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Small Antennas: Miniaturization Techniques and Applications

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Original scientific paper

The paper presents research results in the field of small antennas obtained at the Department of Wireless Communications, Faculty of Electrical Engineering and Computing, University of Zagreb. A study comparing the application of several miniaturization techniques on a shorted patch antenna is presented. Single and dual band shorted patch antennas with notches and/or slot are introduced. A PIFA designed for application in mobile GSM terminals is described. The application of stacked shorted patches as array elements for a mobile communication base station as well as for electromagnetic field sensor is presented. The design of single and dual band folded monopoles is described. Prototypes of the presented antennas have been manufactured and their characteristics were verified by measurements.

Key words: Small Antenna, Planar Antenna, Shorted Patch Antenna, PIFA, Stacked Patch Antenna, Folded Monopole, Dual Band Antenna

Male antene: postupci smanjivanja izmjera i primjene. U radu su prikazani rezultati istraživanja u području malih antena ostvareni na Zavodu za Radiokomunikacije, Sveučilišta u Zagrebu Fakulteta elektrotehnike i računarstva. Prikazana je primjena više postupaka za smanjivanje izmjera skraćene mikrotrakaste antene. Opisane su izvedbe skraćenih mikrotrakastih antena s urezima i prorezom za rad u jednom i u dva frekvencijska područja. Prikazana je izvedba planarne invertirane F-antene (PIFA) za primjenu u ručnim terminalima sustava pokretnih komunikacija GSM. Višeslojne skraćene mikrotrakaste antene uporabljene su za izvedbu antenskog niza za baznu postaju sustava pokretnih komunikacija te kao elementi osjetila za mjerenje jakosti elektromagnetskog polja. Prikazana je izvedba savijenih monopolnih antena za rad u jednom te u dva frekvencijska pojasa. Izrađeni su prototipovi opisanih antena i mjerenjima su ispitane njihove osobine.

Ključne riječi: mala antena, planarna antena, skraćena mikrotrakasta antena, PIFA, višeslojna mikrotrakasta antena, savijeni monopol, dvofrekvencijska antena

1 INTRODUCTION

Development and wide usage of personal communications and handheld devices such as smart phones, organizers, tablets, computers, navigation devices, etc. which are using wireless access points to exchange and transfer data opened large interest in research and development of small antennas and antenna miniaturization techniques. From the engineering point of view the antenna is a necessary part of any handheld and/or mobile wireless devices.

On the other hand, for the designers and users, an antenna on the device is something inelegant which should be avoided or at least should be made invisible. These two requests are reconciled through the development of small antennas, usually integrated in the handheld device body. On the other end of the wireless link the base station or wireless access point must also have an antenna. The antennas are placed outdoor on buildings and masts and indoor. For outdoor antennas wind load and weight become a critical factor. Indoor antennas have to be integrated in buildings and made esthetically acceptable to general public. The answers to these requirements are again small antennas.

Antenna size and its performance are strongly linked together. The first fundamental results showing the link between antenna size and its maximum bandwidth and gain were presented in the late 1940s [1, 2]. The antenna size is not mainly determined by the technology used for its fabrication (like in electronic chips) but rather by physical laws. Good antenna performances are obtained when the antenna is resonant and when its size is comparable to the wavelength. At usual operating frequencies of mobile communications and wireless networks this means that the antenna should be quite large. Several techniques and approaches have been introduced to reduce antenna dimensions and maintain good radiation properties [3 – 6]. Research and development of small antennas is of great importance for all future wireless applications [4, 6]. To reduce the antenna dimensions mostly shorted patches and PIFAs are used [7 – 11]. To further reduce the antenna dimensions modifications have to be introduced in the patch [5, 12]. The research results and antenna designs presented in this paper range from case studies used for gaining experience in application of miniaturization techniques up to antennas and arrays designed for specific applications in prescribed frequency bands.

2 PATCHES WITH SLOTS

Patch antennas offer several advantages over classical antennas like low cost, easy fabrication, planar shape, conformability, etc. [13]. However, a rectangular patch offers good radiation properties when it is resonant, i.e. when its resonant dimension is half of the guided wavelength.

2.1 Step-by-step miniaturization

The first step in size reduction is to use mirroring in a conducting wall, which reduces the resonant length roughly to quarter wavelength. The next step can be to increase the path length for the current in resonant mode by introducing notches and slots in the patch. A step-by-step size reduction was presented in [14, 15]. The proposed antennas are shown in Fig. 1. All antennas are designed for operation at 2 GHz. The substrate is air. The obtained results have been compared with a reference antenna, a quarter wavelength shorted patch antenna with dimensions: resonant length $L = 32.2$ mm, width $W = 50$ mm, and height $h = 5$ mm. The parameters of the reference antenna are calculated by using HFSS 3D electromagnetic-field simulation package from Ansoft. The reference values are input impedance bandwidth of 120 MHz (SWR < 2) and gain of 2.6 dBi. All antennas in Fig. 1 are excited by a coaxial probe which position is optimized for best impedance matching. The antenna dimensions are also given in Fig. 1. The first example is the antenna in Fig. 1a. It has two notches along the resonant dimension L to increase the electrical length for the current of the resonant mode. In this case the shorting wall has the same width as the patch. When the shorting wall width is smaller than the patch width W, the current path is longer (Fig. 1b). Here the shorting wall was realized with five shorting posts. Further size reduction was realized by capacitive loading of the patch i.e. by folding the radiating edge towards the ground plane (Fig. 1c). The patch width W was also reduced. However, all size reductions so far were paid with bandwidth reduction.

The last antenna from this example (Fig. 1d) is nor the smallest, nor the one with largest bandwidth. However, it is the only one which offers larger volume reduction than the reduction of the input impedance bandwidth. The results are summarized in Table 1.

