Single and Double Layer Planar Multiband PIFAs

Benito Sanz-Izquierdo, John C. Batchelor, Richard J. Langley

The DOI is: 10.1109/TAP.2006.874323

Single and Double Layer Planar Multiband PIFAs

Benito Sanz-Izquierdo, John C. Batchelor, *Member IEEE*, Richard J. Langley, *Member IEEE* and Mohammed I. Sobhy *Member IEEE.*

Abstract— **A compact multiband PIFA antenna suitable for distributed radio-over-fiber repeater networks is modified into a planar structure. It is shown that the planar antenna performance is not degraded with respect to the original PIFA and further, a 2 layer design is demonstrated to offer improved feed matching. The European bands for GSM, DCS-1800, DECT, UMTS, Bluetooth and HiperLAN2 are all covered. A model of the antenna is introduced as a first stage to developing an equivalent circuit.**

***Index Terms*—Planar Antennas, Printed Antennas, PIFA, Multiband Antennas, Radio-over-fiber.**

I. INTRODUCTION

THIS paper describes a multiband antenna suitable for deployment in an indoor repeater system for personal communications and WLAN. The proposed system utilizes a centralized base station with distributed antenna units and is intended for environments such as shopping malls or airports where there may be a heavy localized traffic demand across a variety of user services. The intention is to create a relatively low cost distributed network solution by requiring only one centralized multi-system repeater station. The antenna units would be wall or ceiling mounted and the connection to the base station is made by optical fiber with an Electro-Absorption Modulator (EAM) serving as both optical-to-electrical and electrical-to-optical transducer in the down and up links respectively [1].

The broadband nature of the optical link from base station to antenna unit makes it feasible to include all the major personal communications systems subject to creating a sufficiently multiband antenna. The systems for which the proposed antenna has been designed are given in Table I; all these services fall within the wireless communications frequency bands used in Europe, i.e. 890-960 MHz, 1710-2175 MHz and 2400-2483.5 MHz and 5150-5725 MHz for Bluetooth and WLAN applications.

Although the antenna has been tuned for European systems, it would also be possible to re-tune to the US and Japanese frequencies, the main differences being at the lower band which are 824-894 MHz and 810-956 MHz respectively. The systems are predominantly vertically polarized.

Various approaches to creating multiband antennas for personal communication systems have been reported in recent years. These are often aimed at handset applications and can broadly be defined as:

(i) Fractal or Sierpinski Gasket Antennas over ground planes [2], [3], [4] and in [5] where fractalization has been used to achieve size reduction.

(ii) Modified Printed Inverted-F Antennas (PIFAs) [6], and [7] where a PIFA with slots cut on the radiating element was described. An increased bandwidth at the DCS-1800 band was achieved.

TABLE I
EUROPEAN WIRELESS BANDS

System	Frequency Band (MHz)
GSM	890-960
DCS-1800	1710-1880
DECT	1880-1900
UMTS	1920-2170
Bluetooth/WLAN	2400-2483.5
HiperLAN/2	5150-5350
	5470-5725

This paper reports a new compact multiband PIFA which evolves from a dual band design described in [8] that covered the GSM and DCS bands and possessed dipole type radiation patterns. The antenna size was reduced by removing metallization in areas of low current density. The construction was simple with the metal etched from a thin mylar sheet folded around a honeycomb former.

TABLE II
PIFA TUNING ELEMENTS

Frequency Band	Tuning Element (Predominant, secondary)
Lower	1,3
Upper (lower frequency)	2,3
Upper (mid frequency)	4,3
Upper (upper frequency)	4,1

A series of design innovations made to the original PIFA of [8] will be reported. In all cases Zeland's IE3D software was used to theoretically study and optimize the design of these new antennas. Finally, a system model will be introduced as a first stage to developing an equivalent circuit of the antenna.

II. MULTIBAND PIFAS

In [9] it was reported that an extra band could be added to the dual band PIFA of [8], Fig.1, by including a patch in the ground plane. This patch, labeled element 3 in Fig.1, had no direct connection to the PIFA and was parasitically coupled to element 4. Element 3 was half wave resonant at 2.1GHz and extended the GSM/DCS matched regions to encompass UMTS (1920–2170 MHz). The tuning of the frequency bands was achieved by altering the element lengths as shown in Table II.

A beneficial feature of this design was the predominance of element 1 in tuning the lower band while having only a minor effect on the upper. This reduced the complexity of the tuning process. The radiation patterns remained of good quality and were similar to those of a dipole at all frequency bands. The measured peak gain varied by 0.5, 3.3, 1.1 and 2 dBi across the GSM, DCS1800, DECT and UMTS bands respectively and never fell significantly below -1dBi.

It has been shown that multiband antennas can be successfully implemented in planar form. Wong and Chiou [10] describe the design of an original planar antenna fed by single layer microstrip and serving GSM, DCS, PCS and UMTS. The planar antenna was fabricated on an FR4 substrate 0.4mm thick with no rear ground plane. The antenna area was 30mm x 12mm. Current flow was found to be directed such that, at higher frequencies, modes combined to form a single band with a large matched bandwidth. The patches operated at a quarter-wavelength fundamental mode which reduced the patch size. The radiation patterns were generally good but had some nulls of more than 10-15dB depth. Leelaratne and Langley [11] have developed a planar triple band PIFA for automotive applications and a related technique will be shown here to transpose the PIFA of Fig.1 into planar form.

