

Article

Broadband Two-Port Rectangular Patch Radiating Element Based on Self-Complementary Structure

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Abstract

In this article, a new approach to the applicability of the self-complementarity concept in a classical two-port microstrip patch antenna element is presented. This was accomplished through an illustrative design and an electromagnetic analysis of a broadband two-port rectangular printed radiating element in transmission configuration. A calculated ultra-wide matching bandwidth up to approximately 11 GHz was achieved ($BW_{\text{sim-RL} \geq 10 \text{ dB}} \approx 11 \text{ GHz}$, $f_o = 5.5 \text{ GHz}$, i.e., $BW_{\text{sim-relative-matching}} \approx 200\%$). One of the advantages of this topology is that only two degrees of freedom are needed to acquire a very wide impedance bandwidth: the length and the width of the slot. Full-wave analysis shows that suitable combinations of the patch and slot dimensions allow to obtain the broadband matching behavior. It has broadside radiation toward both hemispheres, which is conserved and considerably stable over a wide frequency range. Its linear polarization, radiation patterns, gain values, and radiation efficiency are adequate from 1 to 8 GHz ($BW_{\text{sim-radiation}} \approx 7 \text{ GHz}$, $f_o [\text{sim-rad}] = 4.5 \text{ GHz}$, i.e., 63.6% of its $BW_{\text{sim-matching}}$ and 156% of its $f_o [\text{sim-rad}]$). Moreover, the gain and radiation efficiency exhibit very good flatness across wide frequency ranges. Measurements of S-parameters and radiation patterns validate the calculated results. The proposed antenna element is simple, compact, and light-weight. It has a very wide operation bandwidth (7 GHz), its design is easy and flexible, and it is simple to manufacture. It could be used as a radiating element in different linear polarized antenna arrays.

Keywords: broad impedance bandwidth; broadband matching; wideband; ultra-wideband (UWB); microstrip antenna; rectangular patch; radiating element; self-complementary structure; two-port device; transmission configuration; antenna arrays



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1. Introduction

Microstrip patch antennas are widely used in communications and wireless applications. As is well known, one of their main disadvantages is their narrow impedance bandwidth, which is one of the major limitations to their operation, particularly in emerging wireless applications, like wireless networks, mobile communications, satellite, radar, i-maging, research on Oceanic Engineering, biomedicine, and others. Their narrow impedance bandwidth also implies a tight radiation bandwidth. Various solutions have been researched, analyzed, and proposed to solve the narrow matching bandwidth of this type of antenna, such as the use of thicker substrates, slots in the patch, the use of resonant

structures, using metamaterial-inspired structures, as well as modifications to the antenna (on or/and around the patch or/and in the ground plane), and others.

Yasuto Mushiake presented the self-complementary structure, which has the property of constant input impedance in the frequency [1–4]. Although the qualifying adjective “complementary” was already used by G. Deschamps in [5], was in [3] where the term *self-complementary* was first used by Y. Mushiake. Prof. Mushiake called his achieved analytical results the “*Self-complementarity Principle*” [4,6]. It has been applied mostly in wire and printed antennas by Mushiake and other engineers and researchers, mainly when the self-complementary parts (the conductive element and its complementary counterpart) are situated close to and next to each other in the same plane and layer [1–6]. This topology, initially discovered and used by Mushiake, will be referred to as *self-complementary structures situated contiguously in the same plane*.

The self-complementarity concept was applied to broadband antennas. Using this principle, V. Rumsey obtained important results, which he classified and called *frequency-independent antennas* [7]. Later, R. Duhamel and D. Isbell proposed logarithmic-periodic dipole antenna arrays [8,9]. Mushiake obtained very good results in applying the self-complementarity concept, both to simple and three-dimensional antenna configurations [1–6,10–14]. Many radiating elements using the self-complementarity approach have been proposed in the scientific and technical literature, some of which can be found in [1–6,11–17]. Some of these approaches, applying the *Self-complementarity Principle* in a single plane, and in the same layer of the dielectric substrate of printed circuit boards (PCBs) in the case of printed devices, use different shapes, such as ring resonators, X-shape, fractals, and others.

However, few studies and developments involving the self-complementarity concept have been carried out using two or more layers of printed circuit boards, where one of the parts of the structure is on one of the layers of the PCB, and its complementary part is on the next and parallel layer. This topology will be referred to as “*self-complementary structures situated or arranged geometrically in stacking*”. Mushiake and other researchers and engineers have been working in the research and development of antennas using *self-complementary structures arranged in stacking*. E. Abdo-Sanchez et al. proposed a self-complementary structure arranged in stacking as a radiating element [18]. It consists of a slot excited by a microstrip line in two-port and transmission configurations, with a complementary stub perpendicular to the microstrip line and situated in stacking and aligned to the slot [18]. This two-port structure has a large matching and wide radiation bandwidths. Subsequently, this structure was analyzed and presented as a broadband dispersive delay line by M. K. Mandal et al. in [19], where different shapes at the ends of the complementary part were studied. Afterwards, the authors of [18] proposed this structure as a broadband radiating element based on microstrip-slot coupling for series-fed arrays [20]. In [21], a wideband two-port microstrip-fed circular patch with its complementary slot etched on its ground plane, forming a *self-complementary structure arranged in stacking*, was proposed by Yordanis Alonso-Roque et al. This structure has a very wide matching bandwidth and good radiation characteristics.

The analysis, design, and measurement results of a broadband two-port microstrip rectangular patch radiating element in transmission configuration, using the concept of *self-complementarity in stacking arrangement*, are presented here. This proposed antenna element exhibits ultra-wideband matching (11 GHz, i.e., $BW_{\text{sim-relative-match}} = 200\%$), clean linear polarization, radiation in both hemispheres—which are conserved and considerably stable in a wide frequency range (from 1 to 6 GHz)—, good gain from 2 to 8 GHz, and adequate radiation efficiency from 1 to 8 GHz, which are comparable to, or even higher than, other similar radiating elements with two-port self-complementarity in a stacking

arrangement and in transmission configuration, as well as to others which do not necessarily have these three characteristics. This antenna element has a wide operating bandwidth (1 to 8 GHz, $BW_{\text{sim-operation}} = 7$ GHz, operation center frequency $f_{o[\text{operation}]}$ = 4.5 GHz, 63.6% of $BW_{\text{sim-match}}$, and 156% of $f_{o[\text{operation}]}$). In addition, other main and merits radiation characteristics are good and suitable in wide frequency ranges: attractive flatness of the gain in both main broadside radiation directions ($\Theta = 0^\circ$ and $\Theta = 180^\circ$) from 3.3 to 6.3 GHz (3 GHz, i.e., 27% of $BW_{\text{sim-match}}$, 43% of $BW_{\text{sim-rad}}$), and very good flatness of the radiation efficiency from 4 to 7.5 GHz (3.5 GHz, i.e., 32% of $BW_{\text{sim-match}}$, and 50% of $BW_{\text{sim-rad}}$). Moreover, it would be used in different applications, which mainly require broadband operation, such as broadcasting, wireless networks, mobile communications, satellite, radar, imaging, Oceanic Engineering research, biomedicine, and others. Furthermore, the proposed antenna element could be used in different antenna arrays with linear polarization, such as broadband or/and multiband series-fed antenna arrays, wideband or/and multiband corporative arrays, even with broad matching behavior in one or more frequency ranges in the cases of multiband performance, and others.

This paper is structured as follows. In Section 1, an introduction to the object of the research line and different proposed solutions is presented, followed by a brief presentation of the new approach and applicability under consideration. In Section 2, the contribution of this research work to the *state of the art* of broadband antenna elements and antennas is expressed, mainly in the field of two-port radiating elements in transmission arrangement, in special cases when they use the self-complementarity concept, and even others, which do not use two-port structures in transmission configuration and use the self-complementarity concept. After that, a summary of the theory of the *Self-complementarity Principle* is briefly explained in Section 3. In Section 4, the main results of the design of the classical two-port rectangular patch radiating element, in transmission configuration, which will be used as the *reference antenna*, are shown. In Section 5, a self-complementary structure geometrically arranged in stacking, with similar shapes and sizes as the reference antenna, and using a slot, is depicted. Here, the results of an illustrative design and an electromagnetic analysis of a wideband self-complementary microwave device are highlighted. Furthermore, the influence of the slot dimensions (length and width) on the S-parameters is presented in this section. The calculated radiation characteristics of the proposed broadband self-complementary device are then described. Also, a comparison of the analysis results of the proposed antenna element with those of the reference antenna is presented in this section. In Section 6, the measurement results of both S-parameters and radiation patterns of the proposed structure are expressed, analyzed, and compared with their corresponding computation results. Section 7 compares the obtained results of the proposed radiating element with other wideband ones, mainly using the concept of self-complementarity, already exhibited in the scientific and technical literature. In Section 8, a summary of the results of the calculated impedance matching bandwidth and radiation characteristics of an illustrative uniform series-fed antenna arrays with six elements of the proposed broadband antenna element is described, with the objective to show the use of the proposed radiating element in this type of antenna array. Here, the broadband and multiband behavior in the mentioned series-fed antenna array is also highlighted, even with wide matching in one or more frequency ranges in the cases of multiband matching performance, which is possible to achieve in this type of antenna using radiating elements like the one proposed here. Finally, Section 9 summarizes the conclusions of this work.

2. Previous Works and Current Contribution

Self-complementary structures have been applied mainly in wire and printed antennas by Y. Mushiake and other engineers and researchers, primarily when both parts (the

conductive part and its complementary one) are located very close and next to each other in the same plane, and in an identical layer of the dielectric substrate in the cases of printed devices [1–6]. It is the topology initially proposed and used by Y. Mushiake and others, and, henceforward, it will be referred to as *self-complementary structures situated conti-guously in the same plane*. Most of the solutions of this type of structure used in microwave devices and antennas, and presented in the knowledge fields of Electromagnetism, Microwave Engineering, Electronics, Antennas, and Telecommunications, have this topology.

After an exhaustive review of the databases of the scientific and technical publications in the aforementioned knowledge fields carried out by the authors of this study, we consider that there are few research works and results conducted with the aim to know, understand, and apply their theoretical basis from both Electromagnetism and Circuit Fundamentals in the applicability of self-complementary structures in antennas. This poor contribution to the mentioned *state of the art* is much more marked when the parts of the self-complementary structure are in parallel layers of the dielectric substrate (in stacking).

From the knowledge of the authors of this work, the use of self-complementary structures in parallel layers of a dielectric substrate (henceforward, *self-complementary structures in stacking arrangement*), applied to two-port patch radiating elements in transmission configuration, even with high operation bandwidth, as reached in this work, has not been presented in the scientific–technical publication databases in the aforementioned knowledge fields, mainly in letters, journals, and magazines. It is also known that there are no research results of wideband self-complementary structures in stacking arrangement, where at least the cause of obtaining the broadband response in the impedance matching is expressed, explained, and justified, except for [21].

The use of *self-complementary structures in stacking arrangement* in two-port microstrip patch antennas in transmission configuration was carried out and presented for the first time to the international scientific–technical communities of the mentioned scientific and technical knowledge fields by Yordanis Alonso-Roque et al. in [21].

One of the main advantages and contributions of the work presented here to the mentioned scientific–technical knowledge fields is the obtaining of broadband impedance matching, good radiation patterns, wide radiation bandwidth, and other main radiation and merits characteristics in a two-port microstrip rectangular patch radiating element in transmission configuration using the *self-complementarity concept*. It is important to highlight that this is based on a postulate with a solid electromagnetic theoretical basis, which was discovered by Y. Mushiake [1–4,6], and he called it the “*Self-Complementarity Principle*” (*note: more knowledge on this can be found in Section 3*).

This research work describes a full-wave electromagnetic analysis as well as the design and measurement results of the mentioned broadband two-port radiating element in transmission configuration, using the *self-complementarity concept in stacking arrangement*. It has good linear polarization, bidirectional broadside radiation patterns with considerable conservation in the frequency, as well as adequate gain and radiation efficiency values within very broad frequency ranges, and, consequently, it has wide operation bandwidth, mainly comparing this one with similar ones and others (not necessarily with two feeding ports, in transmission configuration, and using the self-complementarity concept) found in the mentioned corresponding *state of the art*. In addition, it has very good flatness of gain and radiation efficiency over wide frequency ranges. This antenna element is not complex, is compact, has little weight, and is easy and flexible to design and manufacture. In addition, it could be used as a radiating element in different types of linear polarized antenna arrays, such as series-fed antenna arrays and corporative-type arrays, both with wideband or/and multiband matching behavior, even with broad matching in one or more frequency ranges –in the case of multiband matching performance–, and others.