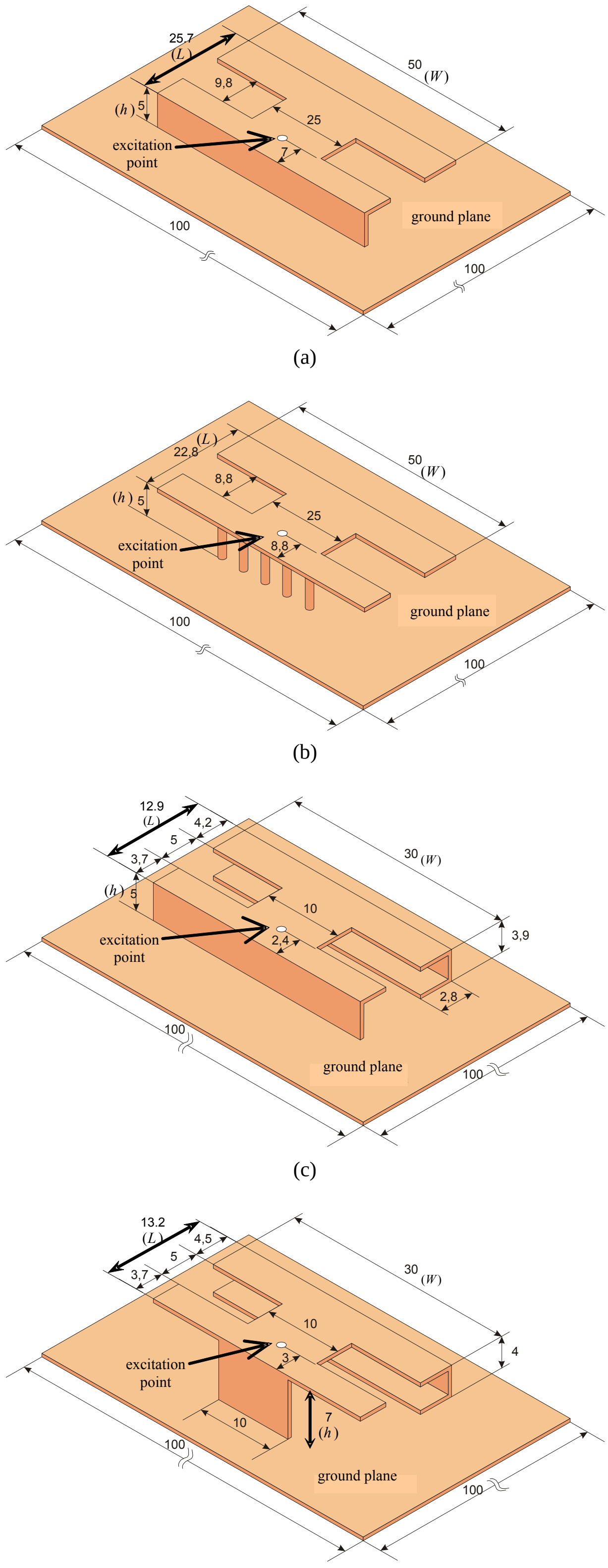

Fig. 1: Shorted patches with notches [14, 15] (all dimensions in millimeters)

Table 1: Comparison of antenna dimensions and obtained bandwidth and gain

Antenna	Reference	(Fig. 1a)	(Fig. 1b)	(Fig. 1c)	(Fig. 1d)
Dimensions [mm] $W \times L \times h$	50× 32.2× 5	50× 25.7× 5	50× 22.8× 5	30× 12.9× 5	30× 13.2× 7
Area reduction [%]	0.0	20.2	29.1	76.0	75.4
Volume reduction [%]	0.0	20.2	29.1	76.0	65.6
Bandwidth [MHz]	(120) calculated	90	55	26	60
Bandwidth reduction [%]	0.0	25.0	54.2	78.3	50.0
Gain at 0° [dBi]	(2.2) calculated	3.1	0.1	2.4	0.0
Max. gain [dBi]	(2.6) calculated	5.1	3.8	3.6	5.3

2.2 Patch Antenna With Notches and Slot

Another example of size reduction by applying notches and slots in a shorted patch is given in [16]. The antenna is designed to be resonant at 900 MHz. Its layout is shown in Fig. 2 and the dimensions are $L = 56$ mm, $W = 48$ mm, $h = 10$ mm, $x = 10.2$ mm. The notches and the slot are of the same dimensions 20 mm × 4 mm, while their centers are positioned at 17 mm, 29 mm, and 41 mm from the shorting wall. The antenna prototype is shown in Fig. 3. Measurement results have shown 24 MHz bandwidth around 900 MHz (SWR < 2). The measured reflection coefficient at the antenna excitation port is shown in Fig. 4. The measured gain at 0° (direction perpendicular to the ground plane) was 4.72 dB, while in the beam maximum (approximately at 10°) it was 4.96 dB. Compared to the shorted patch without notches and slots, a size (length) reduction of 28.5 % was obtained.

2.3 Dual Band Shorted Patch Antenna

Dual band operation is often required for antennas used in devices operating in two frequency bands. A shorted patch antenna for operation in GSM 900/1800 bands is presented in [17]. This antenna is shown in Fig. 5. Here the shorted patch was used to reduce the antenna size, while the dual band operation is obtained by a slot in the patch. The patch dimensions (Fig. 5) are $L = 64$ mm $\times$ $W = 102$ mm. It is placed at $h = 11$ mm above the

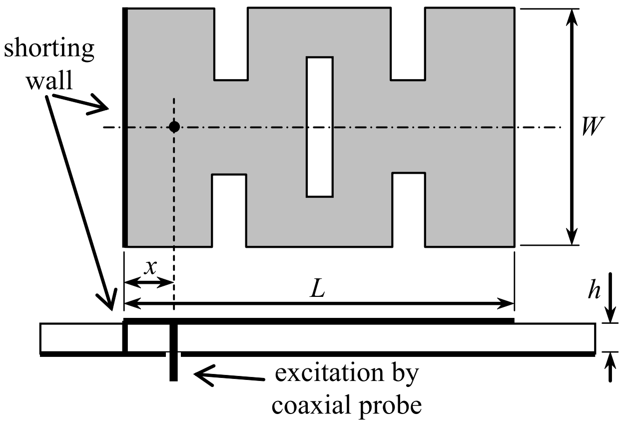

Fig. 2: Shorted patch with notches and slot [16]