III. PIFA TRANSPOSITION TO PLANAR FORM

Fig. 2 presents the plan and elevation views of the PIFA shown in Fig.1. The upper and lower levels are drawn separately for clarity. Figs. 3 to 5 graphically illustrate how the original PIFA was transformed into an equivalent planar design. In Fig.3 the upper and lower planes are bisected along the *x-z* plane of symmetry and half of each layer is removed on opposing sides of the bisecting plane. Fig. 4a shows the structure after the lower plane has been translated to the upper plane. The section of element 1 aligned along the z-axis is rotated to maintain a connection between points A' and B in the *x-y* plane, Figs.4(b) & (c). The electromagnetic simulator IE3D was used to tune each element and simultaneously reduce the overall antenna size. The final geometry is shown in Fig.5 and was printed onto FR4, 0.8mm thick. The connection point A' was moved from the end of element 4 to a position part way along its length. This was necessary to provide a current path sufficiently long to support the lower frequency mode without making the antenna unduly large. The shape of element 1 required that element 2 was folded to avoid overlap. Also, folded stub elements 5 and 6 were added to increase the overall length of element 4 and allow the extension of the matched region to include Bluetooth/WLAN at 2.4GHz. The principal dimensions of the design are given in Table III and the overall length of the PIFA is 87mm making it $\lambda/4$ long at the lower frequency band. More insight into the exact tuning process will be given in section V.

TABLE III
PRINCIPAL DIMENSIONS OF SINGLE LAYER PIFA (DESIGN 1)

Element	Dimension	Length (mm)	Width (mm)
1	1a	12	4
	1b	29	
	1c	57	
	1d	8	
2	2a	39	3
	2b	17	
	2c	41	
3	3a	51	4
4	4a	3	4
	4b	9	
	4c	68	
5	5a	14	2
	5b	13	
6	6a	10	2
	6b	5	

Maximum dimensions of design 2 = 87mm × 29mm

Although successfully simulated, design 1 proved difficult to feed in practice as it was unbalanced. The exact length and connection angle of the feed cable was critical in achieving a good match at all bands. This is clearly undesirable in a practical antenna. Furthermore, implementing a multiband planar balun in limited space would be a significant design challenge.

IV. Double Layer Multiband PIFA

To create a more balanced system a double layer PIFA was produced where an exact replica of design 1 was etched on the underside of the substrate (FR4 0.8mm thick with a relative permittivity of 4.4). Simulation demonstrated the current modes remained essentially unchanged, though their centre frequencies and bandwidths increased in the double layer design. The bandwidth covering GSM rose from 7 to 8% while the band covering DCS-UMTS increased from 26 to 28%. The band centre frequencies rose by 4%.

The metal patternation was identical in both the single and double layer planar PIFAs in order to allow for a direct performance comparison. It should be noted that the 2 layer design was not balanced in the true sense as the layers were not excited symmetrically; this is shown in Fig. 6.

Connection of the single and double layer designs to a Hewlett Packard 8722ES network analyzer demonstrated that for the single layer design; curvature in the feed cable gave rise to a definite degradation in the lower band match and in the worst case the GSM band was lost altogether. There was no discernable change at the upper band. In the double layer case no significant alteration was observed at any band when the feed cable was flexed. Additionally no loss of match at any band was observed when the antenna was connected to cables of different length.

TABLE IV
Principal Dimensions of Double Layer PIFA Design 2

Element	Dimension	Length (mm)	Width (mm)
1	1a	13	4
	1b	29	
	1c	60	
	1d	8	
2	2a	39	3
	2b	18	
	2c	41	
3	3a	49	4
4	4a	3	4
	4b	9	
	4c	67	
5	5a	16	2
	5b	13	
6	6a	15	2
	6b	5	

Maximum dimensions of PIFA design 3 = 94 mm × 29 mm

The resonant frequency increase of 4% in the double layer design meant the antenna needed to become 8% longer. The final tuned dimensions of the double sided PIFA (design 2) are given in Table IV.

TABLE V
Frequencies and Bandwidths

	Frequency Band (MHz)	Bandwidth (MHz)	Percentage Bandwidth
PIFA (Fig.1)	800-965	165	19
	1690-2210	520	27
Design 1, Table III	885-990	105	11
	1510-2170	660	36
Design 2, Table IV	885-973	88	10
	1530-2590	1060	51
	4630-5970	1340	25

The measured and calculated S11 curves for the tuned double sided PIFA (design 2) are shown in Fig. 7 where it can be seen that the middle band now extends from 1.58 to 2.5 GHz; a bandwidth of 45% embracing the DCS1800, GSM1900, DECT, UMTS and Bluetooth systems. The design is also tuned for the HiperLAN bands between 5.15 and 5.725 GHz enabling it to cover all the current mobile networks. The presence of the upper band has arisen due to the modifications made to elements 2 and 4 and the introduction of elements 5 and 6 in designs 1 and 2. A plot of the surface currents at 5.7GHz is shown in Fig. 8 where it can be seen that a $3\lambda/2$ current distribution exists in element 4c along the x-axis.

Although the PIFA is electrically long at 5.7GHz, radiation loss causes the current intensity to drop significantly towards the ends of the elements. The antenna has been tuned such that the current peaks on parallel elements are aligned along the x-axis. This is achieved by trimming the element lengths as described in section V. The position of the connection point A’ between elements 1 and 4 is important in achieving this current mode alignment to reduce phase cancellation and null formation in the H-plane radiation patterns.

At the lower and middle bands, current flowed predominantly in elements 1, 2 and 3 as explained in [9]. Table V compares the frequency bands of the original PIFA (Fig.1), with the single layer PIFA (design 1) and the double layer PIFA (design 2). For design 1, in the 900MHz band, there is a decrease from 19% to 11% fractional bandwidth. In the 2GHz band, the fractional bandwidth increases from 27% to 36% for the planar design. The dual layer PIFA offers improved bandwidth at the 2GHz band and an extra band at 5GHz.

