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Systematic Design of an Ultra-Wideband Six-Port Multi-Mode Antenna Element Using Symmetry Properties of Characteristic Modes

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Abstract—A design of an ultra-wideband six-port multi-mode antenna element intended for use in a massive MIMO array is presented. By leveraging symmetry properties of characteristic modes, six uncorrelated antenna ports can be defined on a square plate while offering wideband potential with minimum dimensions. Excitation slots are introduced and systematically optimized based on symmetry considerations in such a way that an inherent impedance match is realized for all six ports. In order to cover the desired ultra-wide bandwidth from 6 GHz to 8.5 GHz, the excitation slots are stepped in width and the feed network is adjusted accordingly, achieving the design goals.

Index Terms—Characteristic modes, multiple-input multiple output (MIMO), multi-mode antenna, symmetry, ultra-wideband (UWB)

I. INTRODUCTION

Multi-mode antennas designed by means of the theory of characteristic modes [1]–[3] have proved to be a promising approach in order to enable multiple-input multiple-output (MIMO) techniques in spatially restricted environments. This is due to the orthogonality properties of characteristic modes, which state that the characteristic far fields are orthogonal to each other, offering pattern and polarization diversity. For this reason, uncorrelated antenna ports can be realized on a single and compact antenna structure by exciting different sets of characteristic modes with different ports.

In [4] and [5], multi-mode antennas are proposed as elements of a massive MIMO base station antenna array. A complete communication system based on this approach is presented in [6] with the aim to achieve data rates of 100 Gbit/s and beyond. As a distinctive feature, this system is proposed to operate at frequencies below 10 GHz. In order to achieve the desired spectral efficiency, the ultra-wide frequency band (UWB) from 6 GHz to 8.5 GHz is chosen [4]. It is demonstrated in [5] that multi-mode antennas based on characteristic modes are able to support such an ultra-wide bandwidth. This fact is confirmed by other designs, e.g. [7].

A literature review reveals that current multi-mode antenna designs reported in recent publications have a maximum of

four antenna ports, e.g. [5], [7], [8]. For employment in a massive MIMO array, it is in general desirable to have antennas with even more ports. This would offer the potential to further increase the spectral efficiency without significantly changing the array size. Most recently, the authors of this work found that the achievable number of perfectly uncorrelated ports on a multi-mode antenna is governed by its symmetry [9]. This is due to the fact that the characteristic surface current densities are basis functions of the irreducible representations of the symmetry group of an antenna [10]. This has the consequence that characteristic surface current densities belonging to different representations and degenerate surface current densities belonging to the same representation are orthogonal to each other and can thus be excited separately. In particular, a perfectly electrically conducting (PEC) square plate offers up to six uncorrelated antenna ports as demonstrated in [9]. On top of that, it supports a wide modal bandwidth as shown in [5] and is thus an interesting candidate for the above-mentioned system approach.

Based on these findings, this work aims at systematically designing a six-port multi-mode antenna element operating within the ultra-wide frequency range from 6 GHz to 8.5 GHz by making use of the full port potential offered by a square plate. To this end, the symmetry properties and modal characteristics of a square PEC plate are reviewed in section II. Based on this, an excitation using slots is defined in section III. Measures for increasing the bandwidth of the multi-mode antenna are implemented in section IV. The paper concludes with a summary and outlook in section V.

II. MODAL ANALYSIS OF SQUARE PEC PLATE

The symmetry group of the square plate (Fig. 1) has five irreducible representations: Four one-dimensional representations A_1 , A_2 , B_1 , B_2 and one two-dimensional representation E [11]. As analyzed in [9], there are thus six mutually orthogonal sets of characteristic surface current densities which can be excited separately.

The number of significant characteristic modes at a given frequency, i.e. those modes that can be effectively excited, is

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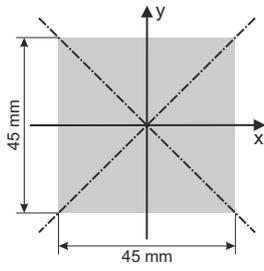


Fig. 1. Square PEC plate and coordinate system.

