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Mutual Coupling Reduction Between Implanted Microstrip Antennas on a Cylindrical Bio-Metallic Ground Plane

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ABSTRACT The mutual coupling between two antennas within a human body model is studied. Our multilayer cylindrical body model includes highly lossy body tissues under which a biocompatible metal implant is inserted. This cylindrical bio-metal implant serves as the common ground plane for the conformal antennas. The mutual coupling between two such conformal microstrip antennas is studied and quantified for different spacing between them. Three methods are proposed to reduce mutual coupling between the two antennas. Each of them are investigated in details and their effectiveness is compared.

INDEX TERMS In-body communication, implanted antenna, mutual coupling.

I. INTRODUCTION

Medical telemetry, also known as biotelemetry, involves the application of telemetry in medicine and healthcare. It allows remote monitoring of various vital signals in ambulatory patients and it is exploited more and more in the modern healthcare systems. If adequately implemented, i.e., allowing real-time transmission of biological signals from a patient (e.g. temperature, blood pressure, cardiac beat) in a plausible way to a far located medical center, it is possible to distantly monitor a patient and for example to send a medical team only if necessary. The use of such technologies can strongly reduce hospitalization time, and consequently associated costs, without compromising the quality of the service. On the other hand, having the possibility to continuously collect the biological data, it is possible to develop algorithms to predict the evolution of the medical condition of patients, which again can reflect in higher quality of service, for example by considering recovery only when it is necessary.

In some cases, on-body sensors can collect the signals of interest, but in other cases, information has to be obtained from inside the body. In this case, the collected information should be transmitted outward from inside the body. Implanted antennas are the basic elements of any of such system, where communication between an implanted device in the human body with the outside receivers is required.

The location of the implanted antennas depends on the given telemetry application. An example medical telemetry system, with an implanted antenna just under the skin, is detailed in [1]. In other applications, e.g., for a wireless RF powered brain machine interface application, antennas are situated in brain [2], [3]. A planar spiral antenna (PSA) to be placed in the brain to detect the existence of tumor was designed in [3]. The resonant frequency of the PSA is higher in the presence of tumor than for healthy tissues, and this difference can be exploited in the analysis. Other examples are antennas implanted in human arms. In [1] it is shown that the position of the implanted antenna and electrical properties of the insulating layer also affect the RF power reception and the properties of the tissues surrounding the implanted antenna can influence the electrical characteristics of the antennas. Implanted cavity slot antenna with H-shape slot is proposed and characterized in [4].

Few examples of antennas on the bone are in present in the literature. In [5], the reason of using implanted antennas in bone is discussed and a comparison between bone-implanted antenna and a muscle-implanted antenna is presented.

Radiation performances of antennas can be increased, for example, by considering an array of radiators. As for example in [6] where an implanted conformal slot array located between the two parts of a broken femur is considered.

The array solution also presents some drawbacks, such as the larger space required, and the effect of the mutual coupling between the radiators, that can, in turn, reduce the gain or increase the level of sidelobes. In the literature, different ways to reduce the effect of the mutual coupling have been proposed. Methods to reduce mutual coupling between a pair of close E-shaped patch antennas are described in [7], including cutting a slit in the common ground plane. In [8], a parasitic tape on microstrip patch elements was experimented. This mechanism of mutual coupling reduction has been studied by observing the field distribution in the presence of the tape, and comparing with the initial case when the tape is not present. In [9], a solution consisting of the use of a pair of slits between two walls of a printed circuit board in air was studied aiming to improve the isolation of a pair of closely packed antenna elements. In [10], a suspended line that links two planar inverted-F antennas (PIFAs) was used to compensate for coupling. By this way, opposite coupling can be introduced that if properly designed will offset the unwanted interaction and in turn can increase the antenna efficiency. Analogous solution was proposed in [11], where a connection between two ports was considered. Such a solution is convenient and easy to be implemented by appropriately designing the connection. However, the reduction of coupling i.e., S21 magnitude is accompanied by a shift of the resonant frequency.

Another class of solutions for reducing the mutual coupling between radiators consist of using Electromagnetic Bandgap (EBG) structures. In [12], a periodic structure on a conformal ground plane, which exhibits EBG in the interested band, was used. In [13], a defected ground structure (DGS) with two H-shaped slots between the antennas were used which are placed very closely to each to other (distance less than 0.3λ). With this structure, the mutual coupling reduces up to 50 dB without significant influence on the radiation pattern. In [14], a comparison between an EBG structure and DGS structure was performed. However, the study of the mutual coupling for implanted antennas is at the early stage, and to the best of the authors' knowledge, only few examples are reported in the literature.

