Band widening technique for small integrated packaged antennas

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Abstract

In this work a different approach to widen the bandwidth of an electrically small antenna is proposed. Unlike other methods reported in literature the idea explored here uses the feeding network to improve the bandwidth. The methodology is illustrated using a circular patch antenna for testing purposes, but there is no fundamental reason why this approach would not work for other types of antenna. All presented results were obtained from full wave simulations of the antenna structure using commercial software.

Introduction

Modern electronic devices increase the demand for more integrated antennas within smaller available volumes. This is challenging for conventional antennas as their ideal half-wavelength working size is almost impossible to be achieved in many practical devices, especially when multiple communication standards are targeted and have to be integrated into a handheld device. With the development and spreading of the 'internet of things' (IoT), everything is expected to be wireless; however, packaging and integrating efficient antennas in all the objects envisaged by IoT is not straightforward and could be one of the limiting factors in the further advances and proliferation of IoT [1].

Electrically small antennas have features that make them suitable in applications such as the one mentioned above, mainly due to their compact size. However, small antennas suffer from poor radiation characteristics, mainly due to their smaller than half-wavelength size at the frequency of interest. Several approaches have been proposed to improve this situation, such as increasing the electrical size of the antenna without increasing its physical footprint, or reducing the quality factor of the antenna by allowing the antenna to use as much volume as possible from a virtual sphere that encloses the maximum physical dimension of the small antenna [2].

The physical size of the antenna with respect to the wavelength is the essential parameter which affects most radiation characteristics. Various approaches have been proposed to reduce the physical size of the antenna. The overall antenna size can be condensed by maintaining the physical length, while increasing its electrical length. Adding slits to the antenna body, or meandering the current path, are some of the popular methods through which the physical size of the antenna is maintained while the electrical length is increased [3]. Increasing the dielectric constant of a dielectric resonator antenna is another approach to increase the electrical length of the antennas [4]. However, the radiation resistance of an electrically small antenna is related to its effective length as $(l/\lambda)^2$, whereas its quality factor Q is proportional to its effective volume, which makes these structures very narrow band. In order to improve the bandwidth the quality factor of the antenna has to be lowered. Using efficiently the space within the effective volume of a sphere enclosing the antenna can help in reducing the quality factor Q. The sphere has a radius a, which specifies the maximum dimension of the antenna. Designing antennas that have geometry which utilize the occupied spherical volume to the greatest extent possible will result in a wider bandwidth behavior. However, this approach may result in complex and difficult to manufacture and package geometries such as the electrically small 4-arm folded spherical helix dipole antenna described in [5].

Another avenue explored to improve the bandwidth of electrically small antennas is using structures based on metamaterials, to either load the antenna with an elementary metamaterial cell [6] or use the metamaterial as the medium nearest to the radiating element [7]. Both these approaches improve the efficiency and bandwidth of the antennas but suffer from similar limitations as mentioned above.

Very recently a new approach based on injection matching has been proposed as a mechanism to improve the efficiency and bandwidth of electrically small antennas. In this technique, a two port configuration is implemented in which one port is exploited (the secondary port) in order to match the other port (the primary port) to the source [8, 9]. The matching of the antenna over the frequencies where it is not inherently matched with the source is done by injecting a current – with a proper phase shift and amplitude proportional to the source current – into the secondary port. Although this method produces relatively good results [8, 9], it transforms the antenna into a non-reciprocal device; therefore it has to be operated differently in the receiving and transmitting modes which will complicate the driving circuitry.

In the work presented in this paper a novel single port, but double excited, patch antenna concept is introduced. The feed of the antenna is designed so that it allows the input current to be split into two components which are coupled to the radiating patch at different positions. By changing these positions, as well as the phases and amplitudes of the two currents, noticeable improvement of the bandwidth of the small integrated antenna may be achieved.