Another of the main goals and contributions of this work is to show the applicability specifically of the *self-complementary structures in stacking arrangement* to a two-port microstrip patch antenna element in transmission configuration. Concretely, this goal consists of making it known that the mentioned applicability in a two-port rectangular patch radiating element in transmission configuration is an excellent solution to increase the matching and radiation bandwidths, as well as to improve some of the main radiation characteristics and merit figures, even the behaviors of at least some of them in the frequency, and very wide operation bandwidth.

From the physical-inside, performance, and technical points of view, another advantage of this research work is the use of the self-complementarity concept, particularly on the mentioned microstrip patch antenna element, which provides added value for wideband or/and multiband radiating elements, taking into account the inherent, known and proven benefits of this type of antenna: compactness, low weight, the possibility of obtaining different operation modes, and the versatility to achieve different performance in terms of impedance matching, polarization, transmission and radiation characteristics, and others, even many of those over considerable frequency ranges.

Therefore, the technique proposed here to achieve wide bandwidths for both matching and radiation is unique and simple, and it allows us, with a singular form, to enhance some main and merits radiation characteristics, even in the frequency and, consequently, a wide operation bandwidth, in the studied topology of the microstrip patch antenna element. Without a doubt, the novel applicability of a very solid electromagnetic principle in a two-port microstrip antenna element in transmission configuration is presented here, primarily reaching very good results for some of the antenna's fundamental parameters and merit figures in the analyzed and proposed topology.

Finally, it is important to express that Section 6 provides a comparison of the proposed structure with other broadband printed antenna elements with one or two feeding ports, in transmission configuration, and using or not the self-complementarity concept, found in the current corresponding *state of the art* in publications in the knowledge fields of Electromagnetism, Microwave Engineering, Electronics, Antennas, and Telecommunications, which confirms the contribution of this article to the mentioned *state of the art*.

3. Theory of Self-Complementary Structures

3.1. Principle of Self-Complementarity

The self-complementarity concept was obtained and presented by Yasuto Mushiaki [1–4,6]. He defined the “*Self-Complementarity Principle*”, which basically states that a self-complementary structure with its two parts situated contiguously has a constant input impedance, independently of the frequency source and of the shape of the structure [4,6]. This is a postulate with very solid and powerful electromagnetic and circuit theoretical bases. A self-complementary structure is composed of a conducting part, with arbitrary form, generally surrounded by a dielectric medium, on a dielectric substrate of a printed circuit board (PCB). In addition, it has a non-conducting part surrounded by a conductive material in the same PCB, with arbitrary and equal forms and contiguous to the mentioned surface (the conducting part). In this section, a summary of the theory of this principle is presented.

Firstly, it is appropriate to begin with the electromagnetic analysis of two planar sheets, as depicted in Figure 1. Each one of these two planar sheets is composed of a perfect electric conductor (PEC) and a perfect magnetic conductor (PMC), which are on the surfaces (S_1 and S_2) of the planar sheets in Figure 1 [4]. Both surfaces, S_1 and S_2 , have arbitrary and equal shapes but different electrical and magnetic properties. Surface S_1 is conductive, while S_2 is non-conductive (generally, it is a dielectric medium) in the planar

sheet in Figure 1a and in the opposite form in Figure 1b. This means that the electric currents should be presented mostly on S_1 , and the magnetic currents should be mostly on S_2 . However, the electric current sources are situated in the sheet in Figure 1a, while the magnetic current sources are situated in the sheet in Figure 1b. The electric current (represented by its corresponding density $J_o = N_+$) in Figure 1a is symmetrical with respect to the plane formed by the sum of surfaces ' $S_1 + S_2$ ', while the magnetic current (represented by its corresponding density $J_{om} = \pm N_+$) in Figure 1b is anti-symmetrical with respect to this same plane ' $S_1 + S_2$ ' [4]. The arrows in Figure 1a,b represent the mentioned symmetrical electric and anti-symmetrical magnetic currents, respectively.

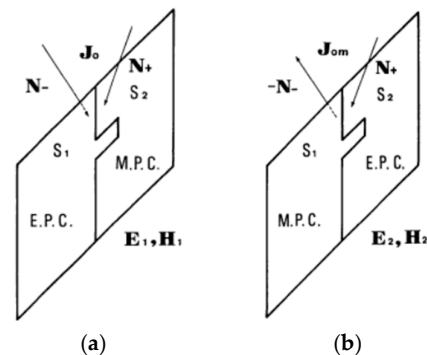


Figure 1. A pair of planar sheets of compound perfect conductors forming an electromagnetically dual structure (*note*: this picture is taken from [4]).

Then, Maxwell's equations in the *self-complementary structures situated contiguously* can be written [4] as follows:

$$\nabla \times E_1 + j\omega\mu H_1 = 0 \quad (1a)$$

$$\nabla \times H_1 - (j\omega\varepsilon + \sigma)E_1 = J_o = N_{\pm} \quad (1b)$$

$$\nabla \times E_2 + j\omega\mu H_2 = -J_{om} = \mp N_{\pm} \quad (2a)$$

$$\nabla \times H_2 - (j\omega\varepsilon + \sigma)E_2 = 0 \quad (2b)$$

where:

ω : the angular frequency ($\omega = 2\pi f$)

f : frequency

σ : conductivity of the medium

ε : electric permittivity of the medium

μ : magnetic permeability of the medium

J_o and J_{om} : density of the electric and magnetic currents, respectively

E_1 and E_2 : electric field intensities of the surfaces S_1 and S_2 , respectively

H_1 and H_2 : magnetic field intensities of the surfaces S_1 and S_2 , respectively

$\pm$: the signs of the right and left sides of the conducting surface in Figure 1

The electromagnetic fields must satisfy the boundary conditions for the PEC and PMC, for the following expressions:

$$E_1 \times n = H_1 \cdot n = 0, \quad \text{on } S_1 \text{ surface} \quad (3a)$$

$$H_1 \times n = E_1 \cdot n = 0, \quad \text{on } S_2 \text{ surface} \quad (3b)$$

$$H_2 \times n = E_2 \cdot n = 0, \quad \text{on } S_1 \text{ surface} \quad (4a)$$

$$E_2 \times n = H_2 \cdot n = 0, \quad \text{on } S_2 \text{ surface} \quad (4b)$$

where n is the unit normal vector on surfaces S_1 and S_2 .

After that, it is possible to find that the electromagnetic field components on surfaces S_1 and S_2 , E_2 and H_2 in Equations (2) and (4), can be replaced by the electromagnetic field components H_1 and E_1 in Equations (1) and (3) using the following relations [4]:

$$E_2 = \mp H_1, \text{ and } H_2 = \pm \gamma E_1 \quad (5)$$

where γ is the intrinsic impedance of an arbitrary medium, which is calculated as follows:

$$\gamma = \frac{j\omega\varepsilon + \sigma}{j\omega\mu} = \frac{\varepsilon}{\mu} - j\left(\frac{\sigma}{\omega\mu}\right) \quad (6)$$

As can be observed, if the term E_1 is interchanged with H_2 , using Expression (5), and similarly H_1 with E_2 , then the pairs of Equations (2a) + (2b) and (4a) + (4b) can be transformed into the pairs of Equations (1a) + (1b) and (3a) + (3b), respectively [4]. Therefore, there is an electromagnetic property of duality between electric and magnetic fields E_1 and H_1 , and E_2 and H_2 , if all electric and magnetic walls and electric and magnetic currents in the sheet of Figure 1a are interchanged for magnetic and electric walls and magnetic and electric currents in the sheet of Figure 1b, respectively [6]. The previously presented analysis is closely related to *Babinet's Principle*, which in Electromagnetic Fields Theory (*Electromagnetism*) is, in turn, derived from the duality property [6].

It is important to highlight that the previously mentioned theoretical electromagnetic analysis explains, analytically and in simple form, the mutual and dual electromagnetic character of both complementary surfaces.

In addition, a brief analytical study and the corresponding explanation of the input impedance of self-complementary structures, mainly with contiguous arrangement, will be presented below.

3.2. Input Impedance of Self-Complementary Structures

Professor Mushiake applied the basic electromagnetic theory on a PMC surface on the symmetrical planes of the above-mentioned surfaces, where the boundary conditions were satisfied, taking into account the electric and magnetic fields and the corresponding currents shown in Figure 1. Then, the impedances of both mentioned surfaces (S_1 and S_2) are obtained as a function of the electric and magnetic fields. Considering the obtained expressions of both impedances Z_1 and Z_2 , a product of them can be expressed as follows:

$$Z_1 \cdot Z_2 = \frac{1}{4\gamma} = \frac{(Z_o)^2}{4} \quad (7)$$

where Z_o is the intrinsic impedance in free space ($120\pi \Omega \approx 377 \Omega$).

From (7), it is possible to obtain Z_o , as follows:

$$Z_o = 2\sqrt{Z_1 \cdot Z_2} \quad (8)$$

As is known in *contiguous self-complementary structures*, the input impedance of medium 1, Z_1 , is equal to the input impedance of its complementary part Z_2 , so that it is possible to state the following:

$$Z = Z_1 = Z_2 \quad (9)$$

From (7) to (9), the following expression is achieved:

$$Z = \frac{Z_o}{2} = \frac{1}{2} \cdot \sqrt{\frac{1}{\gamma}} \quad (10)$$

which is equivalent to:

$$Z = \frac{1}{2} \sqrt{\left(\frac{j\omega\mu}{j\omega\varepsilon + \sigma} \right)} \quad (11a)$$

$$Z = \frac{1}{2} \sqrt{\left(\frac{\mu}{\varepsilon} + j \frac{\omega\mu}{\sigma} \right)} \quad (11b)$$

Hence,

$$\text{Re}[Z] = R = \frac{\mu}{\varepsilon} \quad (12a)$$

$$\text{Imag}[Z] = X = \frac{\omega\mu}{\sigma} \quad (12b)$$

Therefore, in free space, (10) and (11) become:

$$Z = 60\pi \Omega \approx 188.5 \Omega \quad (13)$$

Equations (10)–(12) are frequently found in the scientific and technical literature on Electromagnetism, Microwave Engineering, Antennas, and Telecommunications Engineering, and (11) is known as “Mushlake’s relationships” [4,6].

4. Reference Antenna: Two-Port Rectangular Patch Radiating Element Fed by Microstrip Line in Transmission Configuration

Figure 2 depicts the geometry of the two-port microstrip-fed rectangular patch radiating element in transmission configuration, which is used as the *reference antenna* in this research work. The substrate used in this radiating element is Rogers Corporation’s Duroid RO3003 (relative dielectric permittivity $\varepsilon_r = 3$, loss factor $\tan\delta = 0.001$), with thickness $h_s = 60$ mils (1.524 mm) and copper thickness $t_c = 35 \mu\text{m}$.

The *reference antenna* was designed for a center frequency of 5 GHz using the transmission line model and a full-wave electromagnetic (EM) analysis. The dimensions of this design are as follows: microstrip line width $W_L = 3.8$ mm, patch length $L_p \approx \lambda_g [5 \text{ GHz}]/2 \approx 17.3$ mm (dimension in the direction of the longitudinal axis, y -axis in Figure 2), patch width $W_p = 21.2$ mm (dimension in the direction of the transverse axis, x -axis in Figure 2), ground length $L_g = 60$ mm (longitudinal axis, y -axis in Figure 2), and ground width $W_g = 2W_p = 42.4$ mm (transverse axis, x -axis in Figure 2). The design results are presented below.

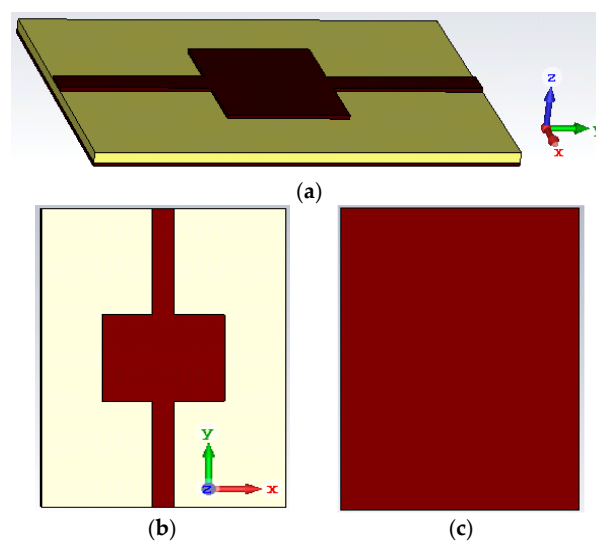


Figure 2. Two-port rectangular patch radiating element in transmission configuration (*the reference antenna*): (a) the isometric view, (b) top view, and (c) bottom view.