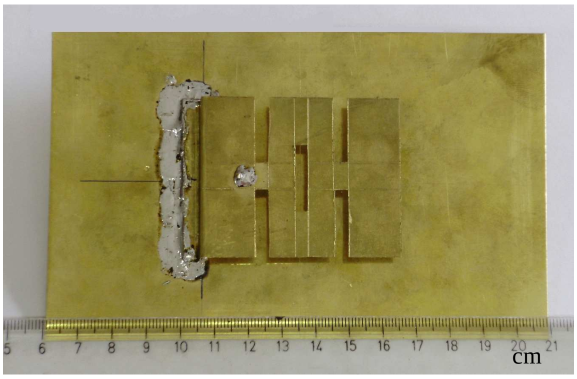

Fig. 3: Prototype of the antenna from Fig. 2

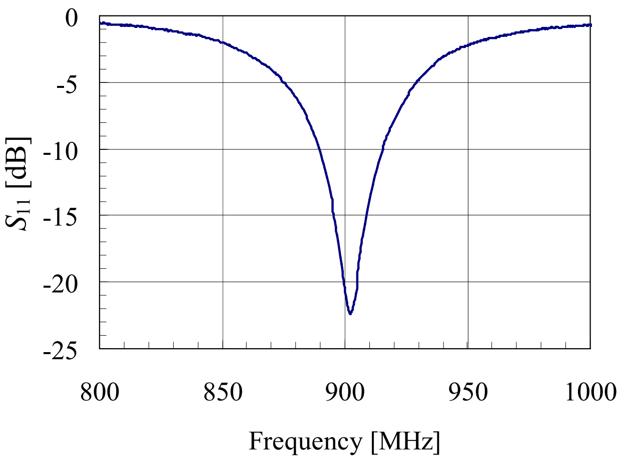

Fig. 4: Measured reflection coefficient at the input of the antenna in Fig. 3

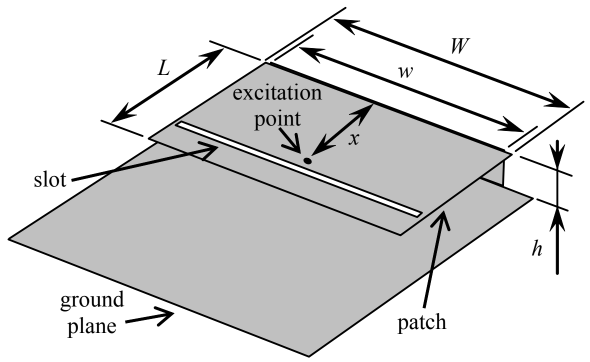

Fig. 5: Dual band shorted patch [17]

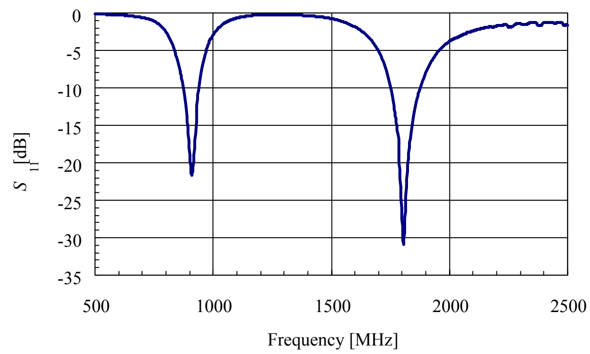

Fig. 6: Measured reflection coefficient at the input of the dual band antenna in Fig. 5

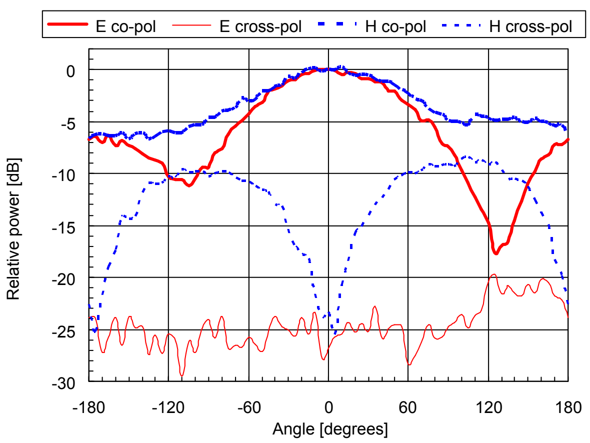

Fig. 7: Measured radiation patterns at 920 MHz (lower band) of the dual band antenna in Fig. 5

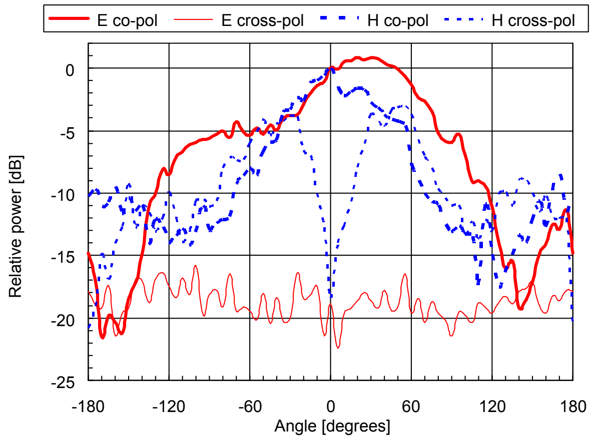

Fig. 8: Measured radiation patterns at 1800 MHz (upper band) of the dual band antenna in Fig. 5

ground plane. The width of the shorting wall is $w = 100$ mm. The patch is excited by a coaxial probe at the line of symmetry at a distance $x = 46$ mm from the shorting wall. The slot dimensions are 98 mm $\times$ 1 mm and it is positioned 16.5 mm from the radiating edge of the patch. The measured reflection coefficient magnitude for the dual band antenna is shown in Fig. 6. Two resonances can be clearly seen, one at each operating band (around 920 MHz and around 1800 MHz). The E- and H-plane radiation patterns have been measured in both operating bands. They are shown in Figs. 7 and 8, respectively. The radiation patterns are normalized to the respective co-polarization level at $0°$. The radiation patterns in the lower band (Fig. 7) are quite symmetric with respect to the $0°$ direction. In the upper band (Fig. 8) the effects of the used antenna configuration (shorted patch) can be observed: the E-plane co-polarization maximum is shifted to $+30°$ and the cross-polarization levels are increased. The measured gain of the dual band antenna in Fig. 5 is between 0.5 dBi and 3.7 dBi in the lower and between 7 dBi and 9 dBi in the upper band.

3 SLOTTED PIFA

Antennas for mobile terminals present continuous challenge. It is usually required that they fit inside the mobile terminal housing in order to allow compact and appealing design. To address this requirement various designs and modifications of shorted patches and PIFAs have been presented [5, 7-11]. A study of a slotted PIFA for the GSM 900 band is presented in [18, 19]. The PIFA and its dimensions are shown in Fig. 9. It is placed on a 50 mm $\times$ 100 mm ground plane, at one of the shorter edges (Fig. 10). The ground plane size was chosen to match an average mobile phone. For testing purposes, the PIFA was excited by a coaxial probe. The final design was resonant

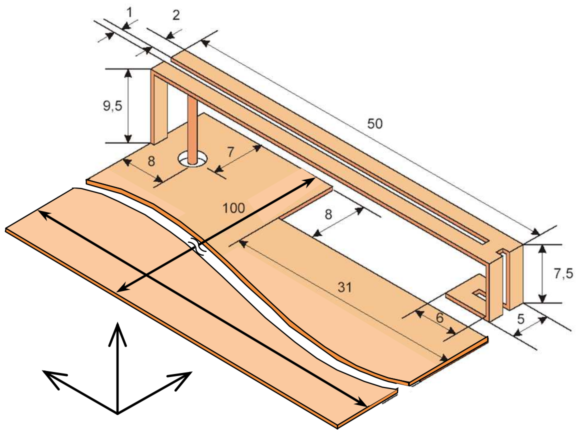

Fig. 9: Slotted PIFA (all dimensions in millimeters)