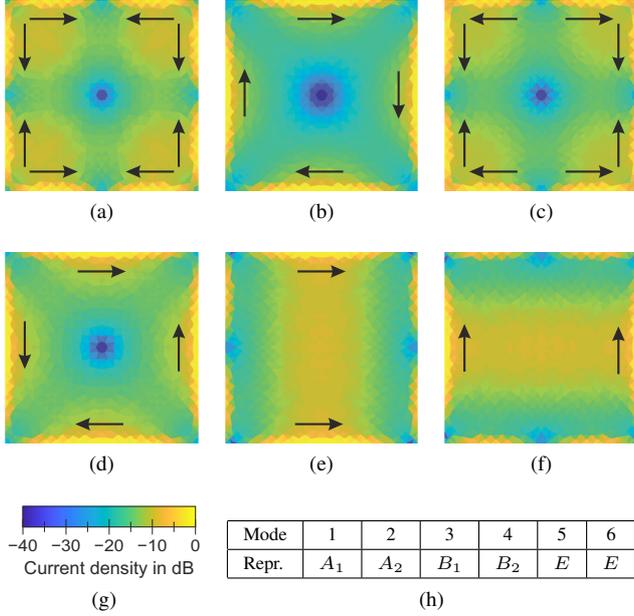


Fig. 2. Normalized surface current densities of fundamental characteristic modes of square PEC plate with 45 mm edge length at 6 GHz. Principal current directions denoted by arrows. (a)-(f) Modes 1 to 6. (g) Colorbar. (h) Assignment to irreducible representations of symmetry group of square plate.

dictated by the antenna size (edge length of the square plate). The aim is to exploit the full port potential of the square plate, i.e. six uncorrelated antenna ports. This means that out of the six mutually orthogonal sets of characteristic modes there needs to be at least one significant mode per set (or representation, as the modes of the two-dimensional representation are degenerate). Those modes of each representation that first become significant over frequency are called the fundamental modes per representation. The antenna size is chosen such that the fundamental modes of each representation are significant. This way, the antenna size is minimized while the number of uncorrelated antenna ports is maximized.

The characteristic surface current densities of the six fundamental modes of the square plate at 6 GHz are depicted in Fig. 2, sorted by representation. The characteristic modes are computed by means of an in-house method of moments solver implemented in MATLAB. The first current density (Fig. 2(a)) is invariant under all symmetry operations of the symmetry group of the square plate and thus belongs to the representa-

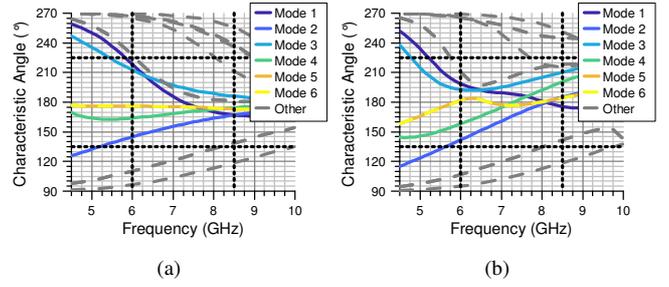


Fig. 3. Characteristic angles of square PEC plate with 45 mm edge length. Fundamental modes in color, higher order modes denoted by dashed gray lines. (a) Square plate in free space. (b) Square plate 16 mm above infinite ground plane.

tion A_1 . The second one (Fig. 2(b)) is a loop-like current density belonging to A_2 . The third and the fourth current density (Fig. 2(c) and (d)) can be considered as quadrupole-like, belonging to B_1 and B_2 , respectively. Ultimately, the fifth and the sixth mode can be regarded as having orthogonally polarized dipole-like current densities (Fig. 2(e) and (f)). They belong to the representation E and are degenerate.