Figure 3 shows the absolute value of the calculated S-parameters of the *reference antenna*. It has an impedance matching bandwidth (of more than 10 dB return loss) from 4.67 to 5.29 GHz ($BW_{RL \geq 10\text{dB}} \approx 620$ MHz), which is about 12% of its computed center frequency (5 GHz). In addition, its transmission coefficient has values up to approximately -3 dB in its matching bandwidth, and it is 0.8 dB at its center frequency. Hence, it has a narrow matching bandwidth and high transmission coefficient values within its impedance matching bandwidth. Therefore, it cannot be considered as a broadband two-port radiating element, nor is it a suitable element for wideband antenna arrays, such as series-fed linear ones.

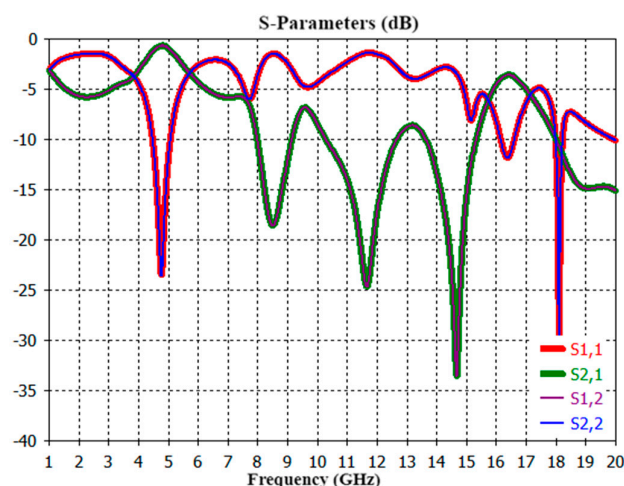


Figure 3. Calculated absolute S-parameters ($|S_{ij}|$ in dB) of the *reference antenna* from 1 to 20 GHz.

In Figure 4, the computed axial ratio (AR) of the *reference antenna* at its main radiation direction (in broadside, $\Theta = 0^\circ$) within its impedance matching bandwidth is presented. It has values of approximately 40 dB at its main radiation direction in the matching bandwidth, like the single-port rectangular patch antenna. Hence, this antenna element has linear polarization with very good purity.

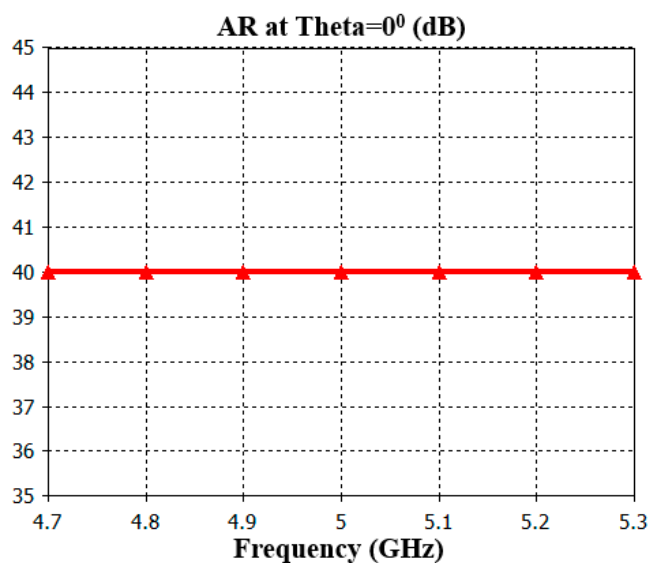


Figure 4. Calculated absolute axial ratio (AR in dB) of the *reference antenna* in its main radiation direction (in broadside, $\Theta = 0^\circ$) within its impedance matching bandwidth.

The calculated gain's radiation patterns in the main radiation planes ($\varphi = 0^\circ$ and $\varphi = 90^\circ$) at its center frequency are presented in Figure 5. As can be observed, the resulting

patterns have a wide main lobe in the broadside direction, the plane that contains the patch, showing unidirectional broadside radiation in both main radiation planes, with symmetry around the mentioned broadside direction $\Theta = 0^\circ$ (with respect to the vertical axis). Its maximum gain is in the broadside direction of the patch plane $\Theta = 0^\circ$, and it is approximately 6.5 dB.

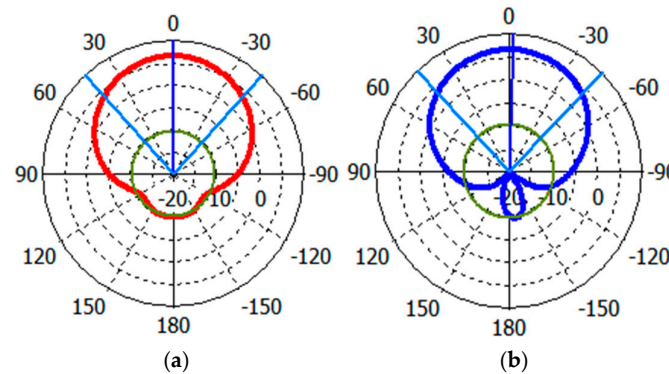


Figure 5. Calculated gain radiation patterns (in dB) of the *reference antenna* at its center frequency (5 GHz) in the main radiation planes: (a) transversal plane ($\Phi = 0^\circ$, *H-plane*, red diagram), and (b) longitudinal plane ($\Phi = 90^\circ$, *E-plane*, blue diagram).

5. Analysis and Design of the Proposed Broadband Two-Port Radiating Element

The proposed structure is a two-port rectangular patch antenna element, fed by a microstrip line, in transmission configuration, like the *reference antenna*. It also has a slot engraved into its ground plane, with the same shape (rectangular) and equal dimensions as the patch, and it is in stacking arrangement and aligned with respect to the patch. In other words, the patch and the slot constitute a *self-complementary structure in stacking arrangement*, aligned in two-port and transmission configuration and excited by a microstrip line. The dielectric substrate used in this two-port topology is the same Duroid RO3003 as that of the *reference antenna*. Photographs of one of the fabricated and measured prototypes are shown in Figure 6.

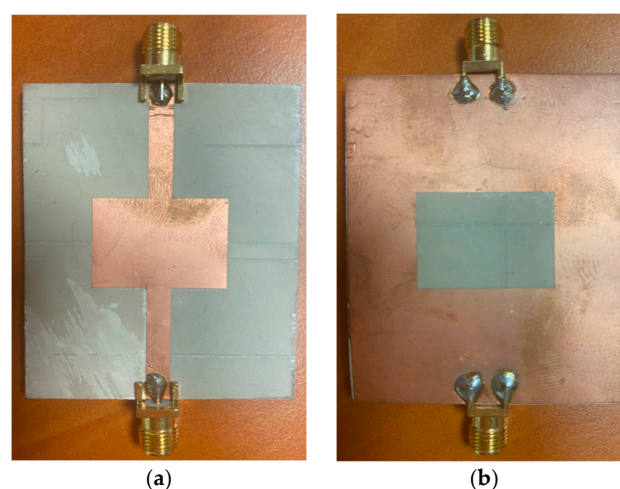


Figure 6. Photographs of a prototype of the proposed broadband radiating element: (a) top view and (b) bottom view.

To carry out the proof of concept and the applicability of self-complementary structures arranged in stacking in a two-port microstrip-fed rectangular patch antenna in transmission configuration, an electromagnetic (EM) analysis and an illustrative design of this

two-port self-complementary topology, with equal dimensions and using the same rectangular coordinate system as the *reference antenna*, were performed. They were carried out with the help of a full-wave EM analysis. The dimensions of this design are as follows: microstrip line width $W_L = 3.8$ mm, patch length $L_p \approx \lambda_g[5 \text{ GHz}]/2 \approx 17.3$ mm (in the direction of the longitudinal axis, y -axis in Figure 6), patch width $W_p = 21.2$ mm (in the direction of transverse axis, x -axis in Figure 6), ground length $L_g = 60$ mm (in the longitudinal axis, y -axis in Figure 6), ground width $W_g = 2W_p = 42.4$ mm (in the transverse axis, x -axis), slot length $L_{slot} = W_p = 21.2$ mm (in the transverse axis, x -axis), and slot width $W_{slot} = L_p \approx \lambda_g[5 \text{ GHz}]/2 \approx 17.3$ mm (in the longitudinal axis, y -axis). This element is completely symmetrical with respect to both axes ' x ' and ' y '. The results of an illustrative design and an electromagnetic analysis are described below.

Figure 7 shows the calculated S -parameters of this self-complementary structure. As can be seen, it has an ultra-broad 10 dB return loss bandwidth of about 11 GHz, which is 200% of its center frequency, 5.5 GHz (computed relative matching bandwidth with regard to narrowband antennas, taken as a reference magnitude). The transmission coefficient ($|S_{21}|$) decreases with the frequency in a range from 7 to 13 GHz, with values from about -0.2 to -6.7 dB. Then, it is important to note that $|S_{21}|$ is quite flat, practically from 1 to 3 GHz and from 4 to 7 GHz, with values higher than -2 dB up to 7 GHz, which is a significant improvement compared to the *reference antenna*. Moreover, it is important to highlight that $|S_{21}|$ decreases from 7 to 13 GHz in a practically linear manner. Hence, it has a useful transmission behavior from port 1 to port 2 within its impedance matching bandwidth, mainly from 1 to 7 GHz, which is a very good result considering that it could be used in series-fed antenna arrays.

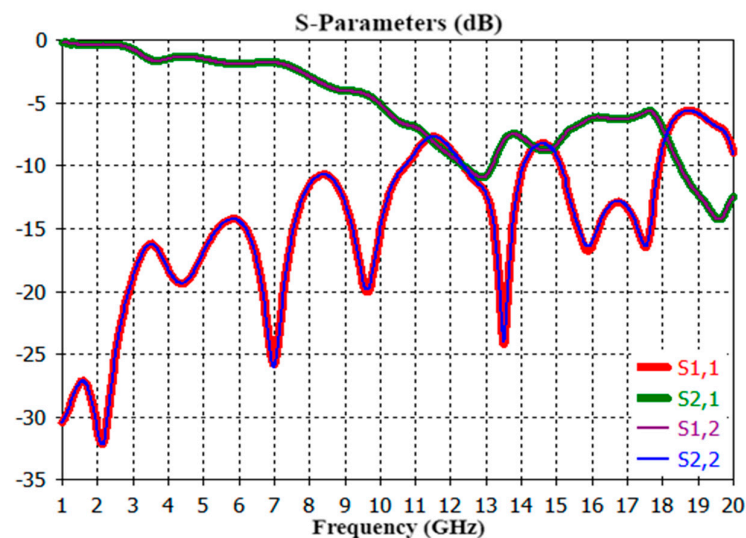


Figure 7. Computed absolute S -parameters of the proposed self-complementary antenna element from 1 to 20 GHz.

The matching bandwidth is very wide, even compared with other two-port and single-port radiating elements that can be found in the current scientific–technical databases [11–44], mainly if the self-complementarity concept in two-port elements with transmission arrangements is involved.

An interesting aspect of this element is that the ultra-wideband matching behavior can be achieved using adequate combinations of width–length values of both the patch and the slot, which provide flexibility to the design of this structure. Figure 8 shows some of the several cases of broadband impedance matching obtained with different width and length values for both the patch and the slot. Table 1 shows the impedance matching bandwidths

and relative matching bandwidth, considering the antenna's narrow bandwidth concept and taking the matching bandwidth's minimum frequency f_{min} , which is considered approximately 1 GHz in the majority of the studied cases, which correspond to the cases shown in Figure 8. As can be observed, for $L_p = W_{slot}$ and $W_p = L_{slot}$, it is possible to achieve broadband matching (Cases from 1 to 5 in Table 1), and, generally, these are the cases of the highest matching bandwidths. In addition, for the cases where $L_p = W_{slot}$ and $W_p \approx L_{slot}$ (Cases from 6 to 10 in Table 1) and $L_p \approx W_{slot}$ and $W_p \approx L_{slot}$ (Cases from 11 to 15 in Table 1), it is also possible to reach wideband impedance matching. It should be noted that, in all fifteen examples presented in Table 1, the calculated relative impedance bandwidth is greater than 150%.