Antenna structure

The antenna structure used in this work is based on a simple circular microstrip patch design. The radiating patch has a radius $r = 17\ mm$ and it sits on a dielectric substrate with a dielectric constant $\varepsilon_r=2.62$. The thickness of the substrate is $h = 3.2\ mm$. The frequency of the first resonant mode of this patch, which will also allow radiation, is the TM_{11} mode shown in Fig. 1. This frequency can be calculated analytically (following [10]) as

$$f = \frac{1.84118 \cdot c}{2 \cdot \pi \cdot r_{eff} \cdot \sqrt{\varepsilon_r}} \quad (1)$$

where c is the speed of light in free space and r_{eff} is the effective radius of the patch. The effective radius is defined as

$$r_{eff} = r\sqrt{1 + \frac{2h}{\pi \cdot r \cdot \varepsilon_r}\left(\ln\frac{\pi \cdot r}{2h} + 1.7726\right)} \quad (2)$$

Equation (2) is valid assuming that $(r/h) \gg 1$ (for this example this ratio is 5.31). The resonant frequency calculated using (1) for this patch is $f = 2.94$ *GHz*.

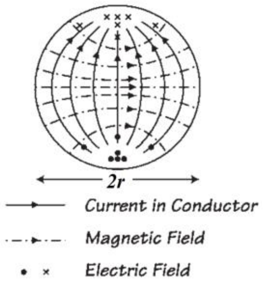
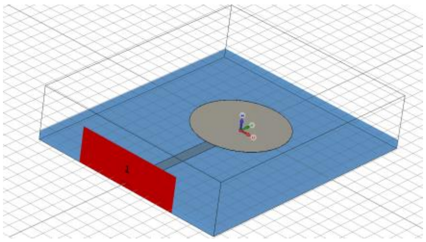
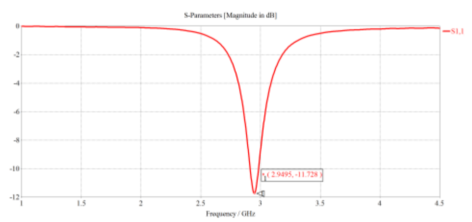


Fig. 1. Electric and magnetic field patterns of a circular microstrip antenna at resonance for the TM_{11} mode [10].

The antenna patch was excited using a strip line designed to have 50 Ω impedance. The CST Microwave software was used to build and solve the full wave model of the structure with the feeding strip line. The 3D model of the structure and the frequency response in terms of absolute value of S11 are presented in Fig. 2. It can be seen that the resonant frequency computed using the analytical approximation (2) matches very well the solution obtained from the full wave solver. It is also clear from the result shown in Fig. 2b that this antenna has a relatively narrow band of 70 kHz.



a.



b.

Fig. 2. a. 3D model of the circular patch antenna above the ground plane and with the strip line feed; b. |S11| response for the circular patch antenna.

Double injected circular patch antenna

Kabiri et all [8, 9] introduced a two port configuration antenna where one port is used to control the impedance seen in the other port through injection of an extra current; such configuration is referred to as the injection matching. The results presented in [8] and [9] show that the patch antenna can resonate at a frequency lower than the intrinsic resonance and also considerably improves the bandwidth of the antenna.

In a two port situation one can use the two port network theory to describe the relationship between the input and output voltages and currents through the Z matrix as

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \cdot \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} \quad (3)$$

where V_1 and I_1 and V_2 and I_2 are the voltages and currents at port 1 and port 2, respectively. If port 1 is the port for which the impedance is controlled by injecting a current into port 2, then the voltage at port 1 can be written as

$$V_1 = Z_{11} \cdot I_1 + Z_{12} \cdot I_2 \quad (4)$$

The ratio between the currents at the two ports can be introduced as

$$\frac{I_2}{I_1} = \gamma e^{j\varphi} \quad (5)$$

where γ is the ratio of the amplitude of the two currents and φ is the phase difference between the two currents. The input impedance at port 1 can be obtained by dividing (4) by I_1.

$$Z_{in1} = R_{in1} + j \cdot X_{in1} \quad (6)$$

To minimize the reflected power at the port 1, the imaginary part of the input port impedance should be zero, hence

$$|Z_{11}| \sin\theta_{11} + \gamma|Z_{12}| \sin(\varphi + \theta_{12}) = 0 \quad (7)$$

The input resistance at port 1 can also be expressed as

$$R_{in1} = |Z_{11}| \cos\theta_{11} + \gamma|Z_{12}| \cos(\varphi + \theta_{12}) \quad (8)$$

The phase difference between the two currents can be then expressed as

$$\varphi = \arctan\left(\frac{|Z_{11}| \sin\theta_{11}}{|Z_{11}| \cos\theta_{11} - R_{in1}}\right) - \theta_{12} \quad (9)$$

while the ratio of the amplitude is

$$\gamma = \frac{-|Z_{11}| \sin\theta_{11}}{|Z_{12}| \sin(\varphi + \theta_{12})} \quad (10)$$

The input impedance of port 2 can also be calculated once Z, θ and γ are known.