The edge length of the square plate is chosen to be 45 mm. The corresponding characteristic angles [12] are shown in Fig. 3(a). The antenna size is optimized in such a way that the six fundamental modes are significant above 6 GHz (characteristic angle between 135° and 225° corresponding to a modal significance greater than $1/\sqrt{2}$). It is also visible that the modes stay significant over the desired frequency band and beyond, offering a large modal bandwidth, which is typical for planar geometries in free space. It should be noted that the modes 5 and 6 have the same characteristic angle (eigenvalue) independent of frequency due to their degeneracy. Furthermore, it is observed that there are higher order modes, some of them becoming significant within the frequency band of interest.

Figure 3(a) shows that the characteristic modes of the square plate have suitable frequency characteristics for UWB operation. However, for practical scenarios, the antenna cannot be assumed to be located in free space. Instead, it may be mounted above a ground plane. This has the advantage that a necessary feed network can be implemented in a circuit layer using this ground plane (see e.g. [5], [7]). It is well known that a ground plane in close vicinity to the antenna compromises its bandwidth, which is reflected in steep eigenvalue curves of the characteristic modes. Therefore, the antenna has to be placed some distance away from the ground plane. This is demonstrated in Fig. 3(b), where the square plate is mounted at a height of 16 mm above an infinite ground plane (xy -plane of the coordinate system). Although the curves of the characteristic angles have changed compared to the free space case, it is achieved that the six fundamental modes are significant within the desired frequency band at a minimum height above ground. It is important to emphasize that the symmetry properties of the characteristic modes are not changed by introducing the ground plane.

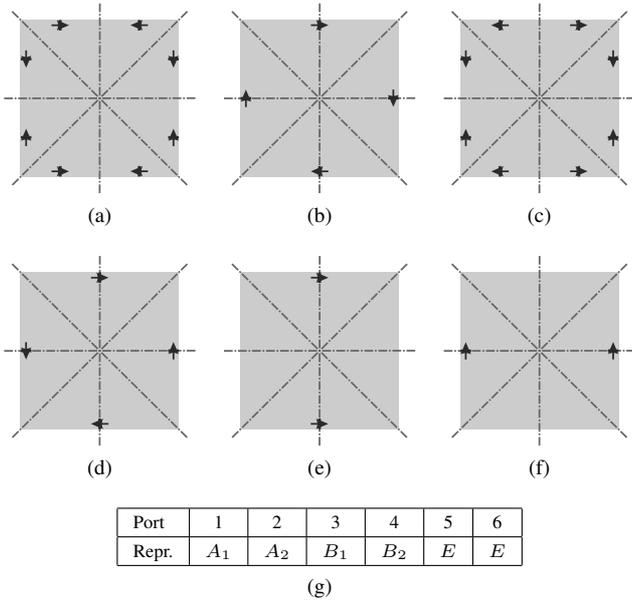


Fig. 4. Port definition of square PEC plate with 45 mm edge length. Feed points and their relative phases denoted by arrows. (a)-(f) Ports 1 to 6. (g) Assignment to irreducible representations of symmetry group of square plate.

III. EXCITATION OF SQUARE PEC PLATE

In the previous section, the size of the square plate and its height above an infinite ground plane have been determined by means of a modal analysis such that the fundamental characteristic modes are significant in the desired frequency range. The next step is to define excitations for the fundamental modes. As explained in [9], the antenna ports have to be designed in such a way that they have the same symmetry properties as the fundamental modes they are supposed to excite, i.e. the ports are designed as basis functions of the irreducible representations. A schematic solution is shown in Fig. 4. Each antenna port consists of symmetrically placed feed points that are driven simultaneously. The arrows denote the relative phase between the feed points that is necessary in order to fulfill the symmetry requirements (cf. Fig. 2). The ports 2, 4, 5 and 6 use the same feed points, which is required due to symmetry in order to achieve the minimum number of feed points per port. Likewise, the ports 1 and 3 use the same feed points. Port 3 could also be realized with four feed points (cf. [9]). However, this would come at the cost of an additional feed network (see below).