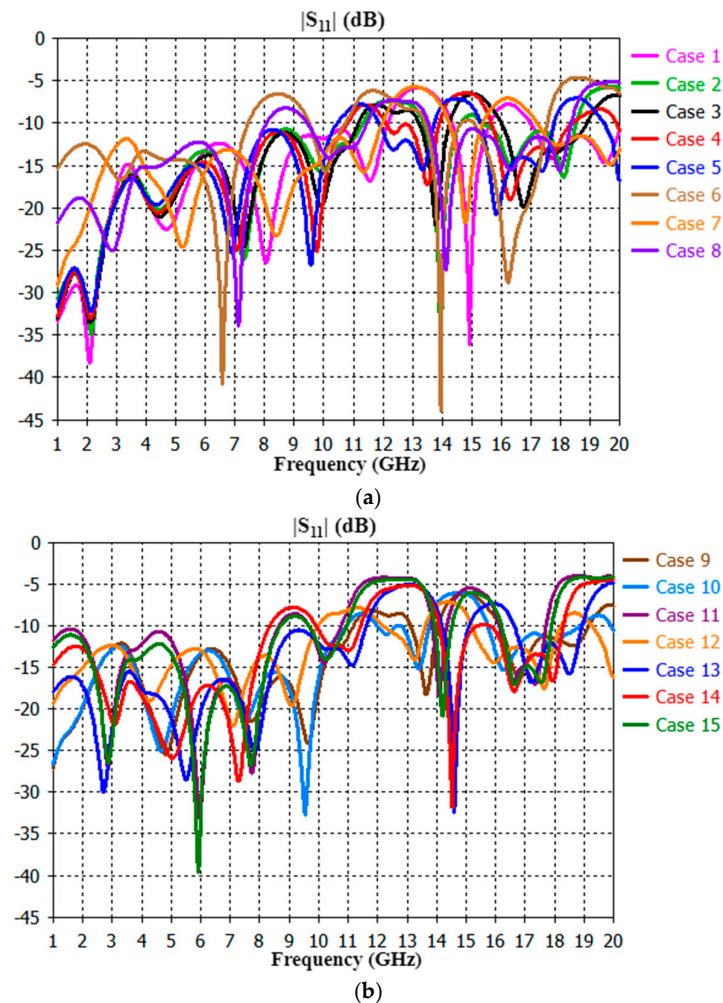


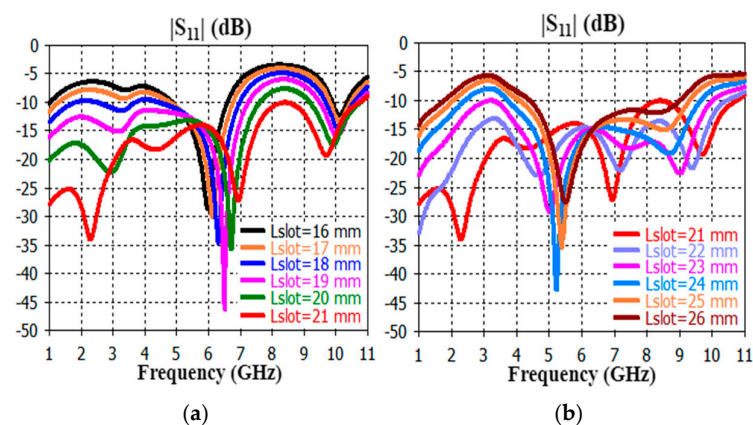
Figure 8. Computed $|S_{11}|$ for some obtained cases of broadband impedance matching of the proposed antenna element: (a) Case 1 to Case 8; (b) Case 9 to Case 15.

Full-wave electromagnetic analysis of the slot dimensions, using fixed (constant) patch dimensions equal to the reference antenna, was carried out. It revealed that increasing the slot length, approximating the constant patch width value ($L_{slot} \leq W_p$), improved the impedance matching, with a slight increase in the center frequency of impedance matching bandwidth, as well as an increase in the impedance matching bandwidth, changing from a narrowband to wideband response. In addition, there is an increase in the transmission coefficient $|S_{21}|$, mainly from 1 GHz to the center frequency of the matching bandwidth (5.5 GHz), while it decreases from the center frequency to the end of the matching bandwidth. These behaviors are presented in Figures 9a and 10a, respectively.

Table 1. Matching bandwidths for some width–length combinations of both patch and complementary slot of the analyzed and proposed structure.

Case	L_p (mm)	W_{slot} (mm)	W_p (mm)	L_{slot} (mm)	BW (GHz)	$BW_{\text{relative-match}}$ (%)
1	15	15	19	19	11	169
2	16	16	21	21	10	182
3	18	18	19	19	10	167
4	19	19	19	19	9.8	166
5	20	20	19	19	9	164
6	17	17	21	20	6.4	152
7	15	15	19	20	11	169
8	16	16	21	20	7	175
9	18	18	19	20	10	167
10	19	19	19	20	10	168
11	17	15	21	19	7.5	157
12	17	18	2	23	9	164
13	16	15	20	19	7.5	176
14	16	15	21	19	7.4	157
15	17	15	21	19	7.7	159

For slot length values greater than the fixed-width patch ($L_{\text{slot}} > W_p$), the results are mostly opposite to the previous ones: a deterioration in impedance matching, a decrease in the impedance bandwidth, and a slight increase in the impedance bandwidth's center frequency are obtained. Moreover, a reduction in the transmission from port 1 to port 2 ($|S_{21}|$) from 1 GHz to the center frequency and an increase ($|S_{21}|$) from the center frequency to the end of the matching bandwidth are reached. Figures 9b and 10b show these performances.

**Figure 9.** Influence of L_{slot} in $|S_{11}|$ of the proposed antenna element in its matching bandwidth for different cases: (a) L_{slot} approximating and equal to W_p ($L_{\text{slot}} \leq W_p$); (b) $L_{\text{slot}} > W_p$.

The performed full-wave EM analysis also allows us to establish that increasing the slot width, approximating to the constant patch length value ($W_{\text{slot}} \leq L_p$), leads to an enhancement in the impedance matching and a slight decrease in the center frequency of the matching bandwidth. Similarly to the mentioned cases, where $L_{\text{slot}} \leq W_p$, in these cases ($W_{\text{slot}} \leq L_p$), the impedance bandwidth also changes from narrowband to wideband, and an increase in the transmission coefficient—evaluated by means of $|S_{21}|$ —is achieved. This can be seen in Figures 11a and 12a.

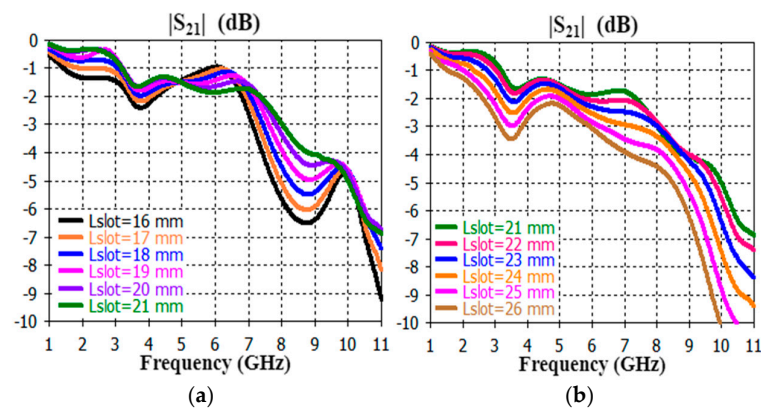


Figure 10. Influence of L_{slot} in $|S_{21}|$ of the proposed antenna element in its matching bandwidth for the following cases: (a) L_{slot} approximating and equal to W_p ($L_{\text{slot}} \leq W_p$); (b) $L_{\text{slot}} > W_p$.

On the contrary, when the slot width is larger than the fixed patch length ($W_{\text{slot}} > L_p$), the effect is mainly the opposite to the previous case: a worsening of the impedance matching and the corresponding matching bandwidth and a decrease in $|S_{21}|$ arise. In addition, a slight decrease in the matching bandwidth's center frequency value is observed. Figures 11b and 12b show these behaviors.

Moreover, is important to express that the knowledge of the influence of the slot dimensions (the length L_{slot} and the width W_{slot}) in $|S_{11}|$ and $|S_{21}|$ is useful in the design of two-port elements, mainly in radiating elements for linear series-fed antenna arrays, where it is necessary to know and control the impedance matching, transmission, and power delivered by each radiating element to the next one, as well as the radiated power, and, consequently, the radiation efficiency of the antenna array.

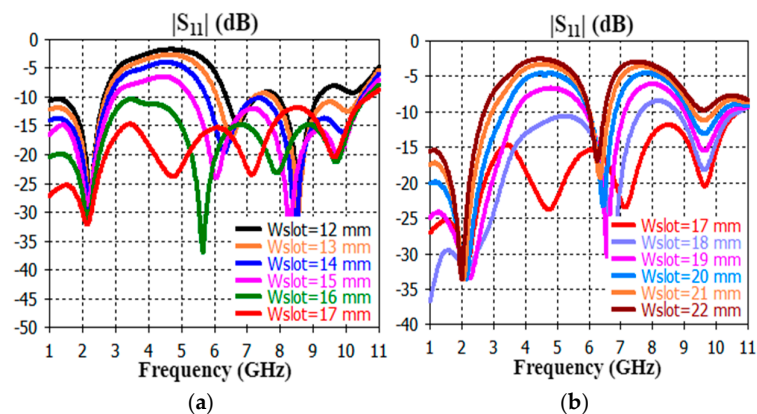


Figure 11. Influence of W_{slot} in $|S_{11}|$ of the proposed antenna element in its matching bandwidth for: (a) W_{slot} approximating and equal to L_p ($W_{\text{slot}} \leq L_p$); (b) $W_{\text{slot}} > L_p$.

After analyzing the influence of the slot dimensions on the S -parameters, it can be concluded that for the best performance in terms of impedance matching, its corresponding bandwidth and transmission coefficient are obtained when the slot is the complementary part and has dimensions similar to the patch (cases where $L_{\text{slot}} \approx W_p$ and $W_{\text{slot}} \approx L_p$). Consequently, radiation efficiency should also increase for these cases. In this sense, it is important to highlight that a very wide impedance bandwidth can be reached when two complementary structures with the same shape, arranged in stacking and aligned, have approximately the same dimensions and are appropriately designed in two-port topology, like in transmission configuration. This result was also similarly obtained in [18–21], which allows us to ratify the above-mentioned statement and conclusion. Moreover, these results also corroborate the theory proposed by Mushiake on two electromagnetically

self-complementary structures situated contiguously, mainly with the approach of the Principle of Self-Complementarity [1–4,6] but, in this case, in stacking arrangement.

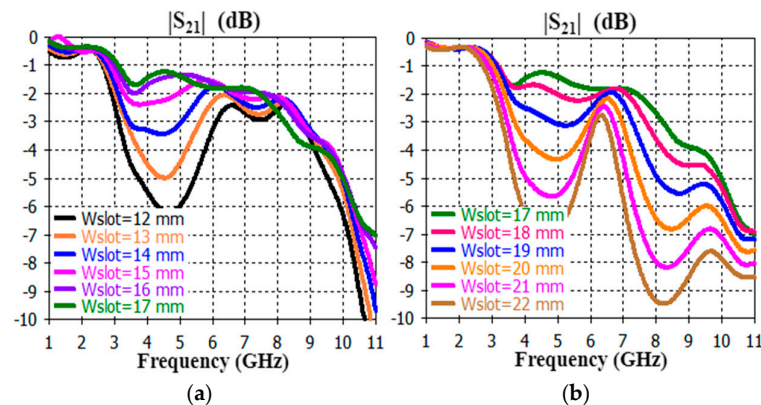


Figure 12. Influence of W_{slot} in $|S_{21}|$ of the proposed antenna element in its matching bandwidth for: (a) W_{slot} approximating and equal to L_p ($W_{\text{slot}} \leq L_p$); (b) $W_{\text{slot}} > L_p$.

Figure 13 shows the computed absolute value of the axial ratio (AR) of the proposed structure in both main radiation broadside directions (in this case, $\Theta = 0^\circ$ and $\Theta = 180^\circ$), within its impedance matching bandwidth (1–11 GHz). It has values around 40 dB at both mentioned main directions in practically all matching bandwidths, except with the minimums of 16.8 dB in 2.6 GHz and 29.3 dB in 8.7 GHz at $\Theta = 0^\circ$, and 13.3 dB in 7.5 GHz at $\Theta = 180^\circ$. These results suggest that this radiating element has linear polarization around both main broadside directions, with adequate purity of linear polarization.