It will be noted that by choosing suitable values for the injection current at port 2 one can control the input impedance at port 1 and thus matching of structures that are not inherently matched can now be achieved.

The method presented in [8] and [9] is exclusively discussing the implementation of the injection method using two separate sources. However, if the two currents injected into ports 1 and 2 of the patch antenna are obtained from the same source by splitting the feeding network of the antenna, similar results as reported in [8] and [9] can be obtained. The major difference between the two approaches is the fact that when using one source the ratio between the input currents at port 1 and port 2 is always below 1, or maximum 1 when two currents are equal. But, on the other hand, it is expected that this approach will produce a reciprocal device which works in the same way when transmits or receives power.

The feed structure and the patch antenna are shown in Fig. 3. For this experiment the second feeding point (port 2) is chosen to be at 90 mechanical degrees with respect to the first feeding point (port 1). The phase difference between the currents fed into the patch can be controlled by the length of the transmission line connecting the second feeding point and the point where the two feeding line split. The ratio of the amplitude can be controlled by reducing the current flowing into the second feeding point; however, this method will only allow the ratio $\gamma < 1$.

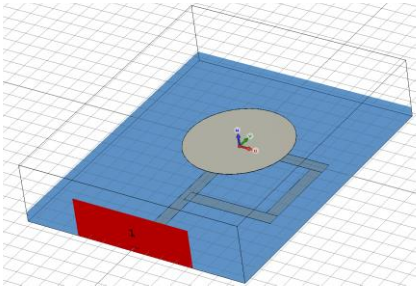


Fig. 3. Patch antenna with dual injection.

A typical result, for different phase differences between the two currents, is shown in Fig. 4. For these results the ratio is $\gamma = 1$. It can be seen that when $\varphi = 90°$ the bandwidth of the antenna is now around 150 MHz, which is double than the bandwidth of patch with the simple stripline feed. For the case when $\varphi = 0°$ the bandwidth of the antenna drops to around 70 MHz but the intrinsic resonance is not anymore 2.94 GHz but a lower value of 2.84 GHz. It will also be noted that an extra resonance appear at 2.55 GHz. When $\varphi = 180°$ the structure has the resonance at 2.84 GHz, but the lower resonance observed before has now dropped further to 2.46 GHz.

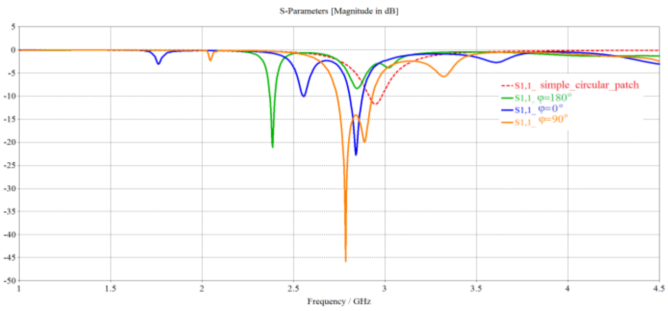


Fig. 4. |S11| response for the circular patch antenna when excited with double injection feeding structure.

It could be argued that the case when $\varphi = 90°$ is identical to a circular polarized patch antenna and the widening of the bandwidth is to be expected as reported in literature. However, the more interesting result is when $\varphi = 180°$ which has a strong resonance at 2.46 GHz. At this resonance the patch is electrically small and the current fed into the secondary point allows matching to be achieved as seen from the input port of this structure. This is the same type of behavior as detailed in [8, 9], so by injecting a secondary current into the antenna and controlling the phase of this current a matched condition can be achieved for the input port.