The measured fractional bandwidths of double sided PIFA design 2 were 9.5% for the lower band, 51% for the middle band and 25% for the upper band. In all cases the PIFA offers sufficient bandwidth to cover all the European wireless systems listed in Table I.

V. Multiband PIFA Parametric Tuning Study

The multiband antenna consists of 6 elements as indicated in Fig.5. The mutual interactions between these tightly coupled elements make the operation of the antenna difficult to describe because loading effects significantly modify the current distribution on adjacent elements. We aim to give insight into the operation and design of the antenna by presenting a parametric tuning study of the various elements that comprise the multiband planar PIFA. The parametric study was carried out by simulation with IE3D where the length of individual elements was varied to establish the effect on the different frequency bands.

Starting with the initial tuned multiband antenna of Fig.5, elements 1 to 6 were modified to show their relative sensitivity to change in length. Practically, a 50Ω matched coaxial cable fed the two sides of the antenna. For the parametric study, the coaxial feed was substituted with a 50Ω planar port to simplify the simulation. The parametric analysis resulted in computed S11 curves giving resonant frequencies for each mode. Referring to Fig.7, it can be seen that the lower band consists of a single mode: (mode 1, at 880MHz). The middle band contains of 4 modes: (mode 2 at 1860MHz; mode 3 at 1950MHz; mode 4 at 2280MHz and mode 5 at 2480MHz) and the upper band of 2 modes: (mode 6 at 4960MHz and mode 7 at 5460MHz). S11 curves were generated for the case of each element being tuned in length and the effect on mode frequencies is tabulated in Table VI where the total frequency deviation across each element tuning range is given.

To give an impression of the tuning process; Fig.9 presents the data of Table VI against measured S11 where the element numbers (Fig.5) are in order of frequency sensitivity to element length. Observation of Table VI and Fig.9 shows that element 1 is dominant for tuning the lower band, while the middle band depends mainly on elements 2, 3 and 5. Finally, the upper band is primarily tuned by elements 4 and 2. The relative independence of the elements at different bands makes the multiband tuning process achievable.

VI. Effect of Substrate Thickness and Type

The effect of the substrate height on the double sided planar PIFA was investigated by printing design 2 on substrates of 0.8 and 1.6mm thickness and the design was tuned for the 0.8mm substrate only. The substrate type in both cases was FR4 with a permittivity of 4.4. The additional loading of the thicker substrate reduced the resonant frequencies of the individual input matched modes. Doubling the substrate height to 1.6mm caused the lower band fractional bandwidth to increase slightly from 7.9% to 8.5%. Modes 2 and 3 become a single mode for the thicker substrate and a similar combination occurs for modes 4 and 5. Defining bandwidth at the -11dB S11 points, the combined modes 2 and 3 had a slightly larger bandwidth for the 1.6mm than for the 0.8mm thick substrate (16.5% and 14% respectively). This was also true of combined modes 4 and 5 (16.5% and 13%). At the upper band, increasing the substrate height increased the bandwidth of mode 6 from 9.6% to 16.5%, but mode 7 was lost on the thicker substrate. This caused the total bandwidth of the upper band to fall slightly, 20.1% and 18.6% for the 0.8mm and 1.6mm thick substrates respectively. It can therefore be concluded that printing the double sided PIFA on a thicker substrate does increase the bandwidth of the individual modes, but care must be taken to retune the antenna in order that the upper and middle bands are matched at all frequencies. Retuning is also necessary on the 1.8mm thick substrate because the individual mode frequencies reduced by 4.9% for mode 1; 7% for modes 2 and 3; 8.8% for modes 4 and 5 and 2% for mode 6. Mode 7 was not matched on the thicker substrate.

VII. Measured Radiation Patterns

The radiation patterns for each band were measured in an anechoic chamber and are shown in Fig. 10 where good omni-directionality can be observed for each band in the y-z plane. Only in the 5 GHz band do significant nulls of about 10 dB form. The antenna patterns are essentially those of a dipole. Although some nulls are present, significant problems are not envisaged as the antenna is intended for operation in an indoor multipath rich environment. Measured gains ranged between 0.2 and 3.0dBi.

VIII. Development of Antenna Model

The complexity of the antenna structure described here and the effect of parasitic coupling between elements are difficult to describe analytically. Therefore, it is desirable to develop an equivalent circuit to help the designer relate the antenna performance to the physical structure. A model also aids the simulation of communication systems to predict the effect of the antenna on the overall performance of the system.

Model development starts by obtaining the antenna characteristics from either measurements or electromagnetic simulation and then fitting a model to the results.

Models can have three forms:

1. A mathematical function that fits the measured or simulated results.
2. A system model developed from the mathematical function and can be included in a complete communication system

TABLE VI
PERCENTAGE CHANGE IN MODE FREQUENCY CAUSED BY TUNING ELEMENTS OF PIFA DESIGN 2

			Percentage Frequency Deviation					
Band	Mode	Tuned Frequency (MHz)	Element 1 (±2mm)	Element 2 (±2 mm)	Element 3 (±2 mm)	Element 4 (±2 mm)	Element 5 (±2 mm)	Element 6 (±2 mm)
Lower	1	880	1.2	0	0	0	1.8	0
Middle	2	1860	1.9	3.6	2.0	0	0.8	0
Middle	3	1950	0.9	2.5	2.5	0	1.5	0
Middle	4	2280	2.1	1.0	0.8	0	6.9	0
Middle	5	2480	0	2.5	3.3	0	6.2	4.7
Upper	6	4960	0	0.7	0	9.6	0.5	0
Upper	7	5460	0	6.0	2.0	0.6	1.4	0

simulation.