In this paper, the reduction of the mutual coupling in the case of an implanted two-element antenna array is investigated. The radiators are placed on a metallic cylinder (the implant) embedded in a polymer dielectric that acts as the substrate between the ground plane and radiators, all of them being conformal. Quantification of mutual coupling is performed. For the reduction of mutual coupling, three methods are investigated, and the amount of reduction of coupling with different methods is studied for different positions of the two radiators.

II. THE BODY MODEL

For the proposed investigation a cylindrical body model is considered. It has dimensions alike to an adult leg. The different tissues modeled as concentric cylinders are characterized by different thicknesses and material parameters (dielectric constant and loss). In all cases the magnetic properties of tissues and dielectrics have been neglected, i.e. relative magnetic permeability is set to unity. Microwave Studio from CST has been used to model the system and to perform the numerical study.

The material parameters, i.e., relative dielectric constant and conductivity (S/m), are reported in Tab. I.

TABLE 1. Electrical properties of the body tissues and other material at f = 2.45 GHz.

	Muscle	Fat	Skin	PDMS layer	Bone /Titanium
Relative permittivity	57.1	5.6	46.7	2.667	Lossy metal
Conductivity (S/m)	0.79	0.04	0.69	0.034	1e7

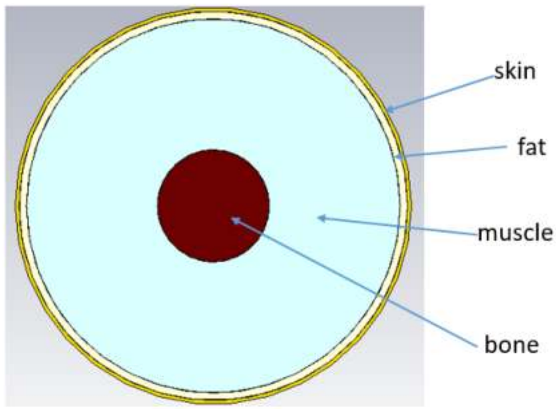


FIGURE 1. Cross section of the considered model. The "bone" consists of a lossy bio-metal.

In the considered model in Fig. 1, the central part of the geometry i.e., the bone, is replaced with an implant of the same dimensions made of a biocompatible metal and metallic alloy. Titanium, titanium alloys, stainless steel, cobalt and their alloys can be used for the manufacturing of implant. Generally, in orthopedic field Titanium and its alloys have been employed, because of their excellent biocompatibility, promising mechanical properties and their high corrosion resistance. Ti–6Al–4V is widely used in a variety of stress-bearing orthopedic applications, but some research [15], [16] have demonstrated that occasionally release of Al and V ions arises, with a negative consequence on tissues. In order to avoid such problems, actually the tendency is to employ metallic alloys with no harmful elements, like a basic Ti alloy composition and substituting the hazardous elements by Nb, Ta, Mo, Zr or a combination of them. Porous Ta has been used for hip and knee arthroplasty, while low occurrence of artifacts can be obtained by addition of Ta in TiNi shape memory alloy [17]–[24]. Spongy structures based on glassy alloys with biocompatible elements is proposed in [25] as an alternative solution to the conventional crystalline and amorphous alloys with superior stiffness than human bone. Additionally, the mechanical behaviors as response to mechanical stimulus like strain and stress, and cell concentrations involving the implant, has also been studied [26].

In this paper, the above mentioned bio-metallic implant is also used as the ground plane for conformal rectangular microstrip antennas, as illustrated in the model in Fig. 2.

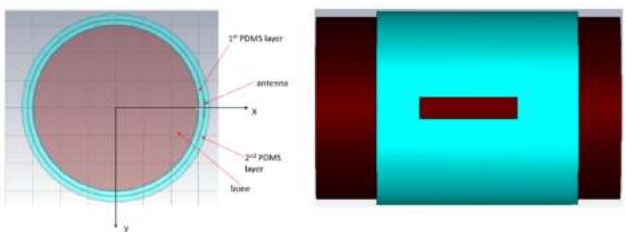


FIGURE 2. Location of a conformal rectangular microstrip antenna in between two PDMS layers over the bio-metal implant that has replaced the bone: top view (left), side view with the external PDMS layer removed for a better rendering (right). In both figures the surrounding tissues (muscle, fat and skin) have been removed for a better rendering. They are present in all simulations.