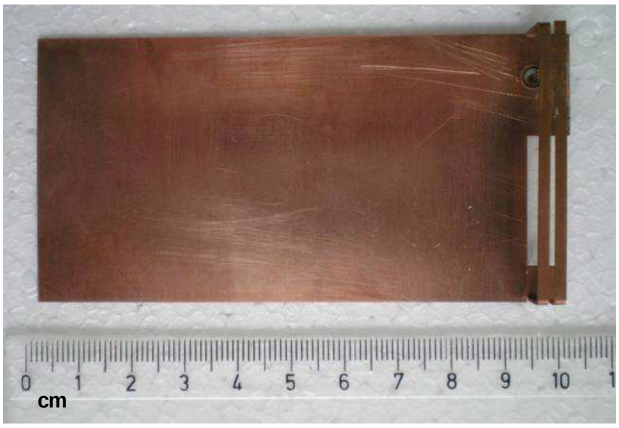

Fig. 10: Slotted PIFA (on the right) with ground plane

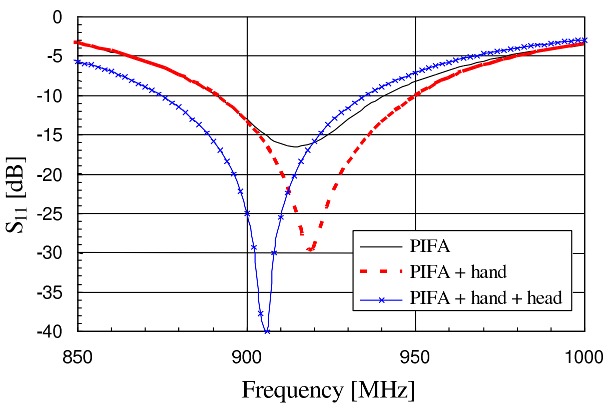

Fig. 11: Measured reflection coefficient at the antenna input for the PIFA in Fig. 11 alone, for the PIFA with hand phantom, and for the PIFA with hand and head phantoms [19]

at 916 MHz and had a bandwidth of 109 MHz (SWR $<$ 3), which covers the band of interest (Fig. 11). The PIFA performances were tested also in the presence of a human hand and head phantoms [19]. Measurement results of the reflection coefficient at the antenna input for the considered PIFA in the proximity of human hand and head phantoms are shown in Fig. 11. For the measurements of the PIFA with only the hand phantom, the hand phantom was covering approximately 8 cm of the bottom part of the antenna ground plane. For the measurements of the PIFA with the hand and head phantom, the position of the hand phantom was the same while the head phantom was placed 2 cm behind the ground plane. The first case simulates the application of the handheld device used with earphones, while the second simulates the case where the handheld device is placed near the user's ear. Measurement results in Fig. 11 show that better impedance matching is obtained in presence of the hand and head phantoms due to the dielectric loss.

4 STACKED SHORTED PATCHES

From the former examples, it follows that obtaining desired impedance matching in a prescribed bandwidth is mostly the problem with small antennas. The bandwidth can be increased on the expense of increased volume by adding a parasitic patch over the excited one.

4.1 Indoor Base Station Antenna

The first example of the application of stacked shorted patches is a reconfigurable indoor base station antenna array [20, 21]. The array consists of three stacked shorted patches placed in three orthogonal planes forming a pyramid-like structure. The array element - shorted stacked patch - is shown in Fig. 12, while its dimensions are given in Table 2. All heights are defined with respect to the ground plane. Both patches are manufactured on air substrate. The shorting wall is common to both patches (driven and parasitic) and it extends over the upper patch (Fig. 12) in order to reduce mutual coupling between the patches in the array. The mutual coupling is further reduced by side walls at the ends of the ground plane along the non-radiating patch edges. Comparison of the calculated and measured reflection coefficient at the single stacked patch input is shown in Fig. 13. Measurements for all three array elements are also shown in Fig. 13. The agreement with calculation as well as the manufacturing repeatability is very good.

Three single antennas (Fig. 12) were integrated in an array (Fig. 14). The array is intended to be put e.g. on the ceiling of the room and to provide appropriate signal coverage for users in all parts of the room. Two excitation schemes of the array have proven to be useful. In the

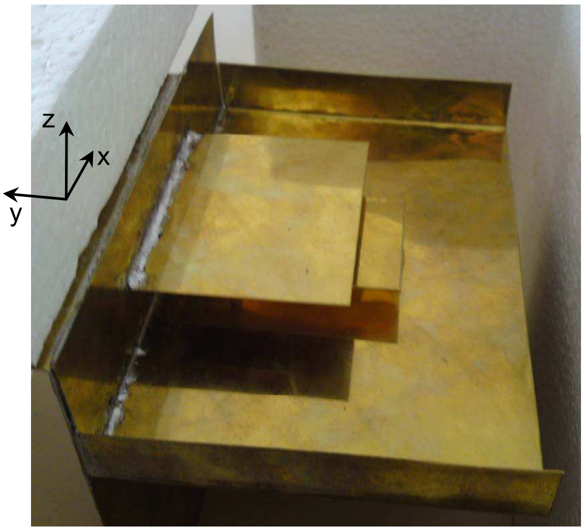

Fig. 12: Single shorted stacked patch used in the antenna array for indoor base station [21]

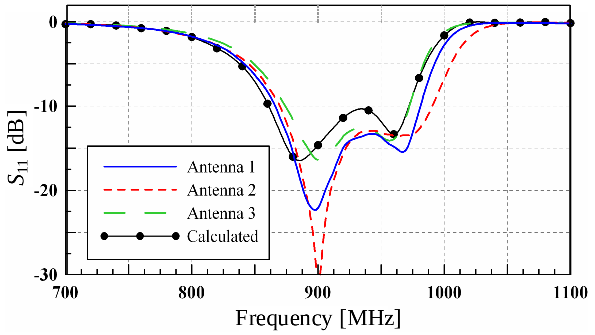

Fig. 13: Calculated and measured reflection coefficient at the antenna input port for the antenna in Fig. 12. Measurement results for all three array elements are shown.