3. A circuit model using lumped circuit elements that can be used in antenna design to relate the antenna topology to its performance.

The mathematical model is a ratio of two polynomials with the complex frequency *s* as the independent variable. The function takes the form

$$F(s) = \frac{a_n s^n + a_{n-1} s^{n-1} + ...a_0}{b_m s^m + b_{m-1} s^{m-1} + ...b_0} \qquad (1)$$

where *n* and *m* are the orders of the function polynomials.

The system model is derived directly from (1) when the *a* and *b* coefficients are known. A representation of the model is shown in Fig.11 when b_0 is normalized to 1. Using this method a system model was developed for the results obtained from the electromagnetic simulator. A model representing the entire frequency range was obtained and the results are shown in Fig.12 for the real and imaginary parts of the input impedance. The complexity of the characteristics necessitated that the order of the model was high (n=30 and m=44). To reduce the order, it is possible to divide the frequency range and obtain a number of smaller models for the entire range. For instance, modeling the 900MHz band alone reduced the order of the model to n=10 and m=14.

To aid the design process for the antenna we propose to complete the modeling by developing a lumped element equivalent circuit with parameters related to the physical antenna topology. In addition we will develop ways of reducing the order of the system models and investigate the accuracy. It will then be possible to apply the model in simulating an entire communication system.

IX. Conclusion

A dual band PIFA covering the GSM and DCS bands has been enhanced with the addition of a parasitic element 3 in the ground plane. This element adds a new mode making the 2GHz band much wider and incorporates all systems between 1690 and 2210 MHz Additional tuning allows coverage to be extended across GSM, DECT, UMTS, Bluetooth and HiperLAN bands. The PIFA has been redesigned in planar form and the performance at all bands has been maintained. Adding stub elements 5 and 6 to the ground element 4 of the planar PIFA made it possible to achieve further bandwidth enhancements for the upper frequencies. Initially, the planar PIFA was difficult to excite in practice due to balancing problems which made the feed cable position and length critical factors in achieving a good match. This issue was resolved by creating a 2 layer planar PIFA on a thin substrate to create a more balanced design and the feed line was consequently found to be less critical in obtaining a good match at all bands. The radiation patterns and gain of the double layer PIFA were dipole like with gains of around 2dB measured at all matched bands. The patterns were comparable with those of the single layer antenna. A system model of the antenna has been developed which is based on the measured input impedance. This model will be used to develop an equivalent circuit model with lumped elements related to the physical antenna topology.

The antenna described has been filed as Multiband Radio Antenna, Patent no. GB0416406.7.

References

[1] D. Wake, "Trends and Prospects for Radio over Fibre Picocells", *IEICE Electronics Society*, *International Topical Meeting on Microwave Photonics*, *MWP* November, Awaji, Japan, 2002, pp.21-24.

[2] J. Soler, D. Garcia, C. Puente and J. Anguera, "Novel combined MOD-P Multiband Antenna Structures inspired by Fractal Geometries", *Microw. And Opt. Tech. Letts*., Vol.41, 5, June 2004, pp.423-426.

[3] C.T.P. Song, P.S. Hall, H. Ghafouri-Shiraz , "Shorted fractal Sierpinski Monopole Antenna", *IEEE Trans. Antenn. And Propag*. Vol.52, 10, October 2004, pp.2564-2570.

[4] J. Yeo, R. Mittra, "Design of conformal multiband antennas based on Fractal concepts", *Microw & Opt. Tech. Letts*., vol.36, 5, March 2002.

[5] H. Elsadek, D. Nashaat and H. Gahli, "Multiband Miniturized PIFA for Compact Wireless Comminucation Applications", *Microw. And Opt. Tech Letts. Vol*.42, 3, August 2004, pp. 230-234.

[6] P. Cias, R. Staraj, G. Kossiavas and C. Luxey, "Compact internal multiband antenna for mobile phone and WLAN standards", *IEE Electron. Letts*. July 2004, Vol.40, 15, pp.920-921.

[7] C.W. Chiu, and F.L. Lin,, "Compact dual-band PIFA with multi-resonators", *IEE Electron. Letts.,* Vol.38, 12, June 2002, pp.538-540.

[8] D. Viratelle and R.J. Langley: 'Dual-band printed antenna for mobile telephone applications', *IEE proc. Microw. Anten. Propag*., 147, No.5, October 2000, pp.381-384.M. Young, *The Techincal Writers Handbook.* Mill Valley, CA: University Science, 1989.

[9] B. Sanz-Izquierdo, J.C.Batchelor and R.J. Langley, "Multiband PIFA antenna with ground plane capacitive resonator", *IEE Electron. Letts*. Vol.40, 22, October 2004, pp.1391-1392.

[10] K-L, Wong, G-Y, Lee, and T-W Chiou., "A low profile planar monopole antenna for multiband operation of mobile handsets", *IEEE Trans. Ant & Propag*., 51, No.1, January 2003.

[11] R. Leelaratne and R.J. Langley: 'Multiband PIFA Vehicle Telematics Antennas', IEEE Trans. Vehicular Tech., 54, No.2, March 2005, pp.477-485.