To further demonstrate the properties of the structure, several models with the length of the secondary feeding point modified, so that φ was varied between 168° to 237°, were investigated. The results in terms of the magnitude of S11 are presented in Fig. 5. It can be seen that as φ is increased from 168°, the first resonance drops from 2.48GHz to 2.28GHz when φ reaches 237°. Moreover, the impedance matching seen from the excitation improves as φ increases and reaches an optimum for $\varphi = 213.75°$. After that, increasing φ further will not improve the matching. However, a return loss better than -10 dB can be achieved over a large bandwidth of about 200 MHz, as shown in Fig. 5.

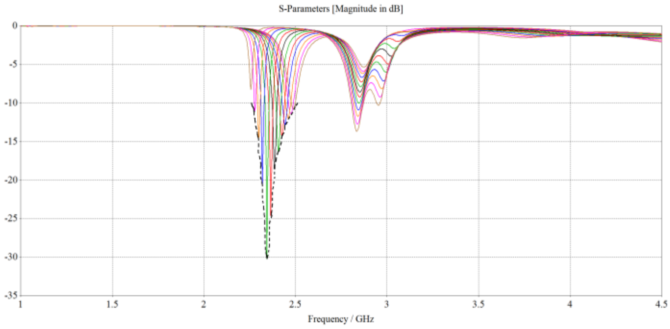


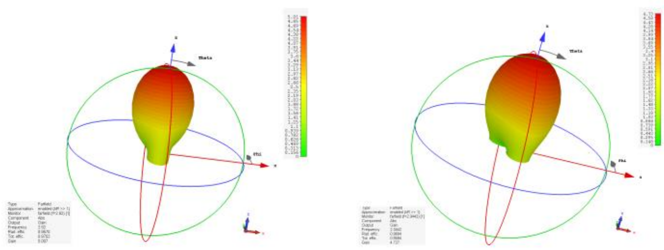
Fig. 5. |S11| response for the circular patch antenna when $168° \leq \varphi \leq 237°$.

Table 1. Input impedance and resonant frequency variation with φ.

φ (°)	Input impedance - Z_{in} (Ω)	Resonant frequency (GHz)
237.15	36.73-j33.43	2.2566
230.625	39.2-j26.6	2.2775
225	45.12-j16.8	2.3
219.375	53-j9.23	2.32
213.75	47.5-j1.17	2.3442
208.125	46.4+j4.9	2.365
202.5	48.4+j9.24	2.386
196.5	34.72+j9.35	2.4
191.25	44.25+j17.8	2.4264
185.625	46.04+j22.2	2.44
180	41.4+j22.2	2.46
174.375	42.5+j24.7	2.475
168.75	40+j24.3	2.487

The results in terms of resonant frequency and input impedance of the structure are summarized in Table 1.

The radiation pattern of the intrinsic circular patch antenna excited by the simple stripline as compared with the radiation pattern of the double excited structure are shown in figure 6. The radiation patterns of the antenna shows a small degree of degradation in the main lobe for the double injected case compared with the intrinsic case, seen as small drop in gain from 5 dB to 4.7 dB. This is caused mainly by the change in current density on the patch.



a. b.

Fig. 6. Radiation patterns

a. Simple circular patch antenna (f=2.94 GHz);

b. Double injected circular patch antenna (2.234 GHz).

The main disadvantage of the approach proposed in this paper is the fact that the feed length has to be modified to achieve the necessary phase difference between the two injected currents. To overcome this issue an alternative method to introduce the necessary phase difference is also suggested here. The electrical length of the feed line can be also altered by introducing appropriate lumped elements in the feeding circuit. For this particular example the characteristic impedance of the stripline computed by the CST full wave solver is 48.8 Ω and the phase constant of 148.9 m^{-1} at 4.5 GHz. Using these parameters one can extract per unit length inductance and capacitance of this line. The losses of the line were ignored in this example. The inductance per *mm* of this line is $L = 0.256\frac{nH}{mm}$, whereas the capacitance per mm is $C = 0.103\frac{fF}{mm}$. By removing a 1 mm line of the feeding structure connected to the second injection point and by replacing it with a series inductor and a parallel capacitor with the values presented above, the overall electrical length of the feeding line has not changed. If the values of the two lumped components are now varied in proportion to the electrical length that needs to be added, the same effect as increasing the physical length of the line is obtained. This works very well when only short increments are necessary (less or equal than 10^{th} of the wavelength at frequency of interest), such as in this case. The results shown in Fig. 7 are obtained with the methodology explained above. It is clear that these results match very well the results presented in Fig. 5 that have been obtained by varying the physical length of the line.