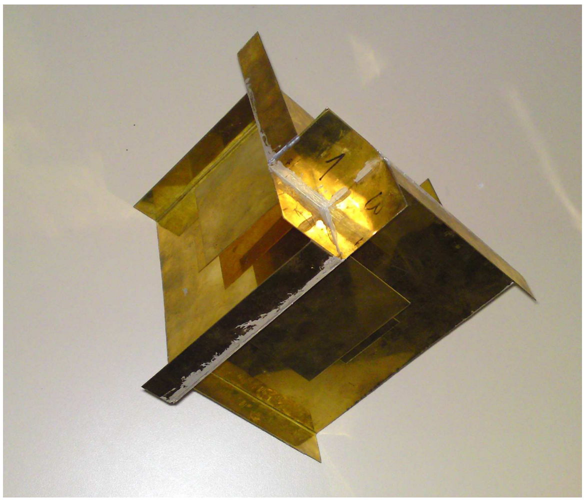

Fig. 14: Antenna array prototype

Table 2: Single stacked shorted patch dimensions

	Length	Width	Height
Driven patch	79 mm	40 mm	10 mm
Parasitic patch	65 mm	72 mm	20 mm
Ground plane size	160 mm × 120 mm		
Shorting wall height	40 mm		
Height of side walls	20 mm		
Feed point location	19 mm from shorting wall on the axis of symmetry		

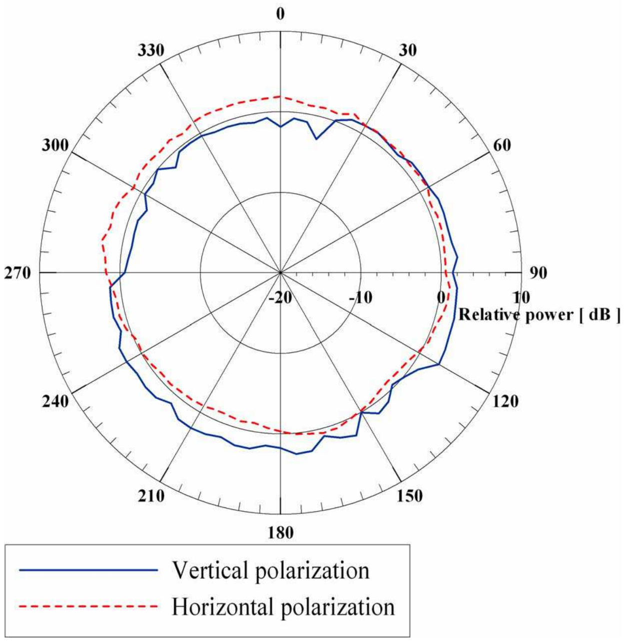

Fig. 15: Measured radiation pattern in azimuth plane of the array in Fig. 14 at 920 MHz for elevation angle 30° and all elements excited in-phase

first excitation scheme all three array elements are excited in-phase. With this excitation the array provides nearly hemispherical coverage. This is verified by calculation as well as by radiation pattern measurement [21]. The radiation patterns were measured in azimuth plane for both horizontal and vertical polarization and for different elevation angles. The measured radiation pattern in azimuth plane and elevation angle of 30° for the array with all elements excited in-phase is shown in Fig. 15. It confirms that the coverage is nearly hemispherical. In the second excitation scheme, each array element operates independently covering an approximately 120° sector. As the radiating elements have different polarizations, the beam maximum for each sector slightly changes its direction depending on the used polarization. However, in indoor environment with numerous reflections and scattering this should not be a disadvantage. The two excitation schemes can be electronically switched by reconfiguring the array feeding network. In such a way the base station capacity can be dynamically adjusted for increased number of users.

4.2 Electromagnetic Field Sensor

Shorted stacked patches have also been used as antennas for electromagnetic field sensor [22, 23]. The number of electromagnetic field sources of various frequencies in the human environment is constantly increasing. These fields can produce adverse effects in the human body and affect health. Therefore, exposure to EM fields should be measured, quantified and finally reduced if possible. To achieve this, electromagnetic sensors which can measure the strength of the EM field in space are needed. The main principle for measuring the total field strength of an EM wave of unknown polarization in a point in space is to measure three orthogonal linear polarizations by using a probe which responds either to electric or magnetic field (so called E-field and H-field probes, respectively). The measured field strength of all three polarizations is then added to get the total field strength. Although measurement methods assume that measurement of all three components is made simultaneously, most commercial sensors actually measure one linear component at a time. This approach extends measurement time and consequently introduces inaccuracies and uncertainties in measurements. The problem becomes even more pronounced in cases when the incident EM field with unknown polarization is pulsed rather than continuous. The EM field sensor [23] consists of three pairs of shorted stacked patches. All three pairs have the same phase center. Two patches forming a pair are placed on opposite sides of a cube (Fig. 16). The radiation pattern of such a pair (Fig. 17) reasonably well resembles

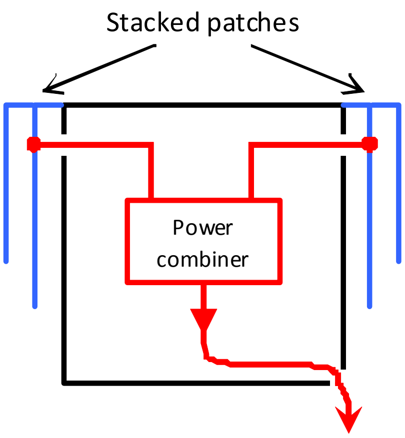

Fig. 16: Pair of stacked patch antennas on a cube forming the sensor for one linear component of the incident wave