The bio-metal conformal rectangular microstrip antenna is separated from the metallic cylinder ground plane by a conformal substrate made up of Polydimethylsiloxane (PDMS). In the considered model, a second layer of PDMS is also present that acts as superstrate. In the numerical modelling, the thicknesses of the two PDMS layers are considered equal. The dimensions are reported in Tab. II.

TABLE 2. The parameters of the model.

Parameter	DESCRIPTION	Value (mm)
r_{bone}	radius of the bone	30
l_{str}	total length of the implant	100
l_{PDMS}	length of each PDMS layer	66
th_{PDMS}	thickness of each PDMS layer	2
th_{muscle}	thickness of the muscle layer	70
th_{met}	thickness of the metal (antenna)	0.5
th_{fat}	thickness of the fat layer	4
th_{skin}	thickness of the skin layer	2

III. DESIGN OF THE SINGLE ANTENNA

In the first step of the analysis, a single antenna element has been designed. It is a rectangular microstrip antenna of length l_{ant} and width w_{ant}, fed by a probe on its symmetry axis, and at a distance l_z from one of the edges. The probe is modeled by a metallic cylinder. Its second end is connected to the ground plane (Ti cylinder).

The three aforementioned parameters have been used in an optimization process to minimize the reflection coefficient with respect to a standard 50 Ω feed at the center of the 2.4 - 2.5 GHz Industrial, Scientific and Medical (ISM) radio band, i.e. at 2.45 GHz. The optimization process was necessary because no analytic formulas for the design that include the body environment are available. After the optimization by a Genetic Algorithm (available in the numerical tool), the dimensions of the antenna are found to be $l_{ant} = 32$ mm, $w_{ant} = 7$ mm and $l_z = 0$ mm. The corresponding reflection coefficient is shown in Fig. 3.

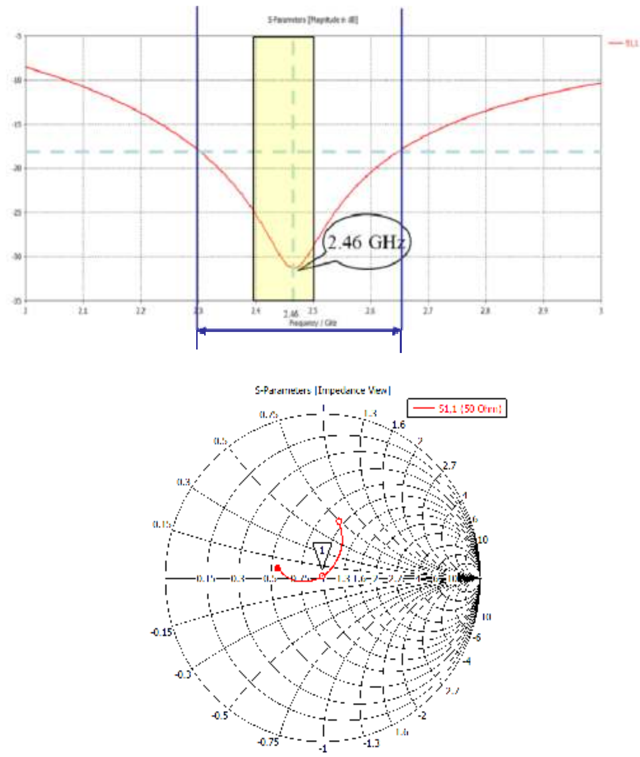


FIGURE 3. Reflection coefficient of the optimized antenna. Reference impedance equal to 50 Ω.

The resulting geometry exhibits good matching at 2.464 GHz, which is close the center of the considered band. The bandwidth is relatively large also due to the losses considered in the modelling.

IV. MUTUAL COUPLING

As mentioned above, our interest is the quantification of mutual coupling between two antennas. The corresponding scenario is presented in Fig. 4. Two identical antennas are considered. The first one is in a fixed position and the second one is rotated around the implant by an angle alpha (α), in such a way that it always remains parallel to the cylindrical ground plane.

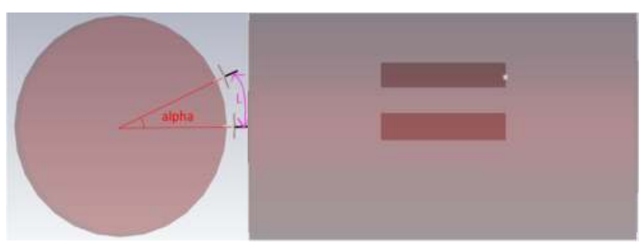


FIGURE 4. Model of the two parallel conformal rectangular microstrip antennas over the cylindrical implant: front view (left), side view (right). The white spot on the right side of the upper radiator corresponds to the probe.