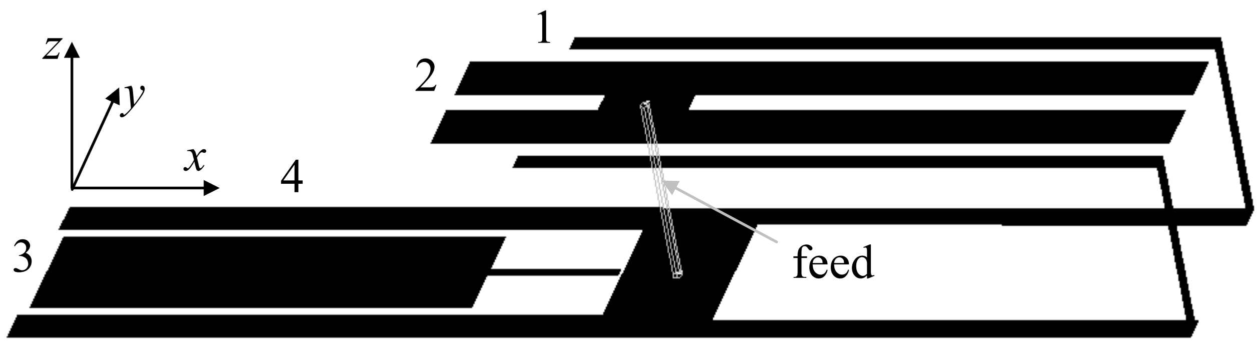


Fig. 1. Multiband PIFA showing element numbering. Novel parasitic element (3) is in the lower plane.

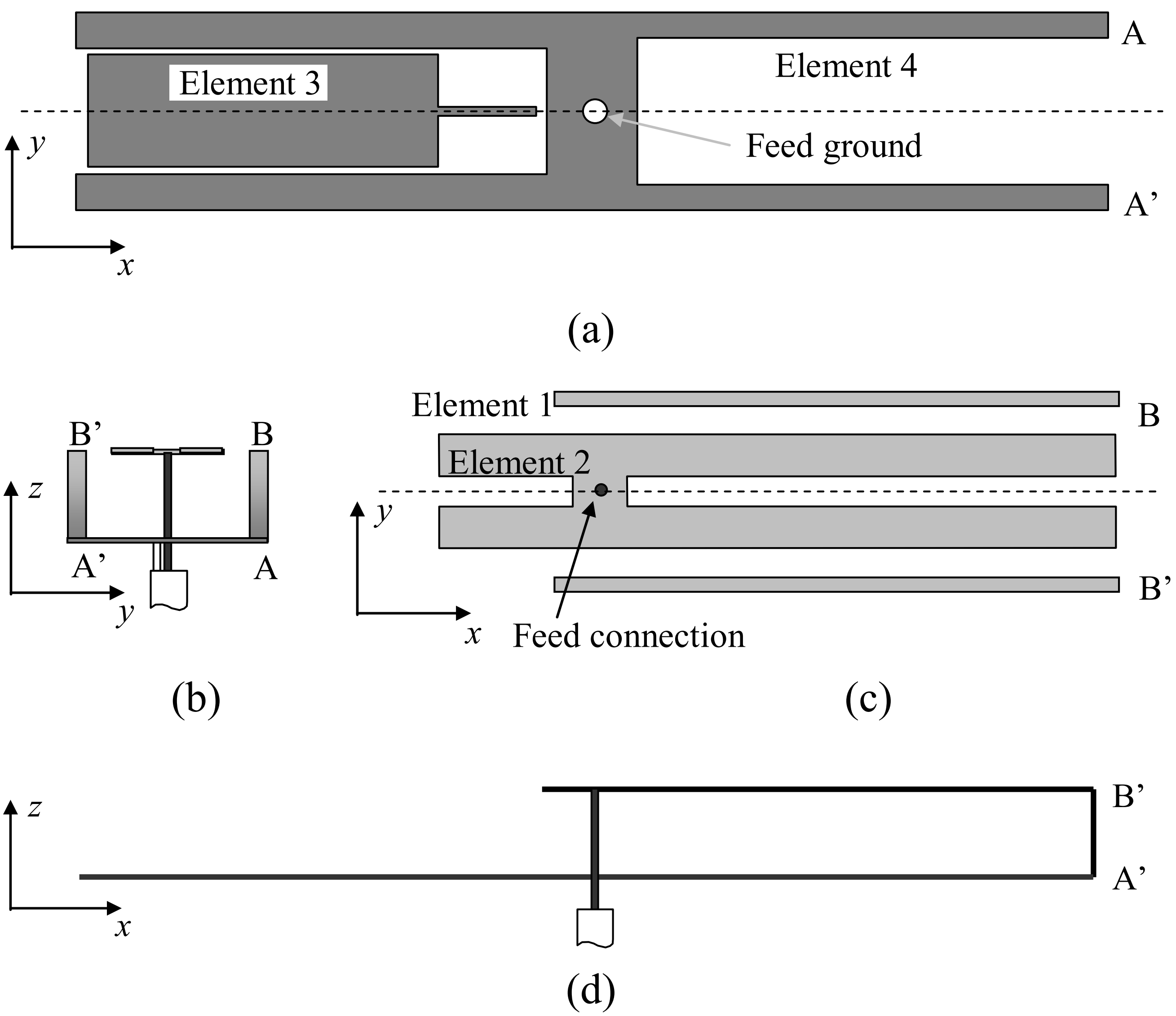
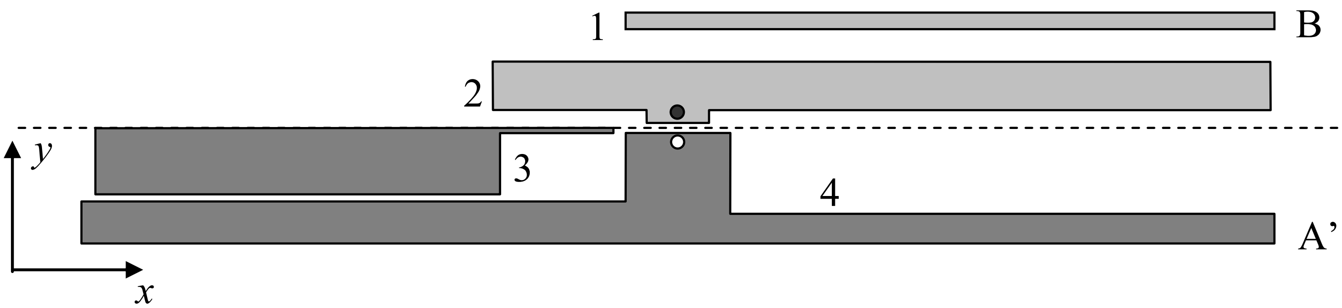
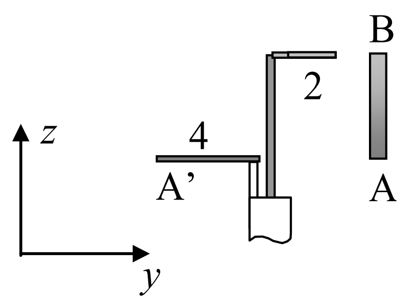