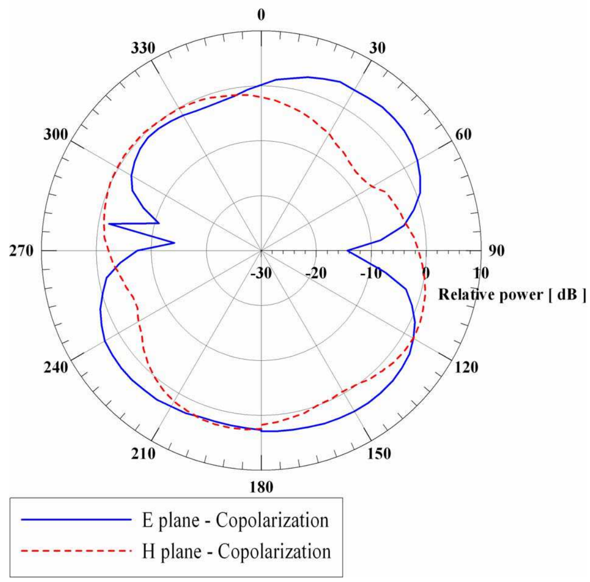

Fig. 17: Measured radiation pattern of the pair of antennas (Fig. 16) at 920 MHz

the radiation pattern of a half-wavelength dipole, canonical antenna used for EM field measurement. The sensor structure is slightly smaller than half wavelength of the measured signal in free space. Nevertheless, it is resonant which improves its sensitivity in comparison to wideband sensors. Of course, its bandwidth is limited to the bandwidth of the considered wireless devices (GSM 900 in the presented case). The proposed sensor can simultaneously measure three orthogonal components of an arbitrarily polarized incident EM wave (each patch pair measures one orthogonal component of the incident EM wave), which makes it suitable for measurement of both steady-state and pulsed field sources. In this case, however, three receivers or a fast RF switch are required. Another advantage of the proposed sensor is that the power combiners as well as other active and passive circuitry (e.g. RF to optical converters) could be placed in the cube formed by the patch ground planes. The circuitry is therefore shielded from the incident EM field and does not act as additional antenna or scatterer which could possibly compromise the measurement results. The sensor prototype is shown in Fig. 18. It is intended to operate in GSM 900 band (880 ÷ 960 MHz) so that, for testing purposes, measurement results can be compared and validated with measurement data obtained by commercial EM field sensors.

4.3 Stacked Shorted Patch With Tilted Parasitic Radiator

One solution of the reduced bandwidth of shorted patches was proposed in [24]. The proposed antenna consists of two stacked shorted square patches and the ground

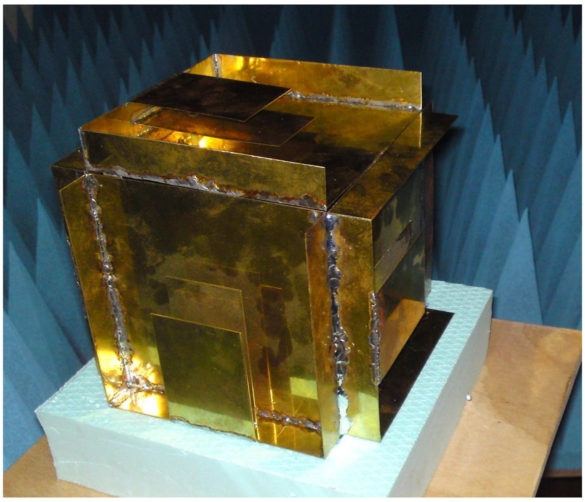

Fig. 18: Prototype of the sensor structure

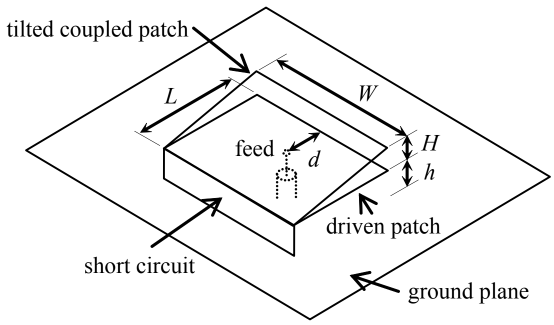

Fig. 19: Stacked patch antenna with tilted parasitic radiator [24]

plane (Fig. 19). The bottom patch is parallel to the ground plane and it is excited by a coaxial probe. The upper patch is tilted and its distance from the driven patch varies from zero (at the position of the shorting wall) to H (at the radiating edge). The dielectric is air. The tilt of the parasitic patch, which resulted in best antenna performances, was determined experimentally. The dimensions of the antenna prototype are marked in Fig. 19. The dimensions of both patches are $W = 50$ mm and $L = 29$ mm. The total height of the antenna is 12 mm ($h = 5$ mm; $H = 7$ mm) which is about $0.10\ \lambda_0$ at central frequency. The coaxial feeding probe is placed at $d = 6$ mm from the radiating edge. Calculated and measured input impedance at the antenna input in the frequency band $1.5 \div 3.5$ GHz is shown in Fig. 20. A VSWR of less than 2 is measured in the frequency band from 2.075 GHz to 3.250 GHz (44% bandwidth). The large input impedance bandwidth is due to the tilted upper patch. The gain of this antenna, measured in the E-plane beam maximum direction, is between 2 and 3 dBi in the whole considered bandwidth.

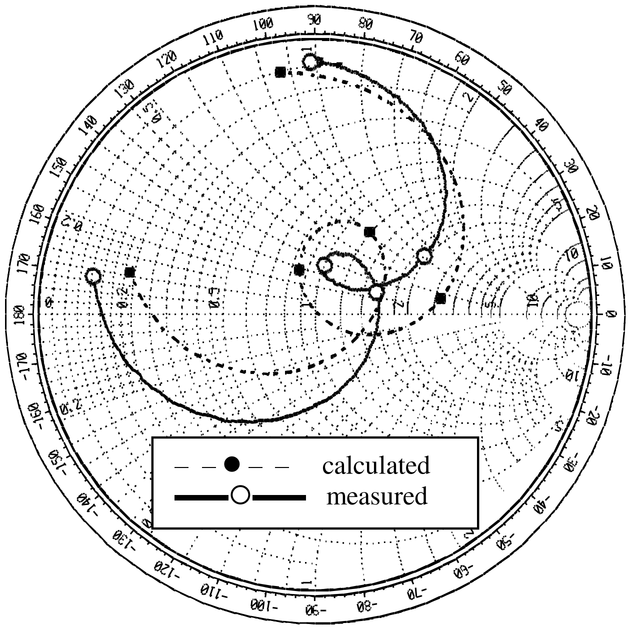

Fig. 20: Input impedance of the antenna in Fig. 19 in the band $1.5 \div 3.5$ GHz, markers at every 500 MHz

5 NON-PLANAR SMALL ANTENNAS

The non-planar small antennas are represented by single and dual band folded monopoles [25]. The size reduction is obtained by mirroring the monopole in the ground plane. Folded monopoles can find their application in handheld mobile devices as well as in base stations and represent good alternative to patches and PIFAs. The operating band of the presented antennas is chosen to allow easy manufacturing of the prototypes and match the available measurement equipment, rather than by a specific application.