Figures 14 and 15 show the computed polar radiation patterns of the co-polar components of absolute gain (in dB) of the analyzed two-port self-complementary structure at the main radiation planes, from 1 to 8 GHz. Obviously, the broadband element radiates toward both hemispheres (bidirectional broadside). These radiation plots show a small asymmetry and a small angular displacement in the main lobe in the longitudinal plane (y - z plane, E -plane), due to the presence of the microstrip line from the second port. Bidirectional broadside radiation is the main difference in the radiation characteristics compared to their classical counterpart (the reference antenna), which obviously radiates only toward the hemisphere of the patch. From the computed results, the analyzed structure can be considered to be like an antenna, being possible to express that their radiation patterns are assumable from 1 to 8 GHz, and the gain has appropriate values from approximately 3 to 8 GHz. Hence, if it is considered an antenna, its radiation bandwidth must be taken from 3 to 8 GHz ($BW_{\text{sim-rad [antenna]}} = 5$ GHz, radiation center frequency $f_0 [\text{sim-rad}] = 5.5$ GHz, i.e., 45.5% of $BW_{\text{sim-match}}$, and 91% of $f_0 [\text{sim-rad}]$).

On the other hand, if it is to be used like a radiating element for antenna arrays, like series-fed ones and corporate-feeding types, then the radiation patterns and the gain are adequate from 1 to 8 GHz ($BW_{\text{sim-rad [radiating element]}} = 7$ GHz, $f_0 [\text{sim-rad}] = 4.5$ GHz, i.e., 63.6% of $BW_{\text{sim-match}}$, and 156% of $f_0 [\text{sim-rad}]$). Moreover, it is important to highlight that for the analyzed structure used like an antenna or as a radiating element for antenna arrays, their radiation patterns are conserved and considerably stable from 1 to 6 GHz, mainly in the longitudinal plane (taking into account, necessarily and with primordial importance, antenna arrays fed in series configuration).

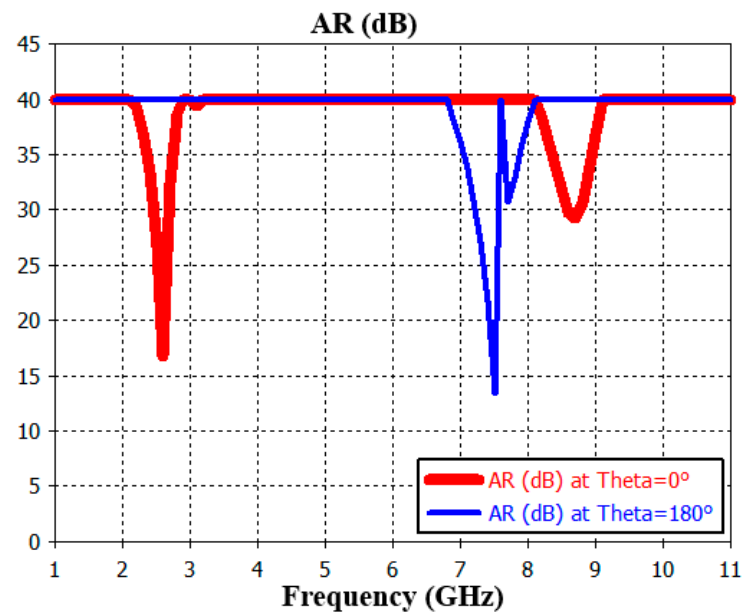


Figure 13. Calculated absolute axial ratio (AR in dB) of the proposed broadband radiating element, within its matching bandwidth, in the main broadside radiation directions: Theta = 0° (red line) and Theta = 180° (blue line).

In Figure 16, the behavior of the computed absolute gain of the analyzed antenna element at the main broadside radiation directions Theta = 0° and Theta = 180°, from 1 to 8 GHz, is shown. As can be observed, the gain has good values in the majority of the studied frequency ranges (from 1.7 to 8 GHz), distributed in the two mentioned main broadside directions. In this frequency range, at any of the mentioned two main broadside directions, the gain mostly has values higher than 0 dB ($G = 1$), with the exception of two minimums (in 2.5 GHz at Theta = 0°, and in 7.5 GHz at Theta = 180°). It has a maximum value of approximately 7.8 dB at 7 GHz in the hemisphere that contains the patch. At Theta = 0° (main broadside direction, in the plane that contains the patch), the gain increases with the frequency from 2.5 to 7 GHz. In this plane and direction, the gain shows a very good flatness, considering a maximum variation of 2 dB, from 3.5 to 7 GHz (3.5 GHz, i.e., 32% of $BW_{sim-match}$, and 50% of $BW_{sim-rad}$ approximately). Similarly, for the other broadside direction, Theta = 180° (plane that contains the slot), a little variation in the gain with the frequency and an adequate flatness from 2 to 6.5 GHz (4.5 GHz, i.e., 41% of $BW_{sim-match}$, and 64% of $BW_{sim-rad}$ approximately) are achieved. Then, with this criterion, it is possible to establish that this two-port device has good gain flatness in the frequency, specifically from 3.5 to 6.5 GHz, in both main broadside directions (3 GHz, i.e., 27% of $BW_{sim-match}$, and 43% of $BW_{sim-rad}$ approximately). These are very good and significant results obtained for an antenna element, mainly considering that the losses increase with the frequency in the printed antennas; consequently, the gain and radiation efficiency decrease with the frequency. Hence, as is well known, it is difficult to obtain high values of gain in printed radiating elements at very high frequencies, such as the studied microwave frequency range, and even more difficult with a broadband operation response. In addition, the losses of this type of antenna element increase notably with the length in antenna arrays, such as series-fed ones, obviously due to their length. Moreover, it is important to highlight, again, the good flatness reached in the gain in both mentioned main broadside directions from 3.5 to 6.5 GHz. Therefore, the mentioned gains in frequency are good and suitable, mainly if this antenna element could be used in antenna arrays, such as series-fed ones.

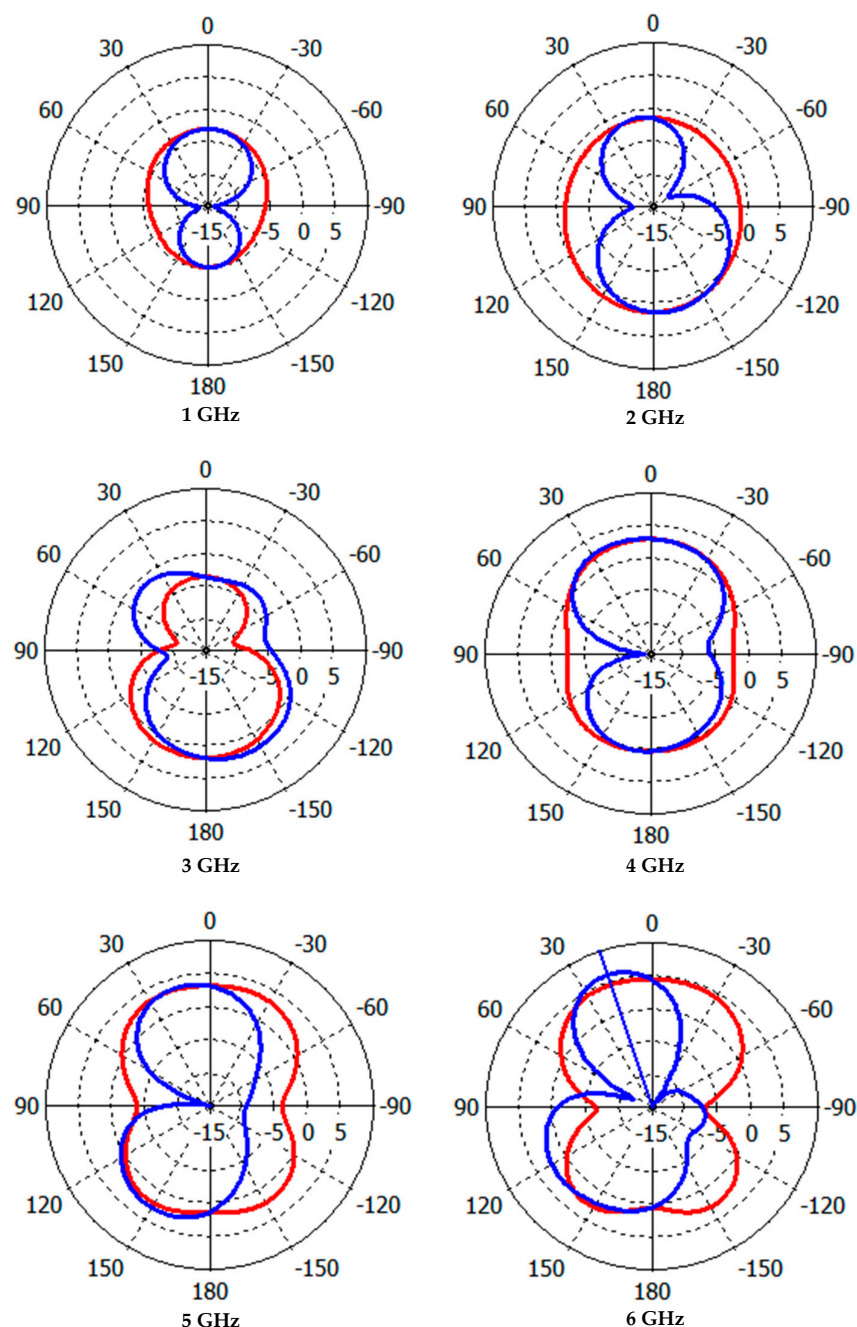


Figure 14. Calculated polar radiation patterns of co-polar components in terms of gain (in dB) in the proposed broadband radiating element from 1 to 6 GHz in the main radiation planes: transverse plane ($\Phi = 0^\circ$, *H-Plane*, red line), and longitudinal plane ($\Phi = 90^\circ$, *E-Plane*, blue line).

The simulated radiation efficiency of the analyzed and proposed structure with a load impedance $Z_L = 50 \Omega$ at the end of port 2, within its impedance matching bandwidth, is shown in Figure 17. It has very good values of radiation efficiency in this frequency range and has a radiation efficiency bandwidth from 1 to 8 GHz ($BW[\eta_{\text{rad}}] = 7 \text{ GHz}$, i.e., 63.6% of $BW_{\text{sim-match}}$, and 100% of $BW_{\text{sim-rad}}$ approx.). Specifically, it has values between approximately 83% and 96% from 1 to 8 GHz, which are very good results, and they allow us to consider it like an antenna, even as a radiating element for antenna arrays, such as series-fed ones. It is important to highlight that the radiation efficiency increases with the frequency from 1 to 1.5 GHz, from 2.5 to 3.5 GHz, and from 7.2 to 11 GHz. The radiation efficiency has little variation from 94 to 96% between 3.5 and 8 GHz ($\Delta\eta_{\text{Efic.Rad}} = 2\%$ in 4.5 GHz, 41% of its $BW_{\text{sim-match}}$, and 64% of $BW_{\text{sim-rad}}$), so that it has adequate stability for

radiation efficiency with the frequency, mostly around the reference design center frequency (5 GHz). Furthermore, it has good flatness for this parameter in the frequency, particularly from 4 to 8 GHz, considering a maximum variation of approximately 1% (4 GHz, 36% of its $BW_{sim-match}$, and 57% of its $BW_{sim-rad}$), which are also very good results.

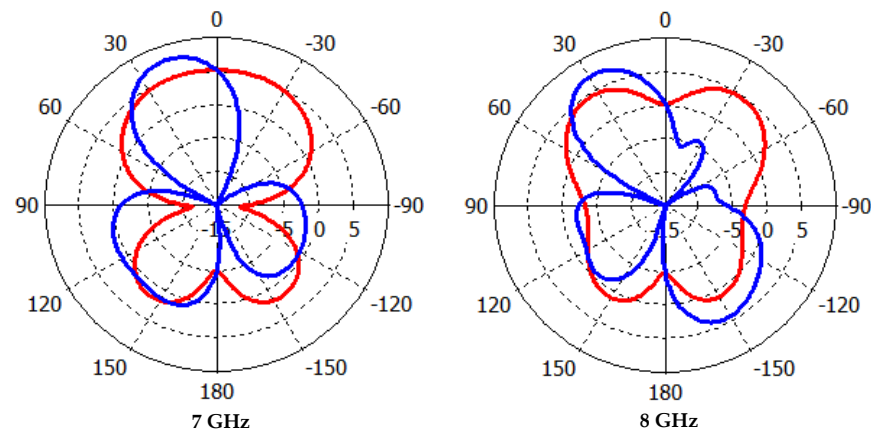


Figure 15. Calculated polar radiation patterns of co-polar components in terms of gain (in dB) in the proposed broadband radiating element for 7 and 8 GHz in the main radiation planes: transverse plane ($\Phi = 0^\circ$, *H-Plane*, red line), and longitudinal plane ($\Phi = 90^\circ$, *E-Plane*, blue line).