As discussed in section II, there are higher order modes which, according to [9], will also be excited by the previously defined antenna ports. This cannot be avoided and it is, anyway, not a drawback as the ports are designed in such a way that they can only excite modes that belong to the same representation. For this reason, the six antenna ports (Fig. 4) are uncorrelated. This fact is shown in Fig. 5 by means of the envelope correlation coefficients (ECC) calculated from the radiated far fields per port [13], where the feed points are modeled as ideal voltage gap sources in the method of

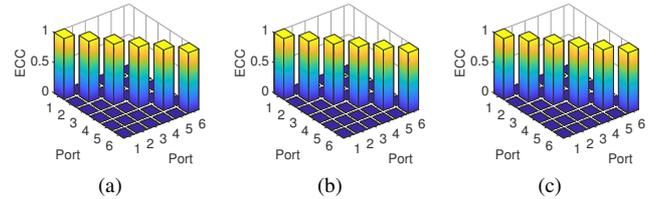


Fig. 5. Envelope correlation coefficients (ECC) of square plate with 45 mm edge length and located 16 mm above infinite ground plane excited according to Fig. 4 with idealized voltage gap sources. (a) 6 GHz. (b) 7.25 GHz. (c) 8.5 GHz.

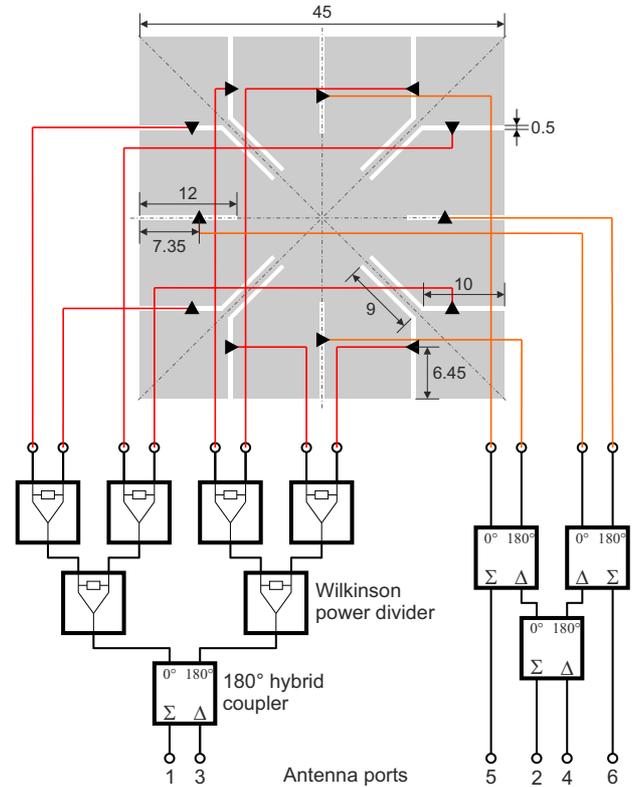


Fig. 6. Square PEC plate with excitation slots and feed network. The antenna is located 16 mm above a ground plane. Dimensions in mm.

moments [14]. It is highlighted that this result is frequency independent due to symmetry.

Idealized voltage gap sources as used above are most convenient for examining the excitation of characteristic modes. Of course, they are not relevant for practical antenna designs. For the practical excitation of multi-mode antennas, some sort of coupling elements are introduced to the original geometry [15]. In [5], slots are cut into the PEC plate as excitation elements. This offers the possibility to control the input impedances of the ports and thus inherently match them to the system impedance.

Inspired by this, slots are introduced into the square plate at the positions of the feed points as defined in Fig. 4. The optimized design is shown in Fig. 6. The feed points are denoted by arrows whose directions are used as phase references for the feed network. The length of the slots and

the position of the feed points within the slots control the input impedances of the ports. The slots of ports 1 and 3 are bent in order to accommodate their necessary length. A feed network is needed to distribute the input signals of the antenna ports to the feed points with the correct amplitude and phase relations. The feed network used here consists of Wilkinson power dividers and 180° Hybrid couplers with 50Ω reference impedance and is adopted from [9].

