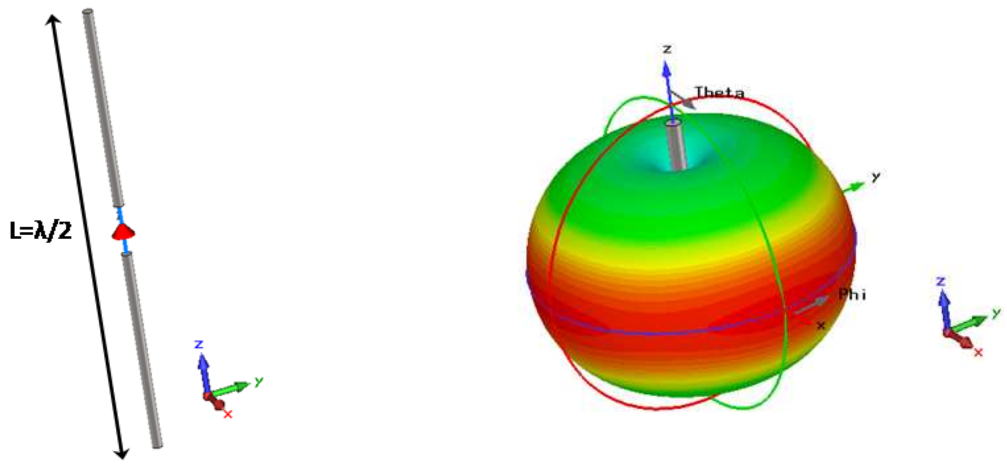
2. Wire antennas — Miniaturization techniques

2.1. Classical wire antenna: The dipole antenna

The dipole antenna has been developed by Heinrich Rudolph Hertz around 1886 and still remains the most widely used antenna (Figure 2). It owns two identical (same length) and symmetrical metal wires, and its feeding device is connected at the center of the dipole, i.e. connected to the two adjacent wires ends. The dipole working results of a standing wave phenomenon depending on its length. The antenna fundamental mode occurs when the whole antenna is a half-wavelength long.



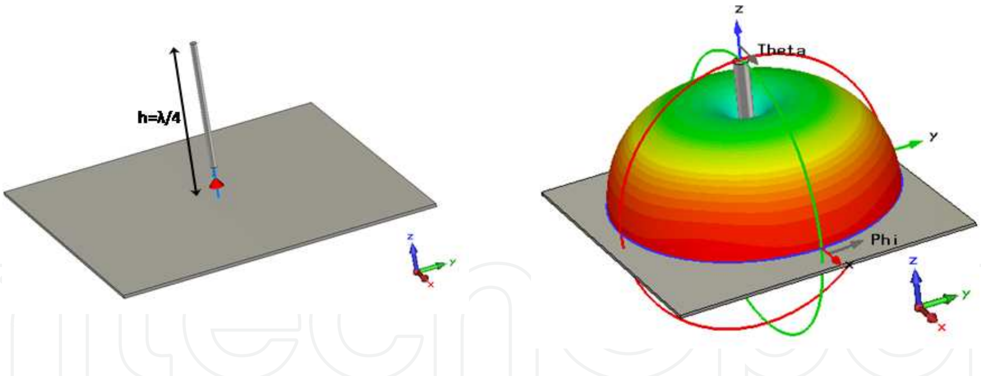
(a) (b)

Figure 2. Dipole antenna shape (a) and its 3D radiation shape (b)

The radiated field of the dipole antenna working on its fundamental mode has a linear polarization. As shown in Figure 2, its radiation pattern is maximum at right angles to the dipole and drops off to zero on the dipole's axis. Its maximum directivity equals 2.15dBi. The impedance bandwidth of this kind of antenna is quite wide since it is between 10% and 20% (it depends on the wire's radius) [28].

2.2. The monopole antenna

By adding a perpendicular ground plane at the center of the dipole antenna, its length can be divided by two: that is the monopole antenna. Theoretically, this ground plane is considered as an infinite Perfect Electric Conductor (PEC) plane. In this case, the current in the reflected image [29-30] has the same direction and phase as the current in the dipole antenna. Thus the quarter-wavelength monopole and its image together form a half-wavelength dipole that radiates only in the upper half of space (see Figure 3).



(a) (b)

Figure 3. Monopole antenna shape (a) and its 3D radiation shape (b)

Therefore it presents a 3 dB gain higher than the dipole antenna. The radiation resistance is proportional to $(h\ /\ \lambda)^2$, this latter is therefore decreasing the square of the antenna height h.

The first mobile phones were using this kind of antennas to receive the Global System for Mobile Communications (GSM) (see Figure 4).

Figure 4. Monopole antenna integrated inside a mobile phone

In practice, the finite ground plane disturbs the radiation pattern and the maximum directivity is decreasing. The monopole antenna bandwidth is quite the same as the dipole, i.e. up to 20%.