Fig. 2. Multiband PIFA of Fig.1 with geometry of upper and lower levels shown separately for clarity. (a) lower level plan view; (b) end elevation; (c) top level plan view; (d) side elevation.



(a)



(b)

Fig. 3. PIFA of Fig.2, bisected along *x-z* plane of symmetry. (a) plan view of upper and lower levels; (b) end elevation.

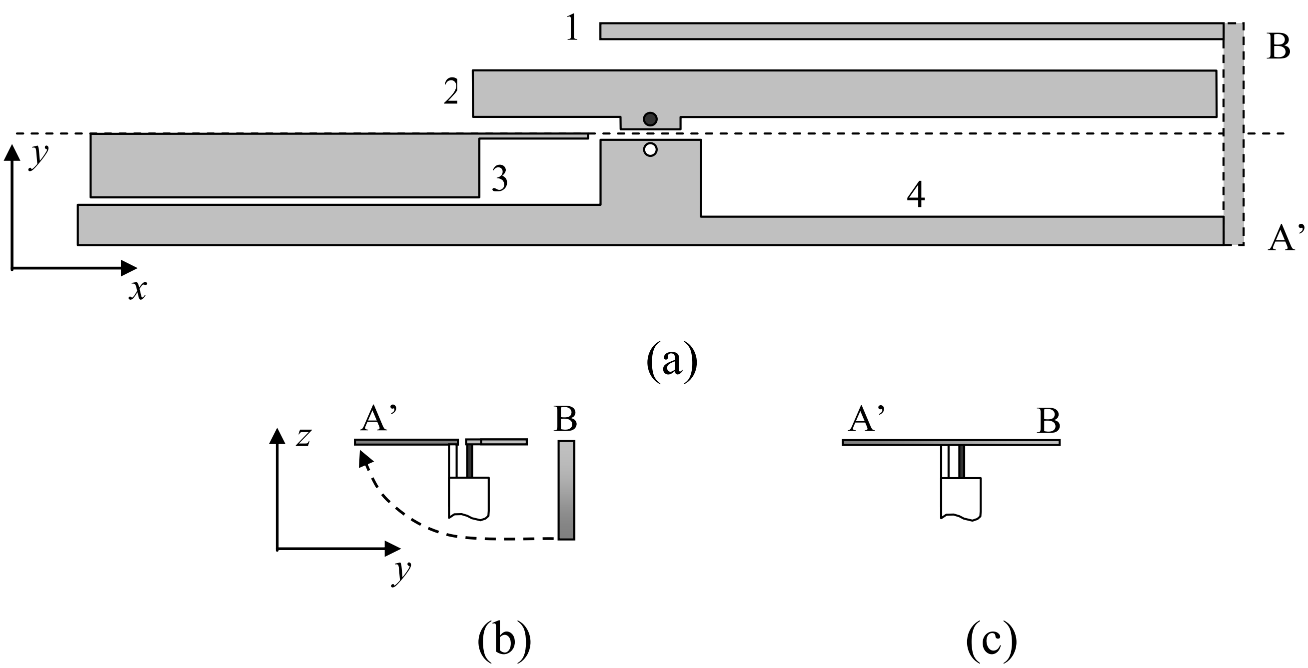


Fig.4. (a) plan view of PIFA with lower layer translated to upper layer; (b) end elevation; (c) segment of element 1 is rotated to complete connection between A' and B in the *x*-*y* plane.