The complex scattering matrix has been computed and the mutual impedance Z_{21} has been evaluated for different rotation angles α, in the interval from $\alpha_{min} = 25°$ to $\alpha_{max} = 180°$ with a step of $\Delta\alpha = 5°$. The corresponding results are reported in Fig. 5.

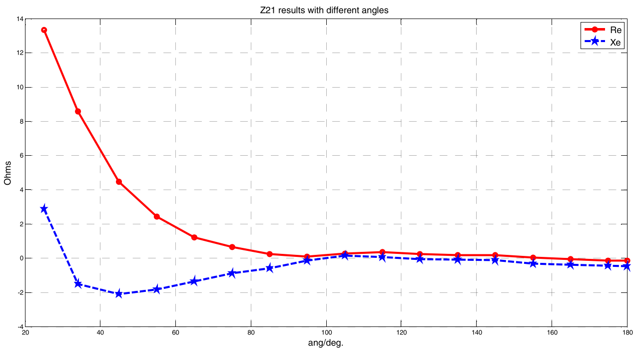


FIGURE 5. Real and imaginary part of the mutual impedance between the two conformal rectangular microstrip antennas for different rotation angles.

The data in Fig. 5 indicates that the coupling has an oscillatory behavior and presents a strong reduction while the distance between the antennas increases, similar to what happens for the planar case [27].

However, since the active input impedance Z_{inp} of the single element is influenced by the self-impedance of the two radiators Z_{11} and Z_{22} and by the mutual coupling Z_m according to

$$Z_{inp} = Z_{11} - \frac{Z_m^2}{Z_{22}}$$

for small angles the large coupling can have a significant effect. In order to reduce this effect, in the following section three methods for the reduction of mutual coupling are proposed and analyzed.

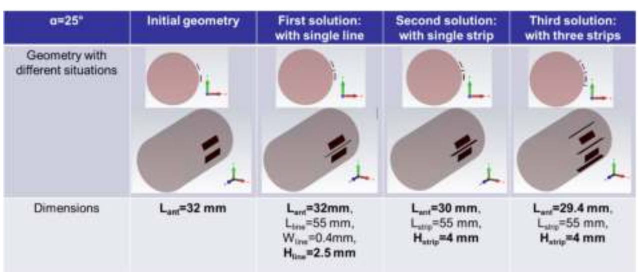


FIGURE 6. Three methods to reduce mutual coupling between the two antennas: first method (top), second method (middle), third method (bottom). For each case: front view (left), side view (right).

V. REDUCTION OF THE MUTUAL COUPLING

Three methods, illustrated in Fig. 6, are investigated in this section in order to reduce mutual coupling between the two parallel antennas. First method is to introduce a grounded line between the two antennas. Second method is to introduce a grounded metallic strip between the two antennas. In the third method this configuration is further extended by adding two more grounded strips at the two sides of the array.

In the first method, the material of the line is the same as of the implant and antennas. Its width has been chosen to be equal to 0.4 mm. Its height has been chosen to be equal to 2.5 mm which is the sum of the thickness of the first PDMS layer and the thickness of the antenna, i.e. $th_{PDMS} + th_{met}$. Its length has been chosen to avoid resonance; the value of 55 mm has been used in the following simulations performed in the angular interval of 25° to 90°. The two ends of the line are connected to the implant by two metallic cylinders. In the second method, the length of the strip is the same as the line of the first method while the height has been chosen to be equal to 4 mm, which is equal to the total thickness of the two PDMS layers. In the third method, all the three strips have the same dimensions as in the second method.

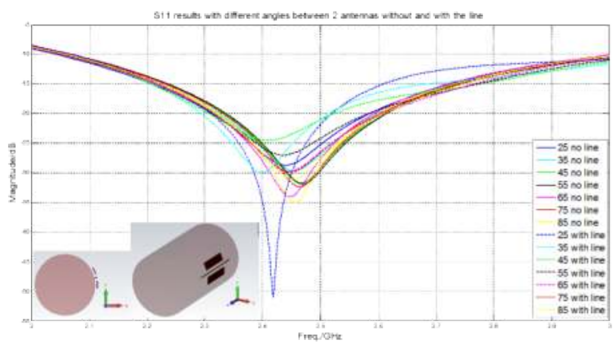


FIGURE 7. Input reflection coefficients for the first method (dotted lines) and for the initial case with no mutual coupling reduction (solid lines).