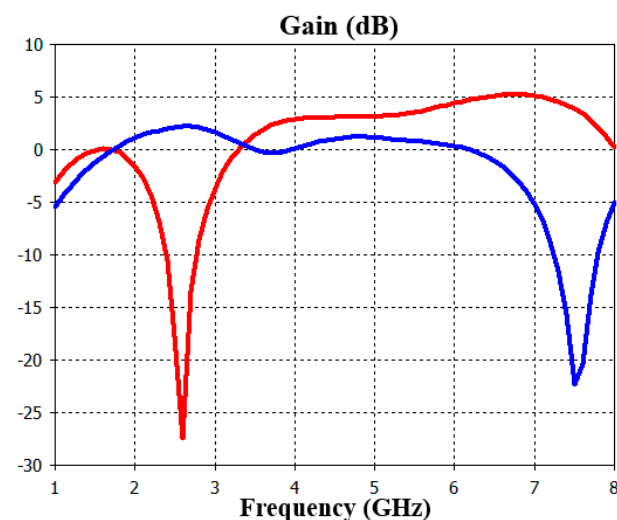


Figure 16. Calculated absolute gain in the proposed structure from 1 to 8 GHz in the main broadside radiation directions: $\Theta = 0^\circ$ (red line), and $\Theta = 180^\circ$ (blue line).

According to the achieved computed results of the radiation patterns, of the gain, and of the radiation efficiency within its matching bandwidth previously analyzed and commented on, a radiation bandwidth from 1 to 8 GHz is assumable ($BW_{sim-rad} = 7$ GHz), which represents approximately 63.6% of its computed matching bandwidth and 156% of its computed radiation's center frequency (4.5 GHz). In this frequency range, the mentioned patterns show only low radiation in the antenna's plane.

If the calculated results of the matching bandwidth and the main radiation characteristics are considered together in this illustrative design example, it is possible to express that this radiating element has broadband performance with a very wide operation bandwidth of at least 7 GHz, limited mainly by the radiation patterns. This means that this element could also be used at other frequencies if the radiation patterns are not critical specifications. Moreover, the transmission coefficient of this antenna element is less than or around -2 dB within its wide operation bandwidth. In general, these are promising results for a

two-port antenna element in transmission arrangement, primarily because it could be used in series-fed antenna arrays.

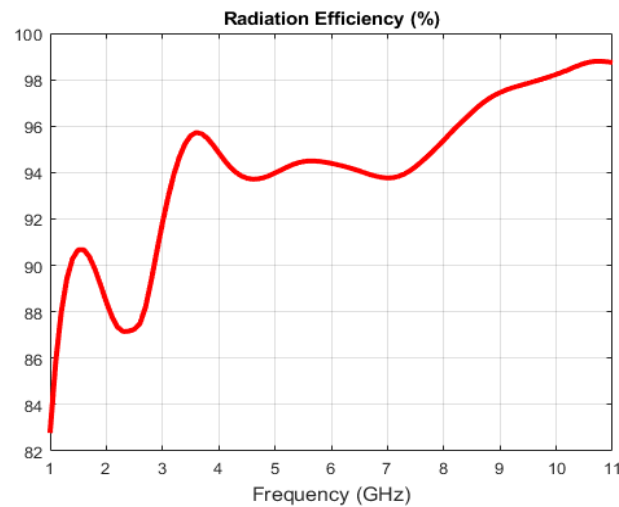


Figure 17. Calculated radiation efficiency of the proposed broadband radiating element with a load impedance $Z_L = 50 \Omega$ at the end of port 2, within its impedance matching bandwidth.

These results, together with those obtained in the previous work of [21], allow us to conclude that the proper design of two-port self-complementary printed patch-slot structures, stacked and aligned, with the same shape and approximately equal dimensions, constitutes antenna elements with large matching and broad radiation bandwidths and, consequently, a wide operation bandwidth. Moreover, it is possible to obtain good radiation characteristics and merits parameters in this stacked printed topology.

6. Measurement Results (Validation)

Three identical prototypes of the analyzed structure were fabricated, and they were measured using a vector network analyzer (VNA) and inside an anechoic chamber. A photograph of a prototype is shown in Figure 6. A picture of the measurement of the S-parameters of this prototype in a VNA is presented in Figure 18.

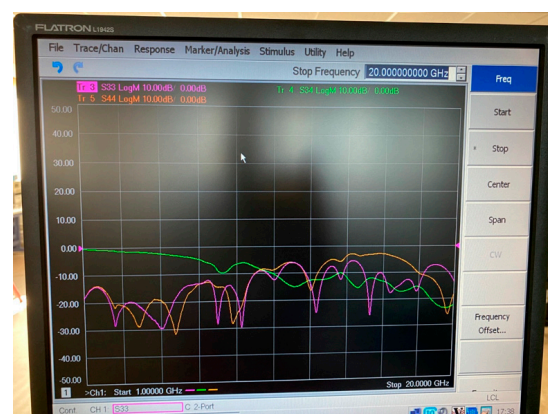


Figure 18. Picture of S-parameter measurement of one of the fabricated prototypes of the proposed broadband radiating element.

Figure 19 shows the calculated and measured S-parameters of one of these three prototypes. Good agreement was achieved between the calculated and measured results of these parameters. Apart from the errors in the numerical methods of electromagnetic analysis, the discrepancies between the calculated and measured results are due to fabrication

inaccuracies, the bad connector performance at frequencies above 8 GHz, and other inherent differences between the computed analysis and measurements. From these results, the measured impedance matching bandwidth is 8 GHz ($BW_{\text{meas-match}} = 8 \text{ GHz}$), which can be improved, e.g., using adequate connectors, at least from 1 to 15 GHz.

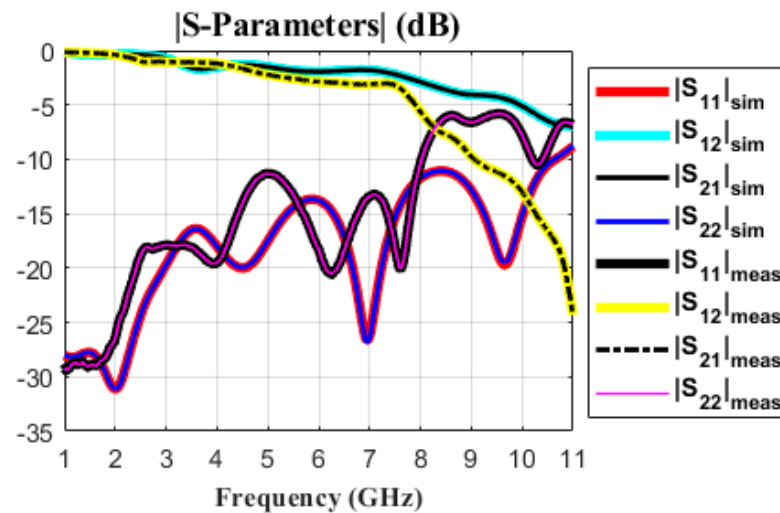


Figure 19. Computed and measured S-parameters (in dB) of a prototype of the proposed broadband antenna element within its matching bandwidth.

Figure 20 illustrates the calculated and measured normalized polar radiation patterns of the absolute gain's co-polar components (in dB) in the main radiation planes, from 1 to 6 GHz, inside an anechoic chamber. As can be seen, appropriate approximation is obtained in the measured radiation patterns with respect to the computed ones. The achieved differences are due to inaccuracies in the measurement procedure of a poorly directive antenna (the analyzed antenna element radiates in many directions toward both hemispheres, resembling an omnidirectional diagram), other intrinsic errors in this type of measurement, and inherent differences between computed electromagnetic analysis and measurements (often, they do not have exactly equal values). Despite these discrepancies from the measured radiation center frequency (4 GHz) to the end of this band (6 GHz), the measured radiation patterns are considerably approximate to the computed ones, which is a very good result. Hence, in this case, the measured radiation bandwidth is from 1 to 6 GHz ($BW_{\text{meas-rad}} = 5 \text{ GHz}$, $f_{o[\text{meas-rad}]} = 3.5 \text{ GHz}$), which represents 45.5% and 62.5% of the computed and measured impedance matching bandwidths, respectively, corresponding to approximately 111% and 143% of their computed and measured radiation center frequencies, respectively. The measured maximum gain is approximately 6 dB at 6 GHz in the hemisphere that contains the radiating patch.

If the computed results of impedance matching and the main radiation characteristics, as well as the measurement ones for this self-complementary structure, are considered jointly, then it is possible to express that this radiating element has broadband performance with a wide operation bandwidth of at least 5 GHz, restricted mainly by the measurement results, specifically by the measured radiation patterns of gain in this case.

This broadband antenna element could be used independently like an antenna, placing a load impedance $Z_L = 50 \Omega$ in the end of port 2, in different applications, mainly in the mostly used, the current, and in the emerging ones, such as broadcasting, wireless networks, mobile communications, satellite, radar, imaging, research in Oceanic Engineering, biomedicine, and others. In addition, it could be used like a radiating element in different antenna arrays.

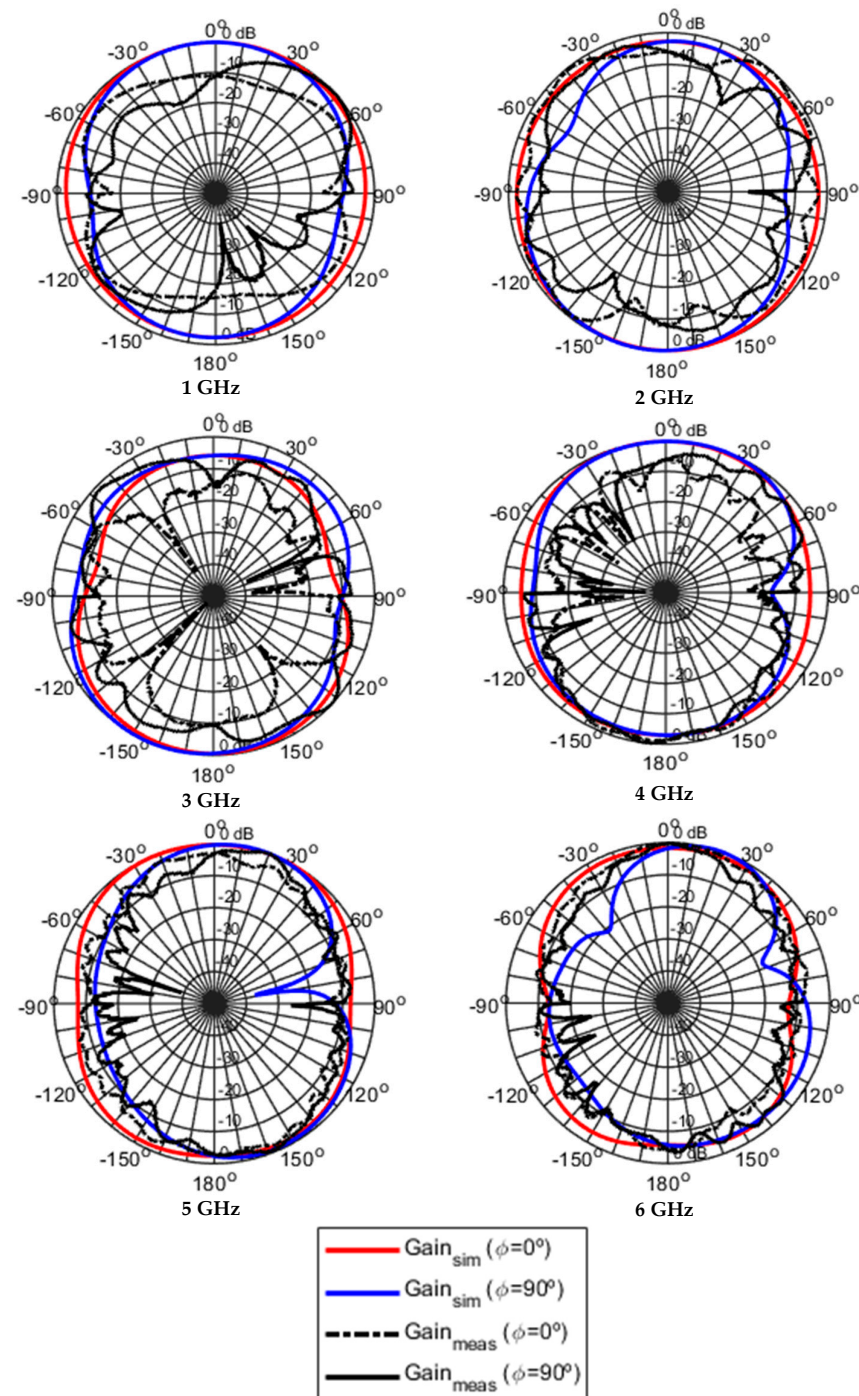


Figure 20. Computed and measured normalized polar radiation patterns of co-polar components of gain of the proposed broadband radiating element in the main radiation planes, from 1 to 6 GHz.