2.3. Inverted L and F antennas (ILA and IFA)

To reduce the monopole antenna global dimensions, we can bend the wire to be parallel to the ground: that is the Inverted L Antenna (ILA) [31]. Its design is depicted Figure 5, there is both a vertical and a horizontal parts. Since its electrical length is the same than the monopole, its

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resonance frequency is also the same. The radiation resistance is proportional to $(h / \lambda)^2$, with h the length of the vertical part (see Figure 5). Actually, the horizontal part occurs as a capacitive charge and this makes the antenna difficult to match on 50Ω. Therefore, the antenna bandwidth is very low and does not exceed 1% [31-33].

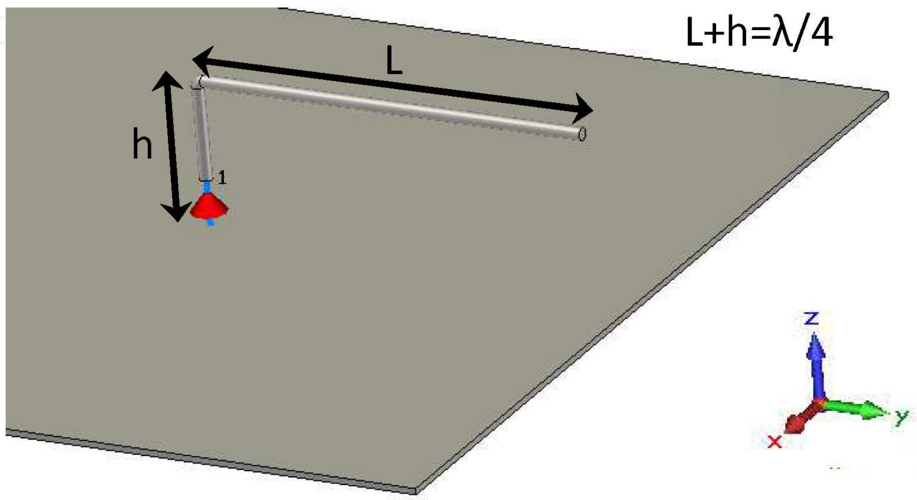

Figure 5. Inverted L Antenna (ILA) shape

Adding a ground wire on the horizontal part facilitates the ILA matching. This new antenna design is called Inverted F Antenna (IFA) (Figure 6). This wire is equivalent to a self-inductance in parallel with the capacitance of the horizontal wire. That involves a parallel resonance at low frequencies.

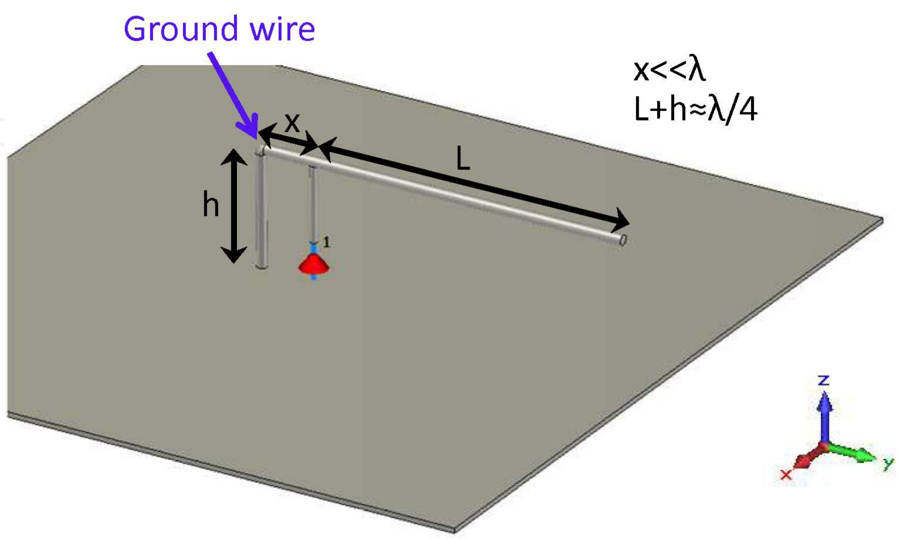

Figure 6. Inverted F Antenna (IFA) shape

To fit the input impedance around 50Ω, we can adjust wire's parameters (radius, distance with the feeding point,…). However, typical impedance bandwidths are around 2% or 3% [34-35].

2.4. The helical antenna

This kind of antenna allows reducing the physical length of an antenna (Figure 7). Basically, its fundamental mode is due to a quarter wavelength resonance. However, its bending structure can involve some capacitive and/or inductive resonances. This antenna has been widely used in mobile phone devices.

Figure 7. Helical antenna

Global dimensions of this kind of antennas are around $\lambda_0/10$ for its height with a $\lambda_0/40$ diameter. Its typical impedance bandwidth is up to 8%. Thus this antenna is covering the entire GSM band [36-37].