5.1 Single Band Folded Monopole

A folded monopole antenna is constructed by truncating the folded dipole antenna by half and attaching the remaining part to the ground plane. The input impedance of the folded monopole is half of the input impedance of the original folded dipole. The impedance can be easily changed by varying the monopole geometry. Appropriate impedance matching is obtained by increasing the width of one arm of the folded monopole. The resonant frequency can be adjusted by changing the height of the monopole. The topology of a single band planar folded monopole is shown in Fig. 21 [25]. The wider strip has a beveled edge to decrease the capacitance between the wider strip and the ground plane. The size of the ground plane is 150 mm$\times$ 150 mm. The measured S_{11} parameter is shown in Fig. 22. Good impedance matching (SWR < 2) was obtained in a frequency band of around 0.8 GHz which is satisfactory result. Dual mode operation was obtained

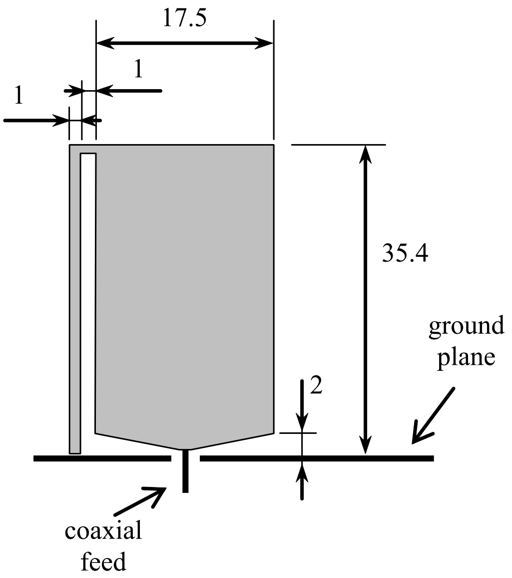

Fig. 21: Single band folded monopole (all dimensions in millimeters) [25]

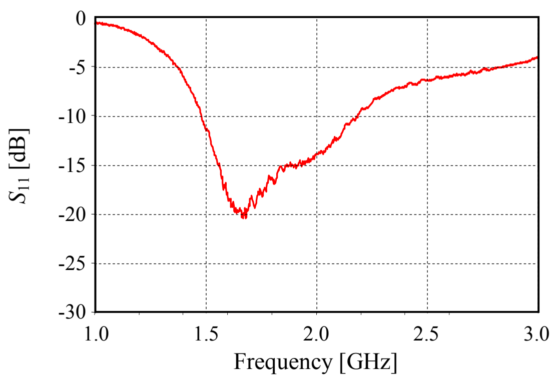

Fig. 22: Measured reflection coefficient at the input port of the folded monopole in Fig. 21

by introducing another resonance in the folded monopole [25]. The first resonant frequency was supposed to remain around 2 GHz, while the second frequency was intended to be between 2 GHz and 4 GHz. The second resonance is achieved by adding an L-shaped slot in the wider strip of the monopole (Figs. 23 and 24). Impedance matching at the second frequency is improved by changing the position of the slot. Two designs are proposed – where the upper frequency band is centered at 3 GHz and 3.5 GHz, respectively. Impedance matching at the lower resonant frequency is slightly disturbed by the slot, but it can be restored by a minor change in the monopole geometry. The reflection coefficients at the antenna inputs in Figs. 25 and 26 show that the monopoles are well matched in both frequency bands. The bandwidth at the resonance frequencies (2 and 3 GHz) of the antenna in Fig. 23 are 533 MHz and

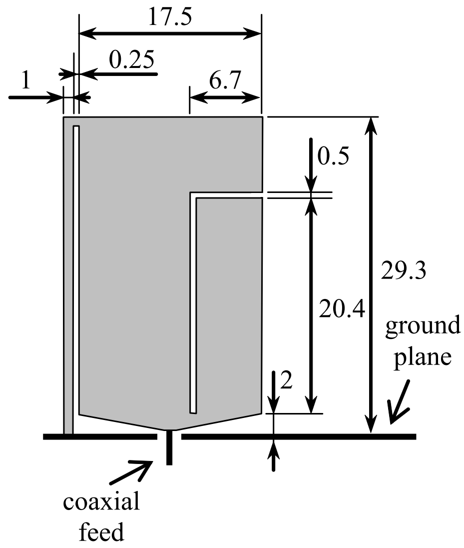

Fig. 23: Dual band folded monopole resonant at 2 GHz and 3 GHz (all dimensions in millimeters) [25]

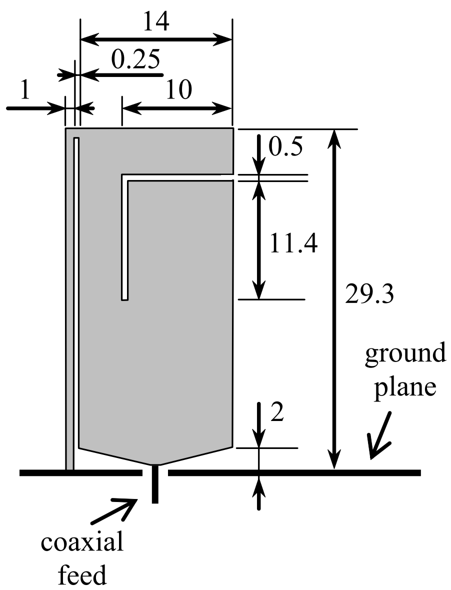

Fig. 24: Dual band folded monopole resonant at 2 GHz and 3.5 GHz (all dimensions in millimeters) [25]

573 MHz, respectively. For the second design (Fig. 24) the bandwidth at the lower resonance (2 GHz) is around 570 MHz, while in the upper band (3.5 GHz) is around 330 MHz.

6 CONCLUSION

The development of new mobile communication devices and systems still offers many challenges to the development of small, but efficient antennas with relatively large bandwidth or possibility of dual- and multi-band operation.

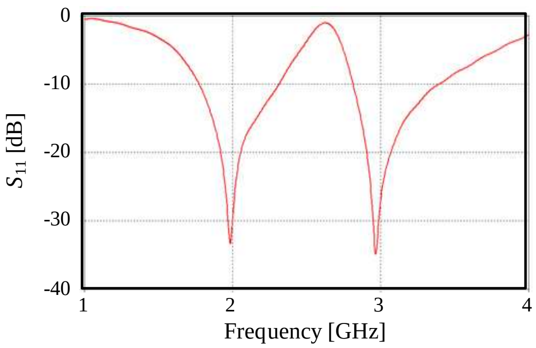

Fig. 25: Reflection coefficient at the input port of the dual band folded monopole in Fig. 23

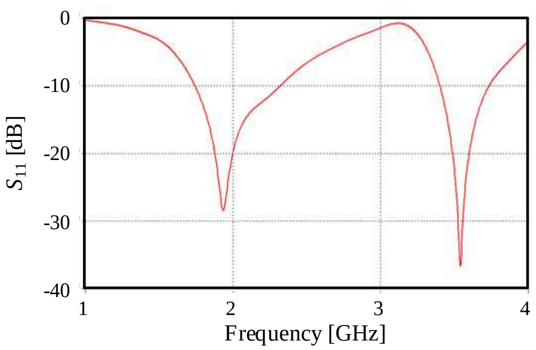

Fig. 26: Reflection coefficient at the input port of the dual band folded monopole in Fig. 24

The techniques of mirroring in conducting planes as well as modifications in the radiating element to extend the current path on the antenna have been applied to obtain size reduction of several different antenna designs. Planar and non-planar antennas were considered. Shorted microstrip patches with notches and slots, PIFAs, stacked patches, and folded monopoles were considered. Case studies as well as antenna designs applied for mobile communication bands have been presented. Dual band operation was achieved by introducing slots in the radiating element in order to obtain two resonant frequencies. Still there is a lot of work to be done. Small antennas are essential for new and emerging wireless services. Fundamental limitations linking antenna size and its electrical characteristics can't be circumvented. However, the ingenuity of antenna engineers and advancements in small antenna technology open new horizons and possible applications, while new applications require new, better antenna designs.