Matching the antenna ports to the reference impedance is intricate as several ports share the same feed points. Nevertheless, the antenna ports can be optimized systematically based on symmetry considerations and design guidelines are derived as follows. First of all, the symmetry of the complete antenna must be preserved in order to realize uncorrelated antenna ports [9]. This means that the final antenna including excitation slots has to have the same symmetry group as the original square plate. As a consequence, the slots of a single port must not be modified independently as this would lead to an asymmetric antenna. For this reason, there are only two optimization parameters per port: the slot length and the feed point position.

The optimization should start with ports 1 and 3. This is due to the fact that they are symmetric with respect to the x - and y -axis. Correspondingly, the currents excited by these ports are symmetric with respect to these axes (Fig. 2) and are hence not affected by the slots of ports 2, 4, 5 and 6. Only after optimizing the ports 1 and 3, the ports 2, 4, 5 and 6 are considered since their input parameters are affected by the presence of the slots of ports 1 and 3. Since the ports 5 and 6 are degenerate, they have the same input parameters and only one of them needs to be optimized actively.

The input parameters of the ports are controlled by the slot length and the feed point position. The slot length affects the frequency behavior of the input impedance. Lengthening the slot leads to a shift of the input impedance to lower frequencies. The position of the feed point within the slot determines the actual values of the impedance. Shifting the feed point towards the open end of the slot increases the input resistance and adds capacitance. Moving the feed point towards the short circuit end of the slot decreases the resistance and adds inductance.

With these guidelines, the antenna ports are optimized in order to achieve an impedance match to 50Ω within the frequency range from 6 GHz to 8.5 GHz. The antenna element is modeled and simulated using Empire XPU, where the feed network is taken into account by means of a circuit simulation. The simulated final input parameters are shown in Fig. 7. The input impedances of ports 1 and 3 show a comparatively flat behavior between 6 GHz and 8.5 GHz (Fig. 7(a) and (b)). This has the consequence that the corresponding input reflection coefficients are below -10 dB within the frequency band of interest and well beyond (Fig. 7(c)). Obviously, the simple slot excitation of ports 1 and 3 is capable of achieving a sufficient impedance match to 50Ω over an ultra-wide bandwidth.

In contrast, the input impedances of ports 2, 4, 5 and 6 show a steeper behavior (Fig. 7(a) and (b)), with the consequence

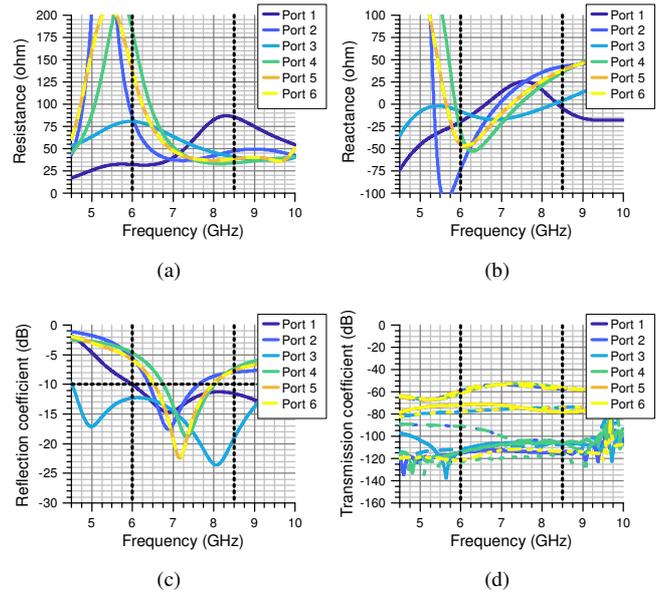


Fig. 7. Input parameters of square PEC plate with excitation slots and feed network located 16 mm above ground plane as shown in Fig. 6. (a) Input resistances. (b) Input reactances. (c) Input reflection coefficients. (d) Transmission coefficients.