7. Comparison of the Proposed Broadband Antenna Element with Previous Works

In this section, the proposed antenna element based on the concept of *self-complementary structures in staking arrangement* is compared to previous similar broadband radiating elements (with two-port self-complementarity in stacking arrangement, and in transmission configuration) that have already been presented in the scientific and technical literature. Table 2 exhibits the results obtained with the new antenna element proposed here (“*This work*” in Table 2) and with the recent similar wideband two-port radiating element (using the self-complementarity concept in stacking arrangement). With the goal to complete a

more exhaustive valuation of the contribution of this work to the mentioned *state of the art*, a comparison of the results obtained in this work with wideband antenna elements with one and two feeding ports, with and without self-complementarity, was performed and is presented in this section.

Firstly, the new antenna element is compared with the broadband slot radiating element based on microstrip–slot coupling, which was presented in [20]. The antenna element of [20] has a simulated and measured 10 dB return loss bandwidth of approximately 16 GHz (i.e., relative matching bandwidth about 200%), while the illustrative example design proposed here is approximately 11 GHz (i.e., $BW_{\text{sim-relative-match}} = 200\%$). The radiation bandwidth of [20] is considered to be approximately 5.8 GHz (from 5.4 to 11.2 GHz, radiation center frequency f_o [rad] = 8.3 GHz, i.e., $BW_{\text{sim-relative-rad}} \approx 70\%$). The new antenna element proposed here has bidirectional broadside radiation (radiates to both hemispheres) like in [20]. The proposed illustrative antenna element has wide computed and measured bandwidths of impedance matching of 11 and 8 GHz, respectively. The radiation bandwidth and relative radiation bandwidth of the proposed radiating element here (7 GHz, i.e., 63.4% of its computed matching bandwidth, and 156% of its computed radiation center frequency) are bigger than in [20]. It is important to highlight that the results obtained in the proposed antenna element can be improved, due to it being an example of an illustrative design, it is not optimized, and the measurements of the main fundamental parameters and merits characteristics would be improved (even they would be surpassed by the mentioned results reached in [20]). The new radiating element has higher gain than [20]. Moreover, the proposed antenna element has the inherent advantages of patch antennas, such as simplicity, compactness, more modes of field distribution and performances, versatility in polarization and radiation, the possibility to reject modes, and others, which are not possible to achieve in the slot, nor in the broadband slot radiating element based on microstrip–slot coupling characterized and presented in [20]. The radiation efficiency of [20] within its impedance matching bandwidth is low, and it has a maximum value of 23%.

A compact two-port I-microstrip–slot coupling radiating element, which has similar topology to [20], was presented in [29]. It has a simulated impedance bandwidth of 11 GHz (from 5 to 16 GHz, f_o [sim-match] = 10.5 GHz, i.e., $BW_{\text{sim-relative-match}} = 105\%$), and it exhibits bidirectional broadside radiation. In addition, there is a size reduction with respect to [20]. Despite the results in [29], the proposed antenna element here has a matching bandwidth approximately equal to that in [29], with a lower matching center frequency and a corresponding relative matching bandwidth greater than [29]. The radiation bandwidth is not available in [29], so it cannot be compared in terms of this parameter with the proposed antenna element and the rest. In addition, Ref. [29] has a radiation efficiency from approximately 22% to 32%, which is bigger than that in [20] and [28]. The proposed radiating element here is mostly better than [29].

Most of the authors in [29] proposed a wideband two-port radiating element in [30]. It consists of microstrip–slot coupled exciting I-shaped resonators. It shows a computed impedance bandwidth of up to approximately 16 GHz (f_o [match] = 8 GHz, i.e., $BW_{\text{sim-relative-match}} \approx 200\%$), which is approximately equal to [20] and comparable with the proposed antenna element and [28]. However, the radiating element analyzed in [30] shows an improvement in radiation in the patch plane containing the I-shaped resonators (increasing the directivity) and an enhancement in the radiation efficiency from 25% to 42%, which is higher than that achieved in [20,28,29]. Consequently, Ref. [30] presents an improvement in the calculated radiation bandwidth (from 4 to 13.6 GHz, $BW_{\text{sim-rad}} \approx 9.6$ GHz, f_o [sim-rad] = 8.8 GHz, i.e., $BW_{\text{sim-relative-rad}} = 109\%$), which is higher than that of the new antenna element presented here, in [20] and [28].

Table 2. Comparison of the results obtained in the proposed radiating element with the *state of the art* in recent wideband two-port self-complementary radiating element in transmission configuration.

Ref.	Type of Radiating Element	Match. Freq. Range [GHz] Calc / Meas	BW _{match} [GHz] Calc / Meas	f_o [match] [GHz] Calc / Meas	BW _[relative-match] [%] Calc / Meas	Type of Radiation	Rad. Freq. Range [GHz] Calc / Meas	BW _{rad} [GHz] Calc / Meas	f_o [rad] [GHz] Calc / Meas	BW _[relative-rad] [%] Calc / Meas	G _{max} [dB] Calc	Rad. Efficiency [%] Calc
[This work]	Proposed Radiating Element	Up to 11/ ≈8	≈11 / ≈8	5.5 / 4	200 / 200	Bidirectional Broadside	1–8 / 2–6	7 / 4	4.5 / 4	≈156 / ≈100	7.5 (@ 6 GHz)	* 83 to 96%
[20]	2 Port-Complementary Microstrip-Slot Coupling	Up to 16/ Up to 16	16 / 16	8 / 8	200 / 200	Bidirectional Broadside	N.A. / N.A.	5.8 / N.A.	8.3 / N.A.	70 / N.A.	N.A. / N.A.	10–23
[28]	2 Port-Cavity-Backed Slot (CBS)	3 to 6.8 / 3 to 6.7	3.8 / 3.7	4.9 / 4.9	78 / 76	Unidirectional Broadside	4–6.7 / 4–6.7	2.7 / 2.7	5.4 / 5.4	50 / 48	≤0 / ≤0	3–30
[29]	2 Port-Compact I-Microstrip-Slot Coupling	5–16 / N.A.	11 / N.A.	10.5 / N.A.	105 / N.A.	Bidirectional Broadside	N.A. / N.A.	N.A. / N.A.	N.A. / N.A.	N.A. / N.A.	N.A. / N.A.	22–32
[30]	2 Port-Microstrip-Slot Coupled Radiating Structure (RS) with I-Shaped Resonators	Up to 16 GHz/ N.A.	16 / N.A.	8 / N.A.	200 / N.A.	Bidirectional Broadside with improvement in F/B ratio.	4–13.6 / N.A.	9.6 / N.A.	8.8 / N.A.	109 / N.A.	D _{max sim} ≈ 7dBi (G _{max} is N.A.)	Up to 42
[31]	2 Port Microstrip-Slot Coupled RS with Radiation Efficiency Enhancement	2 main matching bandwidths Lowest: 0.5–5/N.A. Highest: 12.5–16/N.A.	Lowest: Up to 4.5 / N.A. Highest: 3.5 / N.A.	Lowest: 2.75/ N.A. High: 14.25/ N.A.	Lowest: 164 / N.A. Highest: 25 / N.A.	Bidirectional Broadside	N.A. / N.A.	N.A. / N.A.	N.A. / N.A.	N.A. / N.A.	Enhancement of the directivity respect to [20,29,30].	Up to 35

Notes: “N.A.” means that this data is Not Available in the corresponding paper. * The radiation efficiency of the analyzed and proposed structure is calculated using a load impedance $Z_L = 50 \Omega$ at the end of port 2.

Subsequently, most of the authors of [29,30] analyzed and presented a radiating element coupled with a two-port broadband microstrip slot with improved radiation efficiency in [31], which was incorporated into the above-mentioned *state of the art*. However, once again, it has a narrower matching bandwidth than that achieved in the new antenna element. The radiation bandwidth is not available in [29] and is not clearly defined or expressed in [31], so this antenna element parameter cannot be compared with the rest of those studied.

As a summary of the results found in the *state of the art* corresponding to recent two-port radiating elements in transmission configuration based on self-complementary structures in stacking arrangement, it can be stated that Ref. [20] has the widest impedance matching bandwidth, followed by [30], the proposed radiating element proposed here, with [29], [31] and [28] (in this order). The relative impedance bandwidth of the new antenna element shows the highest result, followed by [20], [30], [31], [29], and [28] (in this order), which is more important than the matching bandwidth, because the relative one takes into account the matching center frequency (it is more approximated to the operation frequency). The proposed radiating element and the antenna elements of [20,29–31] have broadside radiation in both hemispheres (bidirectional), while [28] is unidirectional. It is also worth noting that [30] has the highest radiation bandwidth, followed by the proposed antenna element here, [20] and [28] (this parameter is not available in [29,31]). In this sense, Ref. [20] has the largest matching bandwidth of the studied cases (with the exception of [30], which is equal to [20]), while Ref. [30] has the biggest radiation bandwidth. On the other hand, the radiating element of [28] has the smallest matching, radiation and corresponding relative bandwidths. Taking into account that the operation bandwidth is determined mostly in these cases by the radiation bandwidth, and the relative radiation bandwidth considers the center radiation frequency, which is a very important parameter because it determines the operation frequency, then the relative radiation bandwidth is a better parameter in these cases to analyze and determine the operation bandwidth. So, due to the proposed radiating element, here is a new approach for wideband two-port radiating elements in transmission configuration using self-complementarity in stacking arrangement. It has a bigger relative radiation bandwidth and, consequently, has higher operation bandwidth compared with the rest, and it also has a considerably high maximum gain and very good other antenna fundamental parameters and merit characteristics, even in terms of frequency. Hence, it is considered that the proposed antenna element is one of the above-mentioned similar ones with the best fundamental and functioning parameters. Therefore, it is possible to include the proposed antenna element in the *state of the art* in wideband two-port radiating elements in transmission configuration, mainly using the self-complementarity concept in stacking arrangement.

Below, a comparison of the results found in the proposed antenna element with those obtained in other self-complementary and non-self-complementary structures, both with feeding of a single port or of two ports, in transmission configuration, is also presented.

A single-port self-complementary microstrip-fed slot-coupled patch antenna was presented in [32]. In this case, the patch and its complementary part (rectangular slot) are contiguous in the same plane. In addition, the printed structure self-complementary with the first one was added in staking configuration to increase the matching and operation bandwidths. Despite these topologies, they exhibit wide relative impedance bandwidths of approximately 56% and 51%, respectively, which do not exceed the radiating element proposed in this study or the above-mentioned ones. It has unidirectional broadside radiation, with a radiation bandwidth of at least 6.5 to 11 GHz ($4.5 \text{ GHz}, f_o [\text{rad}] = 8.8 \text{ GHz}$, i.e., $BW_{\text{relative-rad}} \approx 51\%$). In addition, it has an adequate front-to-back ratio. The impedance

matching and radiation bandwidths are not larger than those of the antenna element analyzed and proposed here.

A broadband single-port printed quasi-self-complementary antenna based on a dipole, for WLAN application, was announced in [33]. This antenna has a printed part (like a T-shaped strip), and its self-complementary part is contiguous to the first one in the same plane and axis but in the opposite direction, with both being in the same layer. It has a measured matching bandwidth of 1.5 GHz for a center frequency of f_o [match] = 5.5 GHz (i.e., $BW_{\text{relative-match}} = 27\%$), which is very low compared to the above-compared ones, including the proposed antenna element. In addition, it has a radiation bandwidth like the matching one and very good values of gain (more than 3 dB) within its operation bandwidth. However, the proposed radiating element here has bigger impedance, radiation bandwidths, and maximum gain than [33].