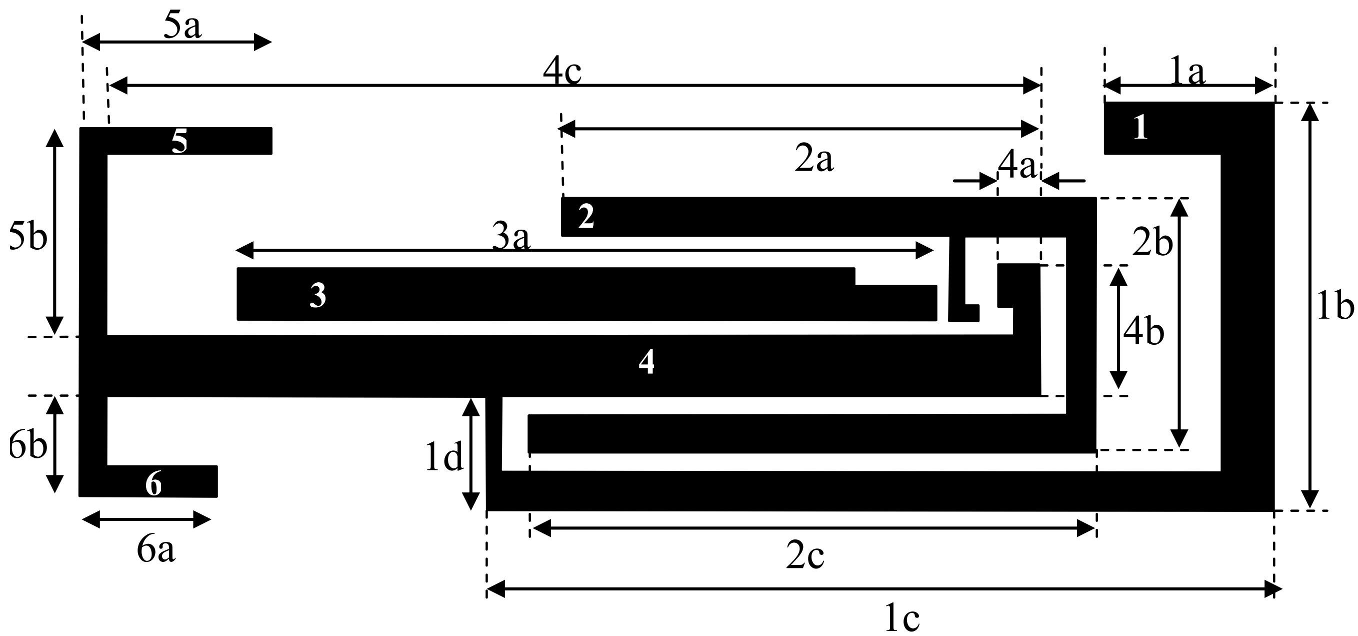


Fig. 5. Dual band PIFA, design 1.

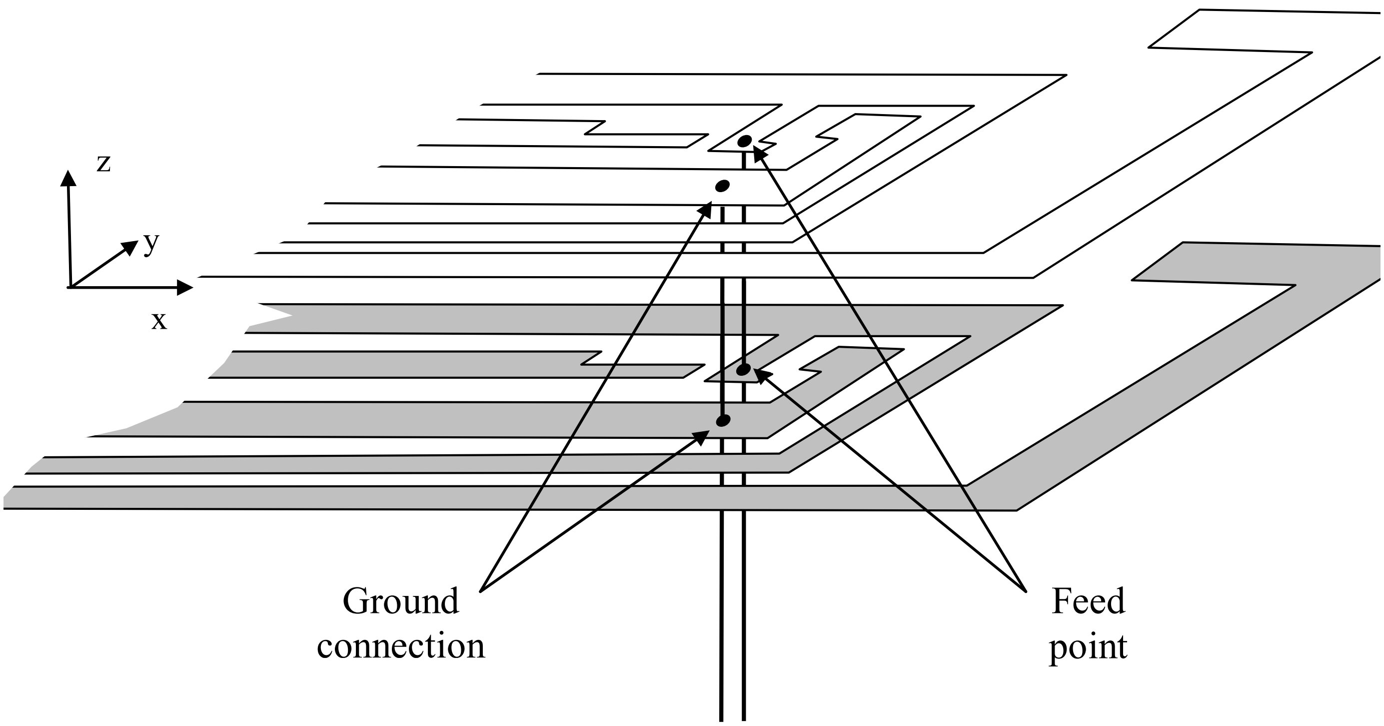


Fig. 6. Feed connections to double sided PIFA design 2. Layer separation has been expanded for clarity.