3. Planar antennas – Miniaturization techniques

3.1. Classical planar antenna: the patch antenna

The patch antenna was introduced by John Q. Howell in 1972 [38]. This kind of antenna presents a metallic top hat mounted on a dielectric substrate. Its lower face is the ground plane and its feeding can be a coaxial probe (Figure 8), a microstrip line or a coplanar waveguide.

The two metal sheets together form a resonant part of a microstrip transmission line with a length equals to a half of wavelength. Thus, its higher dimension is equal to $\lambda_g/2$, with λ_g the the guided wavelength. A simple patch antenna radiates a linearly polarized wave and its radiation can be regarded as a result of the current flowing on the patch and the ground plane. Thus its maximum gain is relative to the vertical axis of the patch and can reach 7 or 8 dB. The

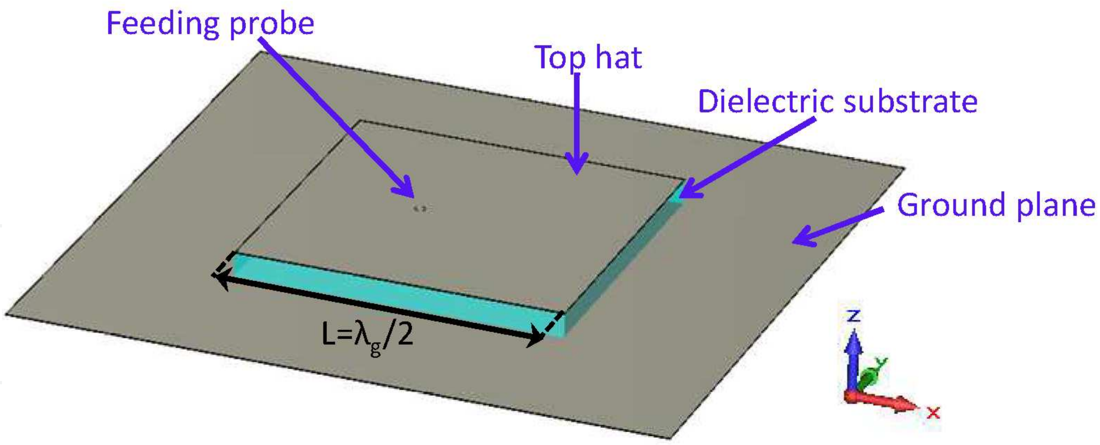

Figure 8. Patch antenna

impedance bandwidth is between 1% and 4% and depends on both the dielectric permittivity and the thickness of the substrate.

3.2. Miniaturization techniques of planar antennas

3.2.1. Use of materials

Using a material allow the reduction of the guided wavelength and thus the physical length of an antenna. Indeed, the patch antenna length is directly proportional to the refractive index of the dielectric substrate $n=\sqrt{\varepsilon_r.\mu_r}$. Using a dielectric material is the most common method to reduce the antenna size [39-40]. In this sub-section, we will show on one hand the antenna size reduction for a planar antenna printed on a dielectric substrate and on the other hand on a magneto-dielectric material substrate.

- **Using a dielectric material**

We consider the patch antenna presented Figure 8 with a 4cm-length and a 3mm-thickness. To show the impact of a dielectric substrate we consider two different cases:

- Substrate with low dielectric permittivity $\varepsilon_r=1$.
- Substrate with higher dielectric permittivity $\varepsilon_r=9$.

The Table 1 summarizes main results for patch antennas with strictly same dimensions.

	Resonance frequency	Matching frequency	Impedance bandwidth
Patch antenna with $\varepsilon_r=1$	3.7 GHz	3.8 GHz	4.1 %
Patch antenna with $\varepsilon_r=9$	1.3 GHz	1.32 GHz	0.98 %

Table 1. Comparison between two antenna patches with same dimensions printed on different substrates

As we can see in this table, the resonance frequency is divided by three with the increase of the dielectric permittivity value. Indeed, the miniaturization factor is close to the refractive index $\sqrt{\varepsilon_r.\mu_r}=\sqrt{9}=3$. However, the antenna miniaturization involves the reduction of its performances as its impedance bandwidth is divided by four.

Another solution is to use a magneto-dielectric material.

- **Using a magneto-dielectric material**

Hansen and Burke [41] have expressed the zero-order impedance bandwidth of a patch antenna printed on a t-thick magneto-dielectric material by the following equation:

$$BW = 96\sqrt{\frac{\mu}{\varepsilon}}.\frac{t}{\lambda_0} \Big/ \sqrt{2}\left(4+17\sqrt{\varepsilon.\mu}\right) \tag{1}$$

Thus, compared to high dielectric permittivity, high permeability materials allow to reduce the size of a patch antenna without decreasing its relative impedance bandwidth. In [42], Niamien et al. investigates magneto-dielectric materials losses and provides expressions of antenna impedance bandwidth and efficiency according to both dielectric and magnetic losses for a patch antenna. They showed that both the radiation efficiency and the impedance bandwidth increase with the permeability.

Considering the previous patch antenna (with a 4cm-length and 3mm-thick) by changing the dielectric material by a magneto-dielectric material, we obtain the Table 2 results.