Input reflection coefficients obtained for the first method (with a line) are compared with the initial case (without the line) in Fig. 7. As angle changes, the resonant frequency has a small shift because the mutual coupling changes with angle of rotation α. With the proposed line, the resonant frequency also shifts compared to the initial situation without the line.

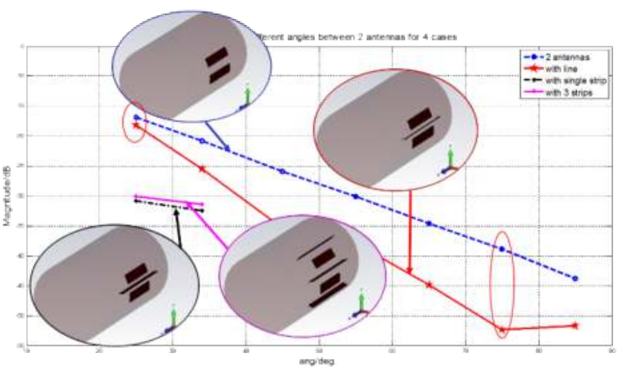
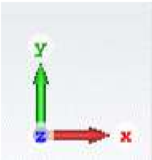
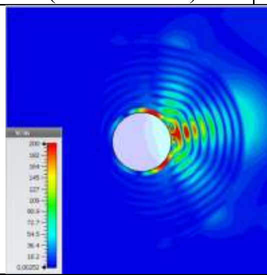
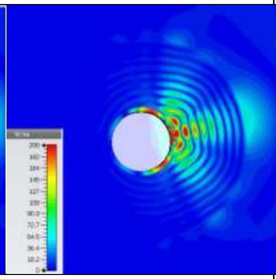
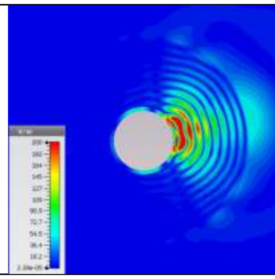
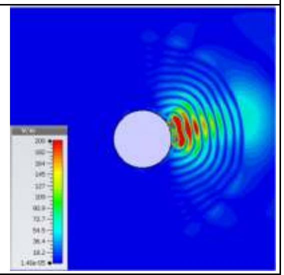
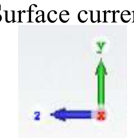
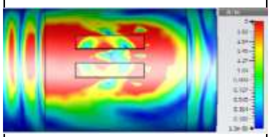
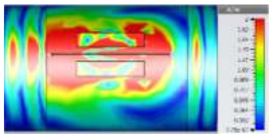
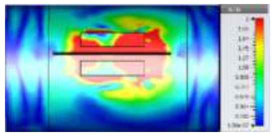
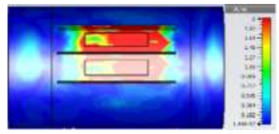
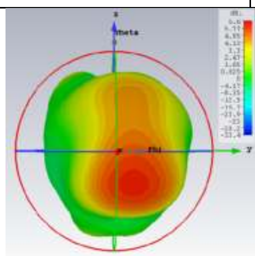
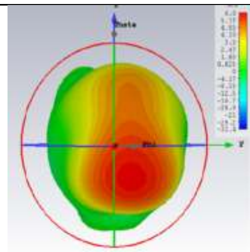
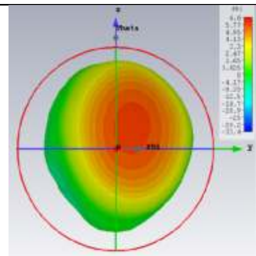
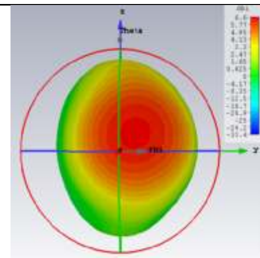


FIGURE 8. Transmission coefficients for four cases: initial configuration and three mutual coupling reduction methods in Fig. 6.

The scattering matrix transmission coefficient magnitudes for the four analyzed cases in the angular interval from 25° to 90° are compared in Fig. 8. It can be observed that all

TABLE 3. Comparison of four cases for $\alpha = 25°$: initial geometry, with single line, with single strip and with three strips.