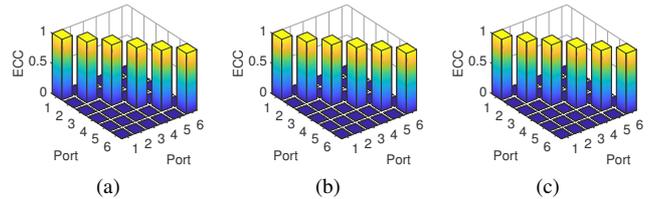


Fig. 8. Envelope correlation coefficients (ECC) of square PEC plate with excitation slots and feed network located 16 mm above ground plane as shown in Fig. 6. (a) 6 GHz. (b) 7.25 GHz. (c) 8.5 GHz.

that they cannot be matched to 50Ω over the whole ultra-wide frequency band. This is due to the fact that their currents are affected by the presence of the slots of ports 1 and 3. Nevertheless, all ports provide reflection coefficients less than -10 dB around the center frequency 7.25 GHz, showing wideband behavior (Fig. 7(c)). For example, ports 5 and 6 have a bandwidth of approximately 1.5 GHz from 6.5 GHz to 8 GHz. If the UWB frequency range is divided into five 500 MHz sub-bands as proposed in [4], these ports are able to cover three such sub-bands.

The transmission coefficients shown in Fig. 7(d) demonstrate that the ports are highly decoupled. Moreover, Fig. 8 reveals that the ports are again uncorrelated, as intended. This is due to the fact that, although the antenna is modified by introducing the excitation slots, the symmetry is preserved and the ports fulfill the symmetry requirements.

Correspondingly, a modal analysis confirms that the six antenna ports excite mutually exclusive sets of characteristic modes independent of frequency, as shown by means of the normalized modal weighting coefficients [13] in Fig. 9. For this analysis, the 18 most significant modes per frequency are

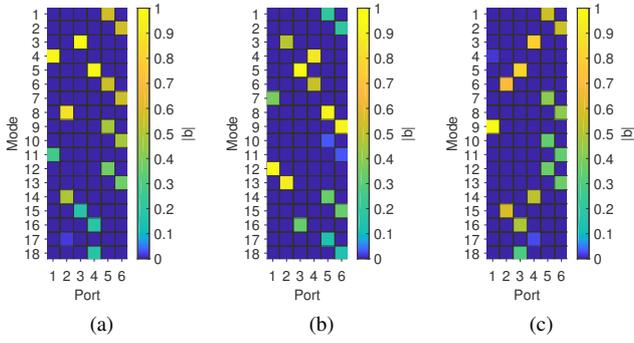


Fig. 9. Normalized modal weighting coefficients b (absolute value) of square PEC plate with excitation slots and feed network located 16 mm above ground plane as shown in Fig. 6. The modes are sorted at each frequency according to their significance. (a) 6 GHz. (b) 7.25 GHz. (c) 8.5 GHz.