	Resonance frequency	Matching frequency	Impedance bandwidth
Patch antenna with $\varepsilon_r=9$ and $\mu_r=1$	1.3 GHz	1.32 GHz	0.98 %
Patch antenna with $\varepsilon_r=4$ and $\mu_r=2.25$	1.35 GHz	1.38 GHz	1.87 %
Patch antenna with $\varepsilon_r=3$ and $\mu_r=3$	1.37 GHz	1.41 GHz	2.82 %
Patch antenna with $\varepsilon_r=2.25$ and $\mu_r=4$	1.38 GHz	1.45 GHz	3.29 %
Patch antenna with $\varepsilon_r=1$ and $\mu_r=9$	1.31 GHz	1.65 GHz	4.66 %

Table 2. Comparison between antenna patches with same dimensions printed on different substrates

This table compares patch antenna results with a same refractive index $n=\sqrt{\varepsilon_r.\mu_r}=3$. It should be noticed that all the materials are considered without any loss.

Therefore the comparison between the dielectric and magneto-dielectric materials shows that using the latter in a patch antenna allows increasing its impedance bandwidth. A patch antenna printed on a magneto-dielectric material presents the same miniaturization factor and allows the increase of its impedance bandwidth.

3.2.2. Modification of the antenna shape

- **Notches integration**

The integration of notches on the antenna top hat is often used. It allows to artificially increase the electrical length of the radiating element by extending the current "path" on this element (Figure 9).

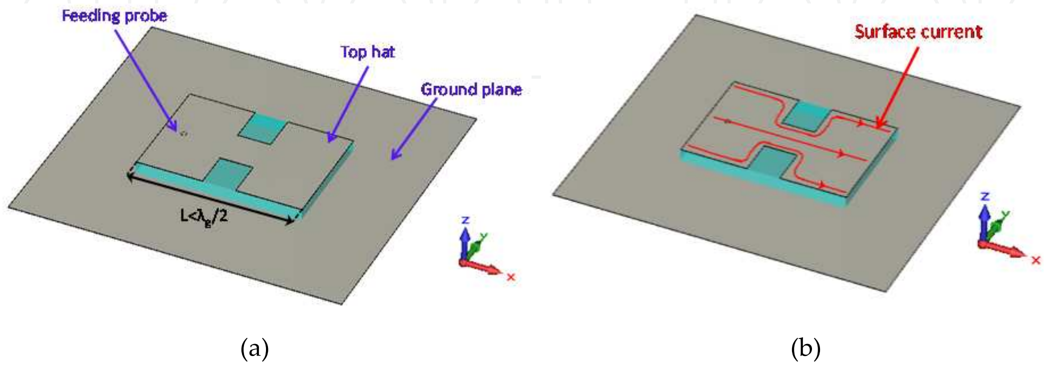

Figure 9. Integration of notches on antenna's top hat (a) Surface current lines (b)

The radiating element dimensions can be reduced up to 50% comparing with a classical patch antenna.

- **Meander antenna**

As for the helical antenna, the meander antenna allows decreasing the physical length of a planar antenna. The advantage is that this antenna is planar and thus easy to integrate inside a mobile phone. We can present on the Figure 10 a widely used meander antenna for the GSM reception on mobile phones. It is printed on a 0.8mm-thick FR4 substrate and is matched on 1%-bandwidth around 900 MHz with $\lambda_0/3$ x $\lambda_0/5$ dimensions.

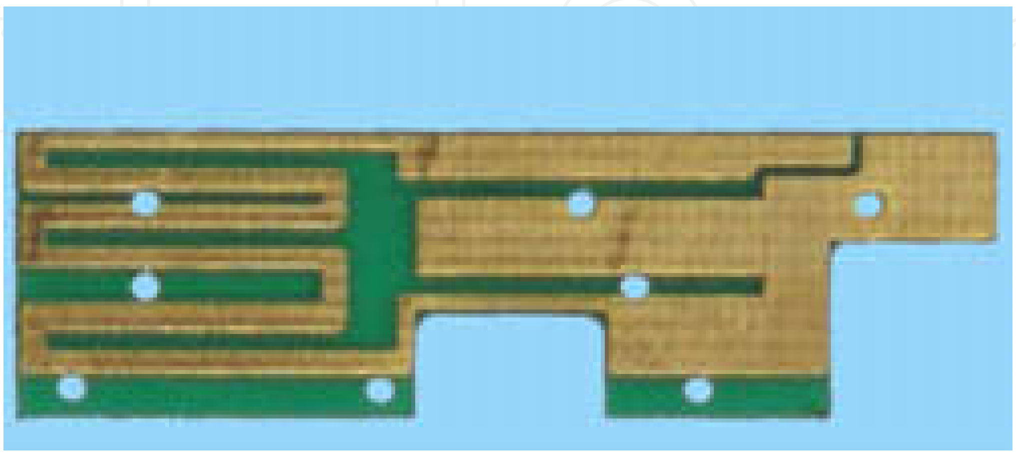

Figure 10. Meander antenna integrated within a mobile phone for the GSM reception

3.2.3. Short cut insertion

- **Planar Inverted F Antenna**

As for the dipole and the monopole, it is possible to integrate a metallic plate inside the patch antenna in order to divide its main dimension by two. Indeed, on the fundamental mode of the patch, we can integrate a short cut where the electric filed is null. To manage to match the antenna the metallic plate dimensions have to be optimised (Figure 11).