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REFERENCES

[1] H.A. Wheeler, "Fundamental limitations of small antennas", *Proc. IRE*, Vol. 35, pp. 1479-1484, 1947.

[2] L.J. Chu, "Physical limitation on omni-directional antennas", *Journal of Applied Physics*, Vol. 19, pp. 1163-1175, 1948.

[3] A. K. Skrivervik, J.-F. Zürcher, O. Staub, J. R. Mosig, "PCS antenna design: The challenge of miniaturization", *IEEE Antennas and Propagation Magazine*, Vol. 43, No. 4, pp. 12–26, 2001.

[4] M. Martínez-Vázquez, "ACE small terminal antennas activities: a review of the state of the art", *Proceedings of the 18th Int. Conference on Applied Electromagnetics and Communications (ICECom 2005)*, pp. 29–32, Dubrovnik (Croatia), October 2005.

[5] K. L. Wong, *Planar Antennas for Wireless Communications*, J. Wiley, Hoboken (New Jersey, USA), 2003.

[6] K. Hirasawa, "Small antennas for mobile communications", *Proceedings Antenn00, Nordic Antenna Symposium*, pp. 11–15, Lund (Sweden), 2000.

[7] H. K. Kan, R. B. Waterhouse, "Small printed-wing antenna suitable for wireless handset terminals", *Microwave and Optical Technology Letters*, Vol. 30, No. 4, pp. 226–229, 2001.

[8] R. Chair, K. M. Luk, K. F. Lee, "Miniature multilayer shorted patch antenna", *Electronics Letters*, Vol. 36, No. 1, pp. 3–4, 2000.

[9] R. Chair, K. M. Luk, K. F. Lee, "Miniature shorted dual-patch antenna", *IEE Proceedings – Microwaves, Antennas and Propagation*, Vol. 147, No. 4, pp. 273–276, 2000.

[10] J. S. Kuo, K.-L. Wong, "A low-cost microstrip-line-fed shorted patch antenna for a PCS base station", *Microwave and Optical Technology Letters*, Vol. 29, No. 3, pp. 146–148, 2001.

[11] K. L. Virga, Y. Rahmat-Samii, "Low-profile enhanced bandwidth PIFA antennas for wireless communications packaging", *IEEE Transactions on Microwave Theory and Techniques*, Vol. 45, No. 10, pp. 1879–1888, 1997.

[12] N. Herscovici, M. Fuentes Osorio, C. Peixeiro, "Minimization of a rectangular patch using genetic algorithms", *Proceedings of the 18th International Conference on Applied Electromagnetics and Communications (ICECom 2005)*, pp. 37–40, Dubrovnik (Croatia), October 2005.

[13] I.J. Bahl, P. Bhartia, *Microstrip Antennas*, Artech House, Dedham (Massachusetts, USA), 1982.

[14] D. Bonefačić, B. Rapinac, "Some Considerations on Size Reduction of a Microstrip Patch Antenna", *Proceedings of the 19th International Conference on Applied Electromagnetics and Communications (ICECom 2007)*, pp. 257–260, Dubrovnik (Croatia), September 2007.

[15] D. Bonefačić, B. Rapinac, "Small H-shaped Shorted Patch Antennas", *Radioengineering*, Vol. 17, No. 2, pp. 77-82, June 2008.

[16] I. Mikulić, *Small Microstrip Antenna with Notches ans Slots* (in Croatian), Diploma Thesis, Faculty of Electrical Engineering and Computing, University of Zagreb, July 2009.

[17] Z. Sriča, *Dual Band Rectangular Microstrip Antenna* (in Croatian), Diploma Thesis, Faculty of Electrical Engineering and Computing, University of Zagreb, July 2011.

[18] D. Bonefačić, B. Rapinac, J. Bartolić, "Slotted PIFA for GSM Band", *Proceedings of the Second European Conference on Antennas and Propagation (EuCAP 2007)*, pp. MoPA.007(1-4), Edinburgh (UK), November 2007.

[19] D. Bonefačić, B. Rapinac, J. Bartolić, "Slotted PIFA for Mobile Communication Devices", *Radioengineering*, Vol. 17, No. 4, Part II, pp. 13-18, December 2008.

[20] B. Ivšić, D. Bonefačić, J. Bartolić, "New Stacked Patch Antenna for Polarisation and Radiation Pattern Diversity", *Proceedings of 3rd European Conference on Antennas and Propagation (EuCAP 2009)*, pp. 3497-3501, Berlin (Germany), March 2009.

[21] B. Ivšić, D. Bonefačić, J. Bartolić, "Reconfigurable Picocell Antenna Array for Indoor Coverage in GSM 900 Band", *Radioengineering*, Vol. 18, No. 4, pp. 388-394, December 2009.

[22] B. Ivšić, D. Bonefačić, J. Bartolić, "3D Electromagnetic Sensor Based on Shorted Stacked Patches", *Proceedings of the 51st Int. Symposium Electronics in Marine (Elmar-2009)*, pp. 321-325, Zadar (Croatia), September 2009.

[23] B. Ivšić, D. Bonefačić, J. Bartolić, "Simple Electromagnetic Sensor for Simultaneous Measurement of Three Orthogonal Linear Polarizations", *Proceedings of 4th European Conference on Antennas and Propagation (EuCAP 2010)*, pp. A01-4 (1-5), Barcelona (Spain), April 2010.

[24] D. Bonefačić, J. Bartolić, D. Kocen, "Stacked Shorted Patch Antenna with Tilted Parasitic Radiator", *IEE Electronics Letters*, Vol. 37, No. 18, pp. 1109-1110, 30th August 2001.

[25] M. Banožić, J. Bartolić, B. Ivšić, T. Debogović, "Dual Band Folded Monopole", *Proceedings of the 2010 International Workshop on Antenna Technology: Small Antennas, Innovative Structures and Materials (IWAT)*, Lisbon (Portugal), March 2010.

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