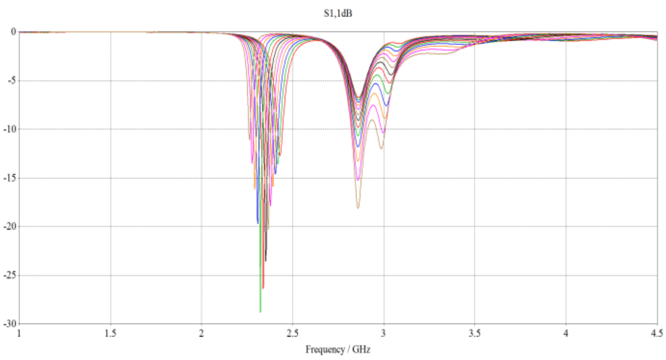


Fig. 7. |S11| response for the circular patch antenna when excited with double injection feeding structure – the electrical length of the injection path is varied using *L* and *C* lumped elements

Conclusions

Small efficient and reconfigurable antennas that can be packaged and integrated in a multitude of applications are highly desirable. In this work a method based on a double feeding has been presented as an efficient way of improving the bandwidth of a circular patch antenna. By choosing an appropriate phase difference between the two currents injected into the radiating patch the resonance frequency can be modified and varied in a relatively wide band. This method, unlike the injected match approach, does not modify the reciprocal behavior of the antenna. The results presented here are based solely on simulation but it is planned to demonstrate them through measurements in the near future.

References

1. Yen-Kuang Chen, 'Challenges and opportunities of internet of things', " *Design Automation Conference (ASP-DAC), 2012 17th Asia and South Pacific*, Jan. 30 2012-Feb. 2 2012 pp. 383 - 388.
2. Kim, O.S.: 'Low-q electrically small spherical magnetic dipole antennas', *IEEE Trans. Antennas Propag*., 2010, 58, (7), pp. 2210–2217.
3. Mavridis, G.A., Anagnostou, D.E., Chryssomallis, M.T.: 'Evaluation ofthe quality factor, q, of electrically small microstrip-patch antennas [wireless corner]', *IEEE Antennas Propag. Mag.*, 2011, 53, (4), pp. 216–224
4. Rotaru, M. and Sykulski, J.K., Design and analysis of a novel compact high permittivity dielectric resonator antenna, *IEEE Transactions on Magnetics* , 2009, 45, (3), pp.1052-1055.
5. Best, S.R., 'Low q electrically small linear and elliptical polarized spherical dipole antennas', *IEEE Trans. Antennas Propag*., 2005, 53, (3), pp. 1047–1053.
6. Sentucq, B., Sharaiha, A., Collardey, S., 'Metamaterial-inspired electrically small antenna for UHF applications'. *15th Int. Symp. On Antenna Technology and Applied Electromagnetics*, (ANTEM), 2012, pp. 1–4.
7. Ziolkowski, R.W., Erentok, A., 'Metamaterial-based efficient electrically small antennas', *IEEE Trans. Antennas Propag*., 2006, 54, (7), pp. 2113–2130.
8. Kabiri Y., Gardner P., Constantinou C., 'A Novel Approach for Wideband Tunable Electrically Small Antennas', *The 8th European Conference on Antennas and Propagation* (EuCAP), 2014, pp. 3633- 3637.
9. Kabiri Y., Gardner P., Constantinou C., 'Injection matched approach for wideband tunable electrically small antennas', *IET Microwaves, Antennas & Propagation*, 2014, Vol. 8, Iss. 11, pp. 878–886.
10. Bancroft R., Microstrip and printed antenna design SciTech Publishing Inc (New York, 2009), pp 76-92.