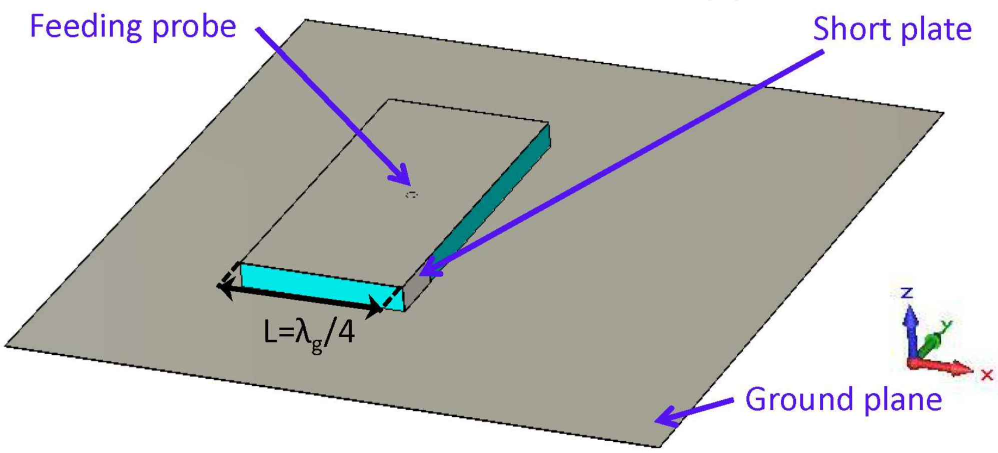

Figure 11. Planar Inverted F Antenna (PIFA)

In [43], a Planar Inverted Antenna with $\lambda_0/6$ x $\lambda_0/8$ x $\lambda_0/35$ dimensions at 2.45GHz is matching over a 6.5% impedance bandwidth.

- **Monopolar wire patch antenna**

The design of a classical wire patch antenna is presented in Figure 12. It is composed by two metallizations etched on each face of a dielectric substrate. The lower metallic plate acts as ground and the upper metallic plate constitutes the antenna top hat. This kind of antenna is fed by a coaxial probe which is connected to the top hat through the ground plane and the dielectric substrate. The ground wire acts as a short-circuit to the capacitance of the antenna constituted by the top hat above the ground plane and allows achieving a new low-frequency parallel resonance. The resonance frequency is smaller than the classical antenna fundamental cavity mode [44]. It is primarily set by the size of the top hat, the height of the antenna, the permittivity of the substrate and the ground wire diameter.

The main antenna parameters to adjust the antenna impedance matching to 50Ω are:

- The ground wire radius. The smaller the radius is, the higher the maximum of the input impedance real part is.

- The radius of the feeding probe. The higher the radius is, the lower the input impedance imaginary part is.
- The ground wire – feeding probe separation. The Q-factor is increasing when the length between the ground wire and the feeding probe core is increasing.

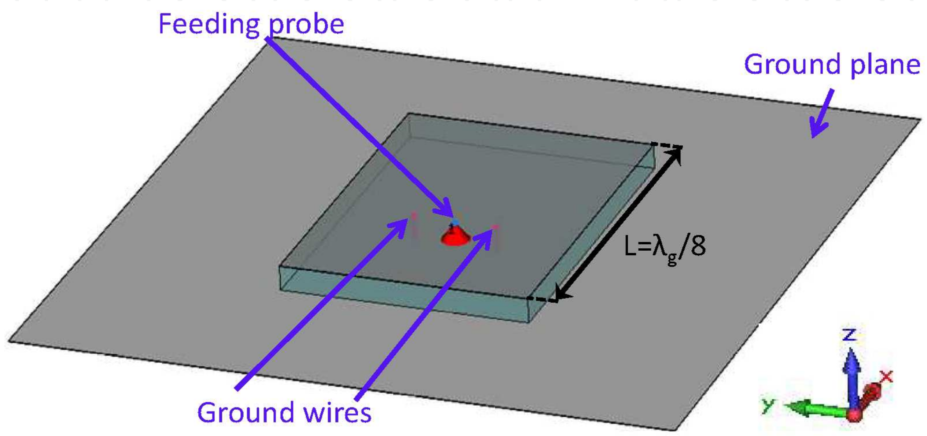

Figure 12. Monopolar wire patch antenna

As presented in [45-46], the use of a closed slot into the antenna top hat involves a significant reduction of the resonant frequency (Figure 13). Indeed, the introduction of a slot in the hat of the antenna changes the equivalent capacitance of the antenna short-circuited hat by increasing its value.