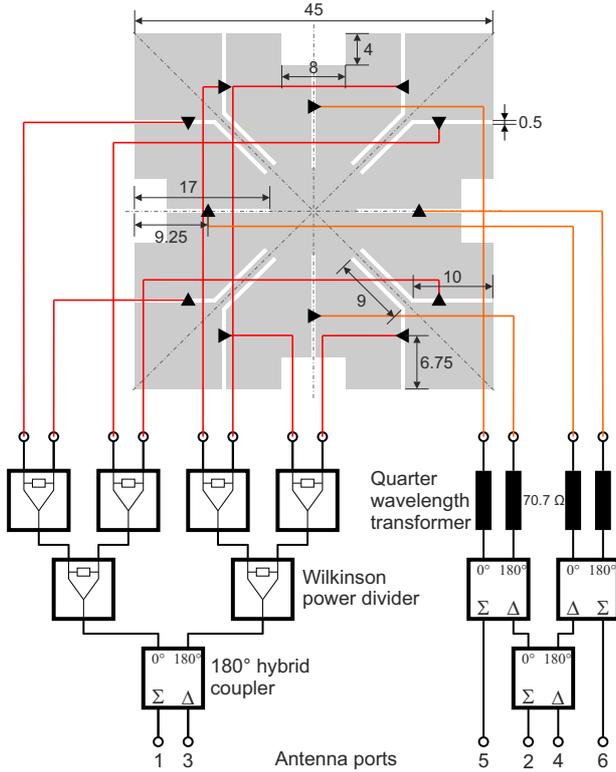


Fig. 10. Square PEC plate with stepped excitation slots and feed network. The antenna is located 16 mm above a ground plane. Dimensions in mm.

taken into account. Each mode is excited by exactly one port, which explains why the antenna ports are uncorrelated. Moreover, there are no further characteristic modes that could be excited separately, demonstrating that the maximum number of uncorrelated antenna ports is reached.

IV. UWB EXCITATION OF SQUARE PEC PLATE

The results of the previous section prove that a six-port multi-mode antenna can be systematically designed with a wideband impedance match to 50Ω . In particular, ports 1 and 3 are matched within the complete ultra-wide frequency band of interest and even beyond. The question arises whether this can

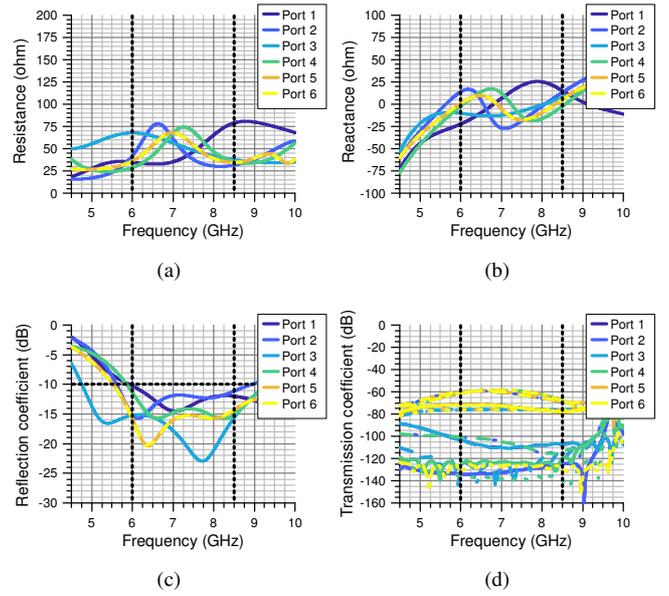


Fig. 11. Input parameters of square PEC plate with stepped excitation slots and feed network located 16 mm above ground plane as shown in Fig. 10. (a) Input resistances. (b) Input reactances. (c) Input reflection coefficients. (d) Transmission coefficients.

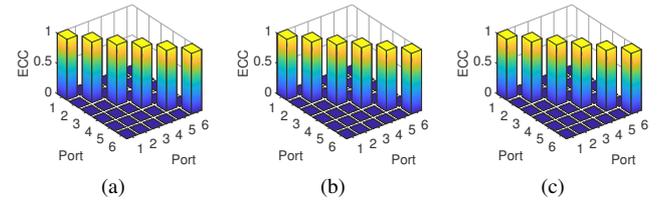
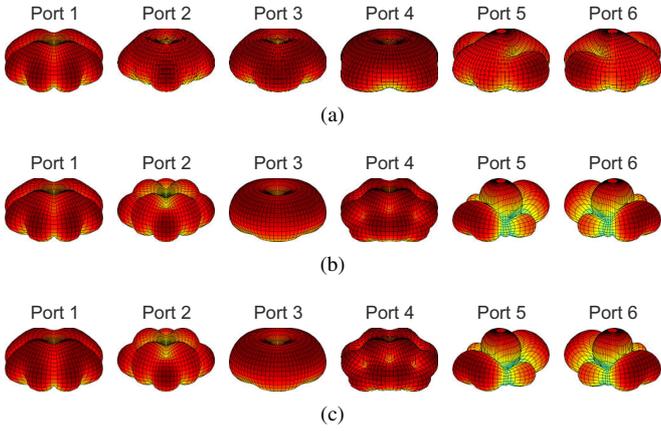