α=25°	Initial case (no reduction)	First method	Second method	Third method
E field 				
Surface current 				
Radiation pattern				
Directivity (dBi)	6.159	6.590	5.828	6.567
Gain (dB)	-12.13	-12.26	-12.12	-11.03
Rad. efficiency (dB)	-18.32	-18.85	-17.95	-17.6
Total solver time	5 h, 43 m, 58 s	8 h, 21 m, 33 s	7 h, 54 m, 52 s	10 h, 34 m, 15 s

three methods can reduce mutual coupling by different levels. With the first method, the maximum coupling reduction is about 7 dB at 75° but for small angles mutual coupling reduction is not significant. With the second and third methods, reasonable mutual coupling reduction of about 13-14 dB can be achieved even for small angles. Consequently, the effect on the detuning is smaller, and the resulting reflection coefficients are closer to that of the single element in the stand-alone case.

In the following discussion, the effects of the proposed methods on the radiation performances are analyzed for the separation angle of 25°. Moreover, a broadside configuration has been considered, i.e., where the phase difference between the feeding signals of the two antennas is equal to zero. Table 2 compares the results for four cases considered before. For the sake of completeness, in Fig. 9 the same quantities, as reported in the Tab. 3, but for the single element are reported.

The first method leads to highest directivity, i.e., 6.59 dBi, but low efficiency, i.e., −18.85 dB. With second method, the efficiency increases, nevertheless the directivity is the lowest one among the three methods. Even though the third method takes the longest simulation time, its gain, radiation efficiency and directivity all demonstrate a significant improvement compared to the initial configuration. These figures are to be compared with the directivity of the single element, i.e. 4.35 dBi (See Fig. 9).

Comparing all the results, one can conclude that the most suitable solution is the third one, which can produce 13 dB reduction in mutual coupling. Moreover, it increases directivity by 0.4 dBi, gain by 1.1 dB and radiation efficiency by 0.9 dB. In situations where implementation of three strips is not practical, the second method may be acceptable as it also leads to good reduction in mutual coupling.

Furthermore, it can be observed that the pointing angle in the plane containing the symmetry axis of the structure

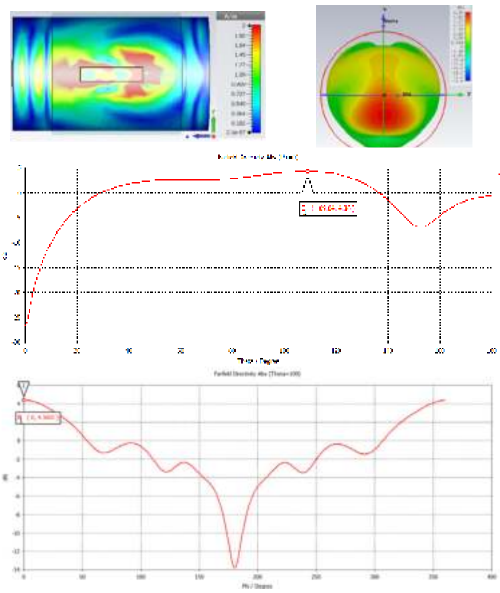


FIGURE 9. Surface current (top left) and 3D radiation pattern (top right) of the single antenna. xOz (middle) and xOy (bottom).

is varying. It is quite different with respect to the direction of the maximum radiation of the single antenna (see Fig. 9). As the mutual coupling reduces, the direction of the maximum radiation is closer to that of the single element.

VI. CONCLUSIONS

Three solutions to reduce mutual coupling between two implanted microstrip antennas has been proposed. The extent of mutual coupling reduction has been quantified, and the best solutions have been identified. That is the insertion of a grounded, non-resonant, metallic strip halfway between the radiators and two additional strips on the two sides of the array. It was numerically verified that the reduced coupling manifests in higher gain and radiation efficiency, as expected. The coupling also influences the current distribution on the single radiators that in turn reflects in the tilted pointing angle of the two-element array. As the coupling reduces, the radiation pattern in the E-plane of the antenna is similar to the single element.

The proposed solution is feasible: in some cases following an injury, piece of a bone has to be replaced by an implant. When this occurs, instead of implanting a bare metallic cylinder (of bio-metal), the proposed geometry, i.e. bare cylinder equipped with the antenna(s) could be considered. The inside of the metallic cylinder could also host the necessary electronic part (signal generator, sensors, etc.).

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