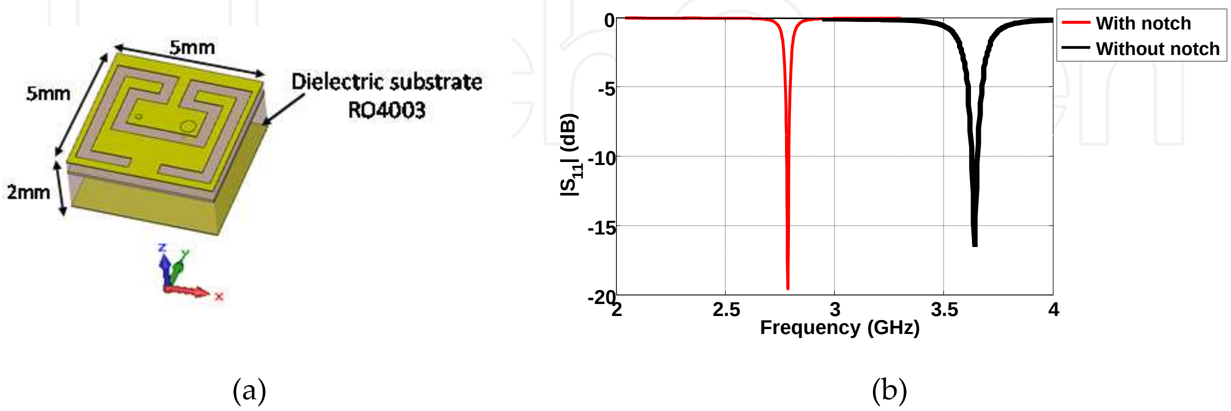

Figure 13. Monopolar wire patch antenna with a notch (a) and corresponding $|S_{11}|$ parameters

The longer the electrical length of the slot is, the lower the resonant frequency is. We can compare the $|S_{11}|$ parameters of the wire patch antenna presented in Figure 13 with and without the notch [47]. As expected, adding a notch inside the wire patch antenna top hat allows decreasing the working frequency but also the impedance bandwidth.

4. Dielectric resonator antennas (DRAs) – Miniaturization techniques

The design of a DRA in any geometry must satisfy various specifications including: the resonant frequency, the impedance bandwidth, the field distribution inside the resonator and also the radiated field. The intent of this part is to provide an overview of main findings of investigations on simple-shaped DRAs. Then, it will deal with the different miniaturization techniques of DRAs.

4.1. DRAs characteristics

A non-exhaustive list of main simple-shaped DRAs characteristics is described below:

- The main dimension of a DRA is proportional to $\lambda_0 / \sqrt{\varepsilon_r . \mu_r}$ where λ_0 is the free-space wavelength at the resonant frequency, ε_r and μ_r are respectively the dielectric and the magnetic constant of the material. In a dielectric material case, $\mu_r = 1$ and the main dimension of a DRA is proportional to $\lambda_0 / \sqrt{\varepsilon_r}$.
- The radiation efficiency of the DRA is highly depending on the material losses. In case of a low-loss dielectric material, DRAs allow to achieve better efficiency than other kind of antennas because of minimal conductor losses associated with a DRA.
- For a given dielectric constant, both resonant frequency and radiated Q-factor are defined according to the resonator dimensions. That allows having a great flexibility and some degrees of freedom to design such an antenna.
- Another degree of freedom is the large spectrum of available dielectric materials. That allows doing the best trade-off between dimensions and impedance bandwidth according to the intended application.
- A number of modes can be excited within the DRA, many of them provide dipolar-like radiation characteristics.
- The most common targeted frequencies presented by the research literatures are ranging from 1GHz to 40 GHz.
- For a given DRA geometry, the radiation patterns can be made to change by exciting different resonant modes.

A large number of DRA excitations are currently used, e.g. microstrip line, coaxial probe excitation, coplanar waveguide… The next subsection will deal with the most commonly used excitations.

4.2. DRAs miniaturization techniques

This subsection examines techniques to design compact DRAs. Targeted applications are mobile handsets or wireless tablet. There are several techniques to make DRAs more compact. By adding metal plates, inserting a high permittivity layer (multisegment DRA) or removing portions of the DRA, a significant size reduction can be achieved.

- **Addition of a metallic plate on a DRA face**

The rectangular DRA shape has been studied in the first part. The perfect metallic wall implies that electric fields are normal to this conductor, while magnetic fields are tangential. E and H fields presented Figure 14 assume that a metallic plate can be inserted in the middle of the DRA according to the y-component. The principle is detailed and explained by the Figure 14. It also shows the E and H fields of the TE_{111} mode.