Fig. 12. Envelope correlation coefficients (ECC) of square PEC plate with stepped excitation slots and feed network located 16 mm above ground plane as shown in Fig. 10. (a) 6 GHz. (b) 7.25 GHz. (c) 8.5 GHz.

also be achieved for the other ports by taking some additional measures.

One possible solution to this problem is to modify the excitation slots in order to have an enhanced control of the input impedance. Inspired by [5] and [7], a step in width is introduced to the excitation slots of ports 2, 4, 5 and 6, as shown in Fig. 10. It is observed that such stepped excitation slots exhibit smoother impedance curves at the cost of increased input resistance and capacitance. In order to compensate for the capacitance, the slot length and the feed point position are adjusted. This way, an ultra-wideband impedance match can be realized, though to a reference impedance of 100Ω . In order to connect the antenna element to the feed network with 50Ω reference impedance, simple quarter wavelength transformers with a characteristic impedance of 70.7Ω are introduced as shown in Fig. 10.

These measures yield a sufficient impedance match to 50Ω over the desired frequency range for all six ports, as evidenced in Fig. 11. Compared to Fig. 7, the impedance curves show a flat behavior (Fig. 11(a) and (b)) and the input reflection coefficients of all ports are below -10 dB from 6 GHz



Port	1	2	3	4	5	6
Correlation (a)-(b)	0.9934	0.7767	0.8908	0.4746	0.5286	0.5286
Correlation (b)-(c)	0.9891	0.9961	0.9995	0.9930	0.9913	0.9913

Fig. 13. Far field patterns of square PEC plate located 16mm above ground plane. (a) With idealized gap sources (Fig. 4). (b) With excitation slots and feed network (Fig. 6). (c) With stepped excitation slots and feed network (Fig. 10). (d) Correlation between patterns of the same port.

to 8.5 GHz (Fig. 11(c)). Furthermore, the ports are still highly decoupled (Fig. 11(d)) and uncorrelated (Fig. 12), which results from the fact that the symmetry of the antenna is not affected by introducing the stepped slots.

Figure 13 shows and compares the far field patterns of the different design stages of the antenna. It is visible that there is some quantitative change from the patterns of the ideal design (Fig. 4) to the patterns of the realistic design with slot excitations (Fig. 6). Ports 2, 4, 5 and 6 are most affected, which is again due to the presence of the excitation slots of ports 1 and 3, whereas ports 1 and 3 are less disturbed. The introduction of the stepped slots (Fig. 10) has no significant impact on the patterns both qualitatively and quantitatively.

V. CONCLUSION

A systematic design of an ultra-wideband six-port multi-mode antenna element based on a square plate is presented. Due to symmetry, such a geometry offers six mutually orthogonal sets of characteristic surface current densities. By means of a modal analysis, the antenna size and height above a ground plane are minimized such that the six fundamental characteristic modes are significant over the desired ultra-wide bandwidth from 6 GHz to 8.5 GHz. Antenna ports are then defined and realized by introducing excitation slots, which are systematically optimized based on symmetry considerations. As a result, the six antenna ports are uncoupled as well as uncorrelated and are matched within the desired frequency range.

The implementation of the feed network is currently in process. The influence of the feed network on the overall antenna performance will be evaluated as the next step. After that, fabrication and measurement of the complete ultra-wideband six-port multi-mode antenna will be conducted.

This work confirms that the results from [9] are frequency independent and are applicable to actual antenna designs. Exhaustively exploiting the symmetry properties of the antenna alleviates the optimization process with respect to impedance matching. It is expected that the observations of this work will facilitate the design of more complex symmetric multi-mode antennas, e.g. [16].

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