In [34], a printed single-port half-disc quasi-self-complementary antenna for band-notched ultra-wideband (UWB) applications was proposed. It consists of a quarter-circular patch and a self-complementary counterpart (quarter-circular slot) contiguous to the first one, on the same plane and layer. It was analyzed from 2 to 13 GHz, showing a notched band from approximately 1 to 2 GHz and from 5.02 to 6.07 GHz. Hence, its simulated and measured broad impedance bandwidths are approximately 6 GHz (from 6 to 12 GHz, f_o [match] = 9 GHz, i.e., $BW_{\text{relative-match}} = 67\%$), and it is not higher than the proposed radiating element and the other mentioned ones. Their radiation patterns were measured at 4, 7, and 9 GHz, and they can be considered acceptable, but, of course, it is not bigger than the new antenna element proposed here. It is important to highlight that it is a single-port fed antenna too, like [32,33], while the aforementioned studies are mostly two-port radiating elements in transmission arrangement. These self-complementary antennas and their comparisons are only to demonstrate that very good results can be achieved with the proposed antenna element, mainly giving an overview of the impedance and radiation bandwidths that can be obtained in similar single-port self-complementary antennas, as well as the other mentioned main performance characteristics.

A compact single-port self-complementary antenna for portable UWB applications was presented in [35]. It has a very wide simulated and measured impedance bandwidth of approximately 8.5 GHz (from 3 to 12 GHz, f_o [match] = 7.75 GHz, i.e., $BW_{\text{relative-match}} = 110\%$). This matching frequency range is less than the proposed antenna element but higher than the aforementioned ones. Its radiation bandwidth is not clearly defined and expressed in [35]; therefore, it cannot be compared with the antenna element proposed here and with the rest. Again, it is important to express that it is an antenna fed with one port, and the rest are mostly in two-port and transmission configuration. Once again, this comparison is only used to provide a simple idea of the matching and radiation bandwidths, the corresponding center frequencies, and the corresponding relative bandwidths in self-complementary single- and two-port antenna elements.

In [36], a single-port quasi-self-complementary rectangular printed antenna in contiguous arrangement was introduced. It has two impedance matching bandwidths, 100 MHz (4.1% at 2.45 GHz) and 2.7 GHz (48.9% at 5.5 GHz), which were validated using measurements. Both cases of matching bandwidths are no bigger than the above-mentioned ones, neither the two-port nor the single-port ones, including the radiating element proposed here. In addition, it has good radiation patterns at 2.45 and 5.5 GHz, but its radiation bandwidth is not clearly defined and expressed; therefore, it cannot be compared with the one proposed here and with the rest. Without a doubt, this antenna does not surpass, in terms of matching and radiation bandwidths and, therefore, also in terms of operation range, the antenna element proposed here.

A two-port ultra-wideband Vivaldi antenna with dual polarization and radar cross-section (RCS) reduction was proposed in [37], mainly for measurement systems of near-field radiation. It has a wide 10 dB return loss bandwidth in both ports of approximately 4.2 GHz (from 1.8 to 6 GHz, f_o [match] = 3.9 GHz, i.e., $BW_{\text{sim-relative-match}} = 108\%$) and other good performance characteristics, like isolation between their ports of more than 23 dB, a realized gain of more than 4 dBi within its impedance bandwidth, and averaged monostatic RCS reduction of less than -30 dB. It has dual linear polarization and a radiation bandwidth of approximately 3 GHz (from 2 to 5 GHz, f_o [rad] = 3.5 GHz, i.e., $BW_{\text{sim-relative-rad}} \approx 86\%$). As can be analyzed, Ref. [37] does not surpass the proposed antenna element here in terms of matching and radiation bandwidths and in their corresponding relative bandwidths.

A broadband compact printed single-port antenna for wireless biotelemetry for future leadless pacemakers was introduced in [38]. Basically, Ref. [38] consists of a slotted printed single-port antenna. It exhibits a wide matching bandwidth of approximately 3.4 GHz (from 0.76 to 4.15 GHz, f_o [match] = 2.46 GHz, i.e., $BW_{\text{sim-relative-match}} = 138\%$), which does not surpass the proposed antenna element, nor [20,28–30], and others. This radiating element has practically omnidirectional radiation patterns mainly at 0.915, 1.4, and 2.45 GHz, but it is no bigger than the proposed antenna element here. Again, it is important to consider that [38] features a single-port antenna, while the one proposed here and the other ones compared previously are two-port structures in transmission configuration.

We believe that the results obtained in the proposed broadband two-port rectangular patch radiating element in transmission configuration, using the concept of self-complementary structures in stacking arrangement, allow us to establish that it can also be considered as a contribution to the *state of the art* in broadband two-port printed radiating elements in transmission configuration, mainly using the self-complementarity concept in stacking [4,6–11], respect to single-port self-complementary topologies both contiguous and in stacking arrangements [12–17,32–36], regarding to two-port stacked self-complementary radiating elements [18–21,28–31], and to other wideband printed antennas [22–27,37–44].

8. An Illustrative Series-Fed Antenna Array with Six Elements in the Proposed Broadband Antenna Element

An illustrative uniform linear series-fed antenna array using six elements in the proposed broadband radiating element is studied with a full-wave electromagnetic analysis. An image of this illustrative antenna array is shown in Figure 21. The main goal is to show the behavior of the impedance matching and its corresponding matching bandwidth, when the proposed broadband antenna element is used in the linear antenna's conformation with feeding in series configuration. In this case, it is a homogeneous and uniform linear series-fed antenna array, with a constant separation between elements of a half-guided wavelength ($\lambda_g/2$) for 5 GHz (reference design frequency), 17.3 mm in this case.

The computed absolute values of S_{11} in the frequency ($|S_{11}|$ in dB) of the mentioned uniform linear series-fed antenna array from 1 to 8 GHz are shown in Figure 22. As can be seen, the impedance matching and its corresponding matching bandwidth are affected when the proposed broadband antenna element is used in series-fed antenna conformation, mainly due to the mutual impedance coupling between elements. Concretely, in this illustrative case, a 10 dB return loss-matching bandwidth with narrow response was obtained at the following frequency ranges: from 2.7 to 3.1 GHz, from 3.2 to 3.5 GHz, from 3.6 to 3.8 GHz, and from 4.1 to 4.3 GHz. In addition, wideband matching was achieved from 4.5 to 6 GHz ($BW_{\text{sim-match-RL} \geq 10 \text{ dB}} \approx 1.5 \text{ GHz}$, f_o [sim-match] = 5.3 GHz, i.e., $BW_{\text{sim-relative-match}} \approx 28.6\%$) and 6.2 to 7.9 GHz (1.7 GHz, f_o [sim-match] $\approx 7.1 \text{ GHz}$, i.e., $BW_{\text{sim-relative-match}} \approx 24\%$). The mentioned first wide 10 dB return loss-matching bandwidth is around the reference design central frequency (5 GHz), which allows it to express that is

conceivable to obtain a wide impedance matching bandwidth in a uniform linear series-fed antenna array using the proposed broadband antenna element. Moreover, these results also allow us to express that it is possible to obtain multiband operation and even with broadband matching in some of the achieved matched frequency ranges.

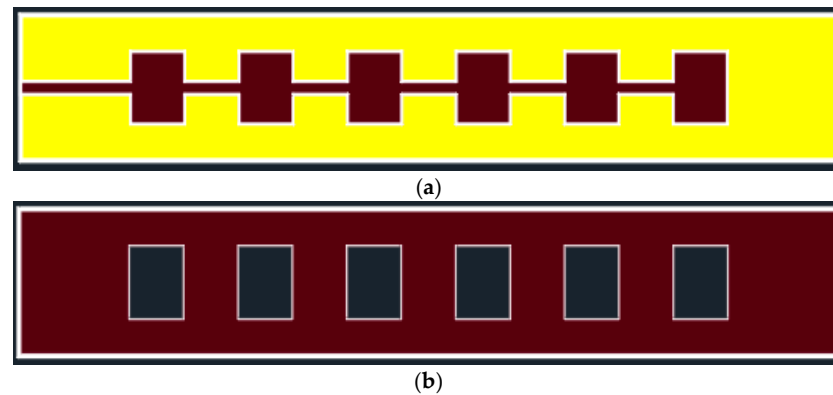


Figure 21. Image of an illustrative uniform linear antenna array of 6 elements in the proposed radiating element fed in series configuration: (a) top view, (b) bottom view (*note*: brown color represents the conductive part (copper), yellow color represents the dielectric part, black color represents the background and holes of the slots, and white color represents the contour lines).

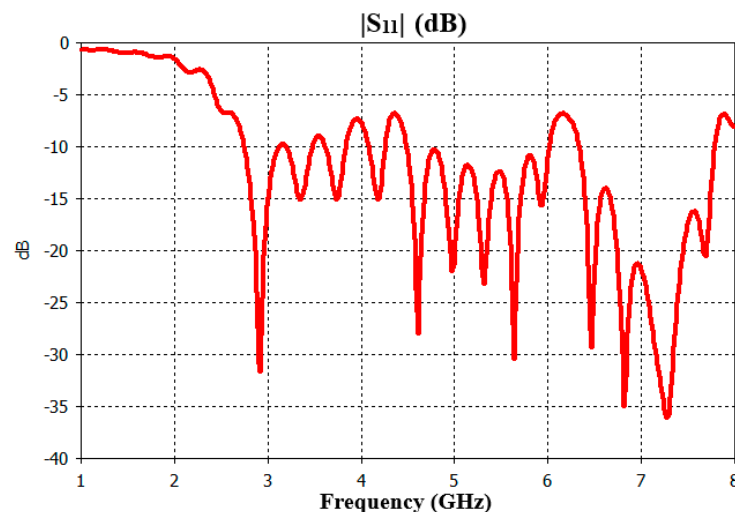


Figure 22. Computed absolute S_{11} ($|S_{11}|$ in dB) of an illustrative uniform linear series-fed antenna array of 6 elements in the proposed antenna element.

Nevertheless, a 7 dB return loss-matching bandwidth is obtained in this antenna array from approximately 2.6 to at least 8 GHz ($BW_{\text{sim-match-RL} \geq 7 \text{ dB}} \geq 5.4 \text{ GHz}$, $f_o [\text{sim-match}] = 5.3 \text{ GHz}$, and $BW_{\text{sim-relative-match}} = 102\%$). Taking into account the performed electromagnetic analysis and the achieved calculated results of the mentioned illustrative uniform linear antenna array, it is important to express that it is possible to enhance the impedance matching and reach a wideband matching response in this type of antenna array, properly designed like this one.

From the mentioned study of the illustrative uniform antenna array in series-feeding configuration, using full-wave analysis, good radiation characteristics were also obtained, mainly their radiation patterns. It reveals that it is feasible to design wideband series-fed antenna arrays using the proposed antenna element, even with multiband performance and broadband matching in more than one matched frequency range.

9. Conclusions

The first and foremost conclusion of the present work is that the use of the self-complementary concept in two-port rectangular patch antennas in transmission and stacking configurations increases both bandwidths: impedance matching and radiation. In this sense, and in a general way, it can be stated that two dual electromagnetically complementary structures of the same arbitrary shape, situated vertically in stacking arrangement and aligned, with similar dimensions, in a common dielectric substrate, and fed directly by a microstrip line, provide ultra-wide matching and broad radiation bandwidths.

Second, only two physical dimensions need to be adjusted to achieve the wideband behavior in the proposed antenna element: the length and width of the slot. Therefore, it only has two degrees of freedom to obtain the mentioned broadband performance, and its design is simple and easy.

Third, its design is flexible, due to there being many possible length–width combinations for both the patch and its complementary part (the slot), which allow it to reach the broadband matching behavior.

Fourth, with this antenna element, it is also possible to obtain very good results in some of the main radiation parameters and other merit performance characteristics, as follows: good and pure linear polarization, appropriate radiation patterns, adequate conservation in the frequency, as well as attractive gain and radiation efficiency values, and very good flatness of the last two mentioned parameters over wide frequency ranges. Consequently, it is possible to establish that it has a very wide operation bandwidth.

As a final remark, the analyzed broadband two-port self-complementary rectangular patch structure is simple, compact, has low-weight, and its synthesis and manufacturing are easy and flexible. The radiating element with an impedance load $Z_L = 50 \Omega$ at the end of port 2 is well suited like an antenna in both existing and emergent wireless applications, where broadband operation is required, such as radiobroadcasting, fixed radio links, wireless networks (Wi-Fi and WiMAX), mobile communications, satellite applications, radar, biomedicine, radiofrequency imaging, Oceanic Engineering research, biomedicine, and others. Furthermore, it could be used as a radiating element in different antenna arrays with wideband or/and multiband operation, such as series-fed ones and others, which could be used in the mentioned applications or/and others.

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