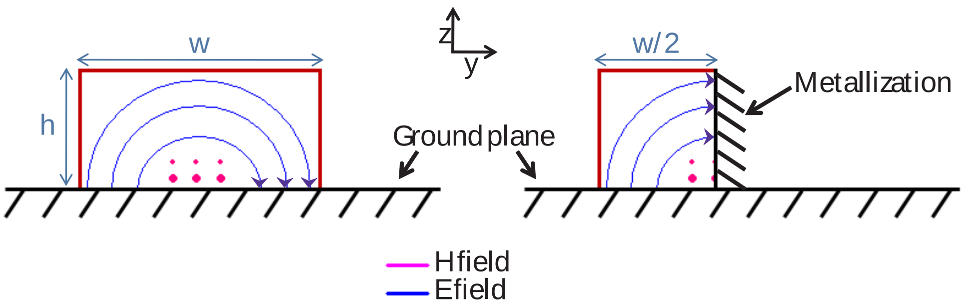

Figure 14. Integration of a metallic plate

By applying the image theory, it is possible to insert a metal plate in the y=w/2 plane. The Table 3 extracted from [48] shows the influence of the metallic plate insertion on resonant frequency and impedance bandwidth.

ε_r	w (cm)	d (cm)	h (cm)	Metallization	f_0(GHz)	Bandwidth
12	2.75	2.75	2.95	No	1.98	10%
12	2.75	2.75	2.95	Yes	1.24	5.6%

Table 3. Influence of the metallic plate insertion on both resonant frequency and impedance bandwidth

Thus, the metal plate insertion allows dividing by two the DRA size, while reducing the resonant frequency. However, as pointed by the Table 3, the metallic plate insertion involves also the decrease of the impedance bandwidth.

- **Multisegment DRA**

Another way to decrease the DRA size is to insert different substrate layers as illustrated Figure 15.

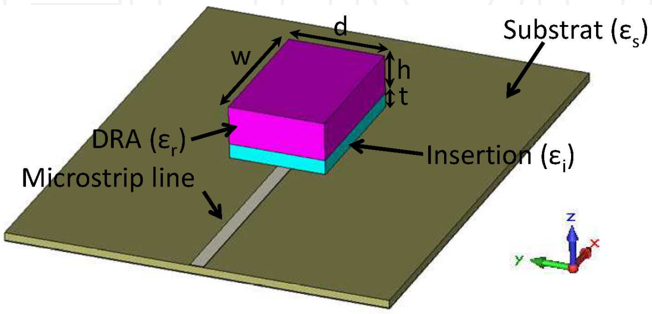

Figure 15. Multisegment DRA

It allows achieving strong coupling when the first insertion has a relatively high dielectric permittivity. This technique is detailed in [48] and [49]. The Table 4 summarizes a parametrical study done in [49] for one layer inserted (Figure 15) with w=7.875 mm, d=2 mm, h=3.175 and ε_r=10. It is mounted on a 0.762 mm height substrate of permittivity ε_s=3. The TE_{111} mode of the DRA is excited with a 50Ω microstrip line.

t (mm)	ε_i	Measured f_0(GHz)	Bandwidth
0	-	15.2	21%
0.25	20	14.7	18%
0.635	20	14.5	18%
1	20	13.9	16%
0.25	40	14.7	20%
0.635	40	13.7	13%
1	40	12.9	5%
0.25	100	14.7	16%
0.635	100	13.1	7%
1	100	10.8	5%

Table 4. A parametrical study done in [31] for one layer inserted

Thus, a thin layer insertion allows improving the coupling of modes inside the DRA while decreasing the resonant frequency thanks to the decrease of the effective dielectric permittivity of the DRA. As the previous technique, the downside is the decrease of the impedance bandwidth.

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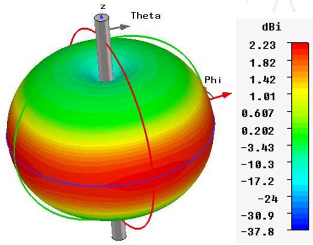
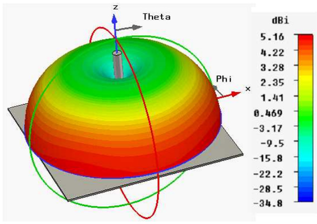
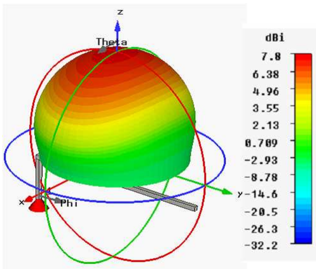
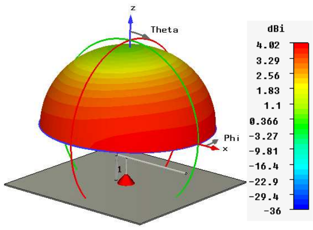
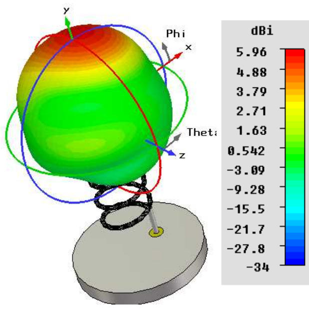
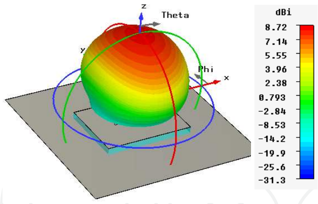
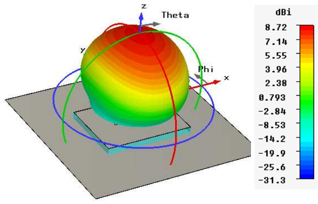
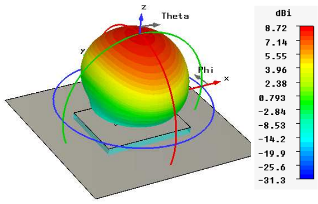
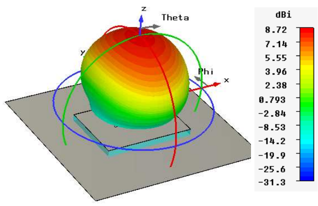
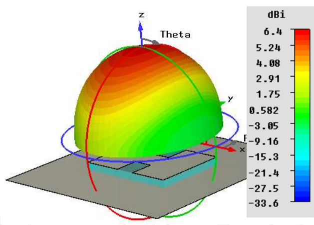
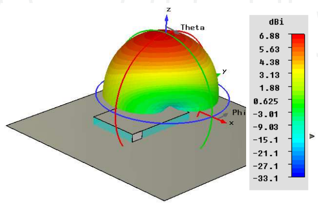
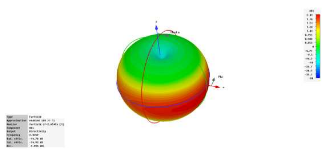
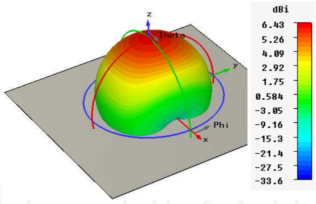
5. Summary of compact antennas performances

In this part, as a first conclusion we can summary the main performances of the previous presented antennas.

	Substrate	Dimensions	Impedance bandwidth	Radiation	Directivity (dBi)	Total efficiency
Dipole	Air	$\lambda_0/2$	10% à 20%		2.1	99%
Monopole	Air	$\lambda_0/4$	10% à 20%		5.1	99%
ILA	Air	$\lambda_0/20 \times \lambda_0/4$	1%		7	98%
IFA	Air	$\lambda_0/20 \times \lambda_0/4$	2%		4	98%
Helical	Air	$\lambda_0/10 \times \lambda_0/40$	7%		6	98%

	Substrate	Dimensions	Impedance bandwidth	Radiation	Directivity (dBi)	Total efficiency
Patch	Air	$\lambda_0/2 \times \lambda_0/2 \times \lambda_0/27$	4.1%		8.8	98%
Patch	ε_r=9 ($\tan\delta$=5.10^{-4})	$\lambda_0/6 \times \lambda_0/6 \times \lambda_0/76$	0.98%		7	89%
Patch	ε_r=2.25 - μ_r=4 ($\tan\delta_\varepsilon$=5.10^{-4} $\tan\delta_\mu$=5.10^{-4})	$\lambda_0/6 \times \lambda_0/6 \times \lambda_0/76$	3.29%		7.2	92%
Patch	ε_r=1 μ_r=9 ($\tan\delta_\varepsilon$=5.10^{-4} $\tan\delta_\mu$=5.10^{-4})	$\lambda_0/6 \times \lambda_0/6 \times \lambda_0/76$	4.66%		7.5	95%
Patch with notches	Air	$\lambda_0/4 \times \lambda_0/5 \times \lambda_0/68$	1.2%		6.4	95%
PIFA	Air	$\lambda_0/6 \times \lambda_0/8 \times \lambda_0/35$	6.5%		6.9	97%
Wirepatch antenna	Air	$\lambda_0/8 \times \lambda_0/8 \times \lambda_0/17$	3%		4	97%

	Substrate	Dimensions	Impedance bandwidth	Radiation	Directivity (dBi)	Total efficiency
DRA (2 layers)	ε_{layer1}=100 ε_{layer2}=10 ($\tan\delta_\varepsilon$=5.10^{-4})	$\lambda_0/4$ x $\lambda_0/14$ x $\lambda_0/7$	5%		6.4	95%

6. Conclusion

To conclude, an overview of classical antennas with their miniaturization techniques has been presented and detailed in this chapter while mentioning a lot of literature references. Classical wire antennas as monopoles present good impedance bandwidth, but they remain too large to be integrated inside last generations of mobile devices. Planar antennas have the advantage to be generally low profiles and thus easier to be integrate. However, patch antennas or planar inverted F antennas have maximum gains relative to the vertical axis. Thus, wire patch antenna presents a good alternative since it radiates as a dipole antenna and is significantly smaller. Concerning the dielectric resonator antennas, they can be miniature and can resonate and be matched on different frequency by creating some partial boundary condition [50].

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