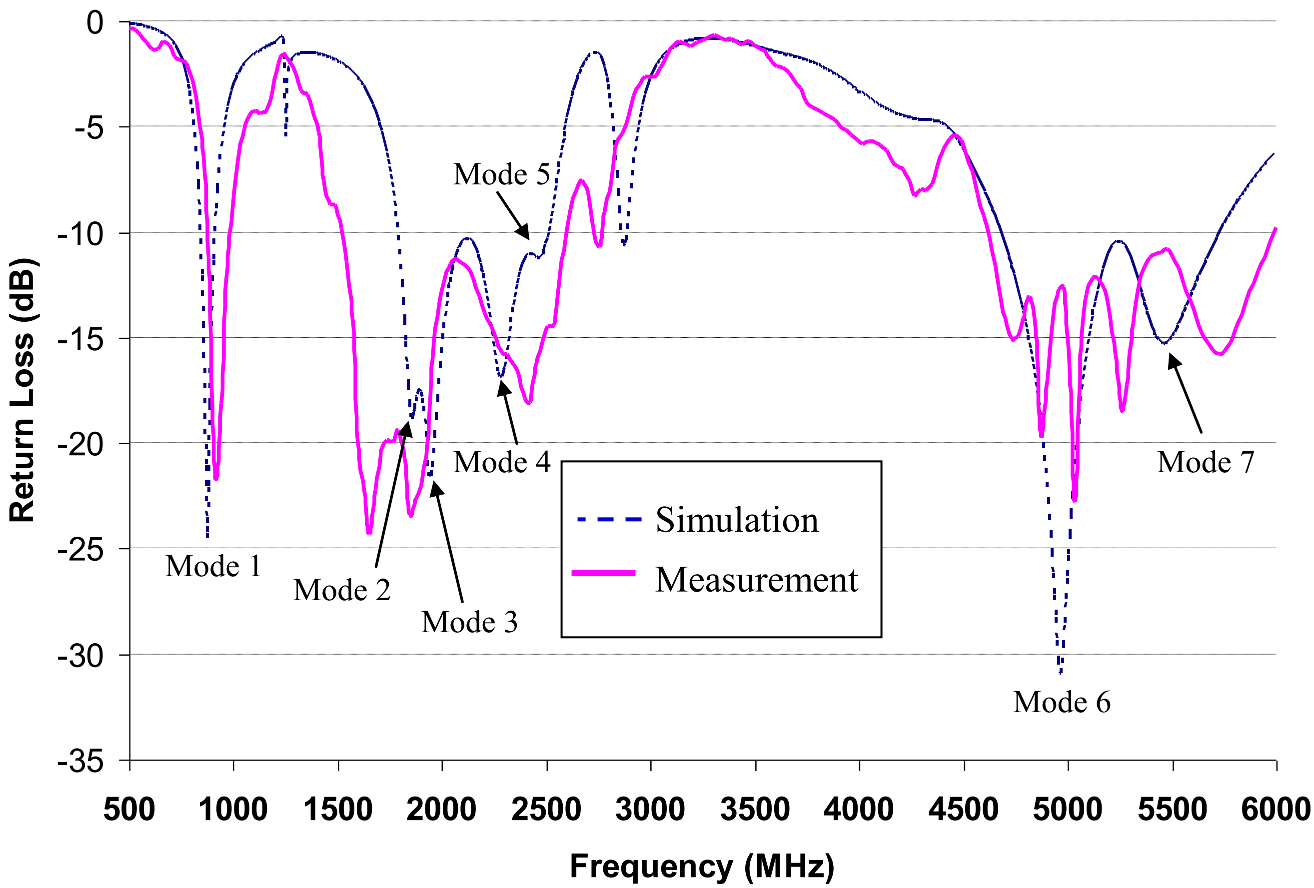


Fig. 7. Measured and calculated S11 curves for double layer PIFA, design 2.

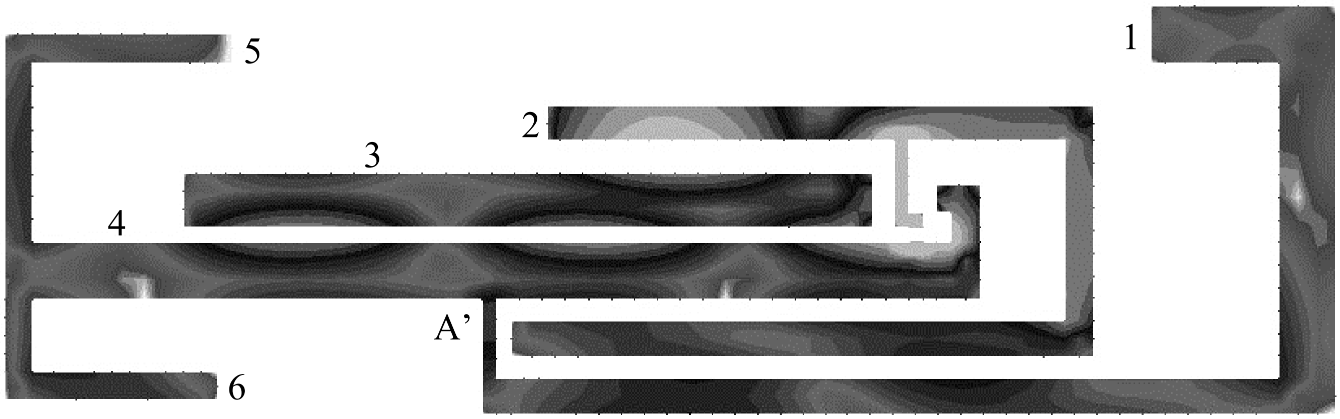


Fig. 8. Surface currents at 5.7GHz on double sided PIFA, design 2. Light areas indicate current peaks.

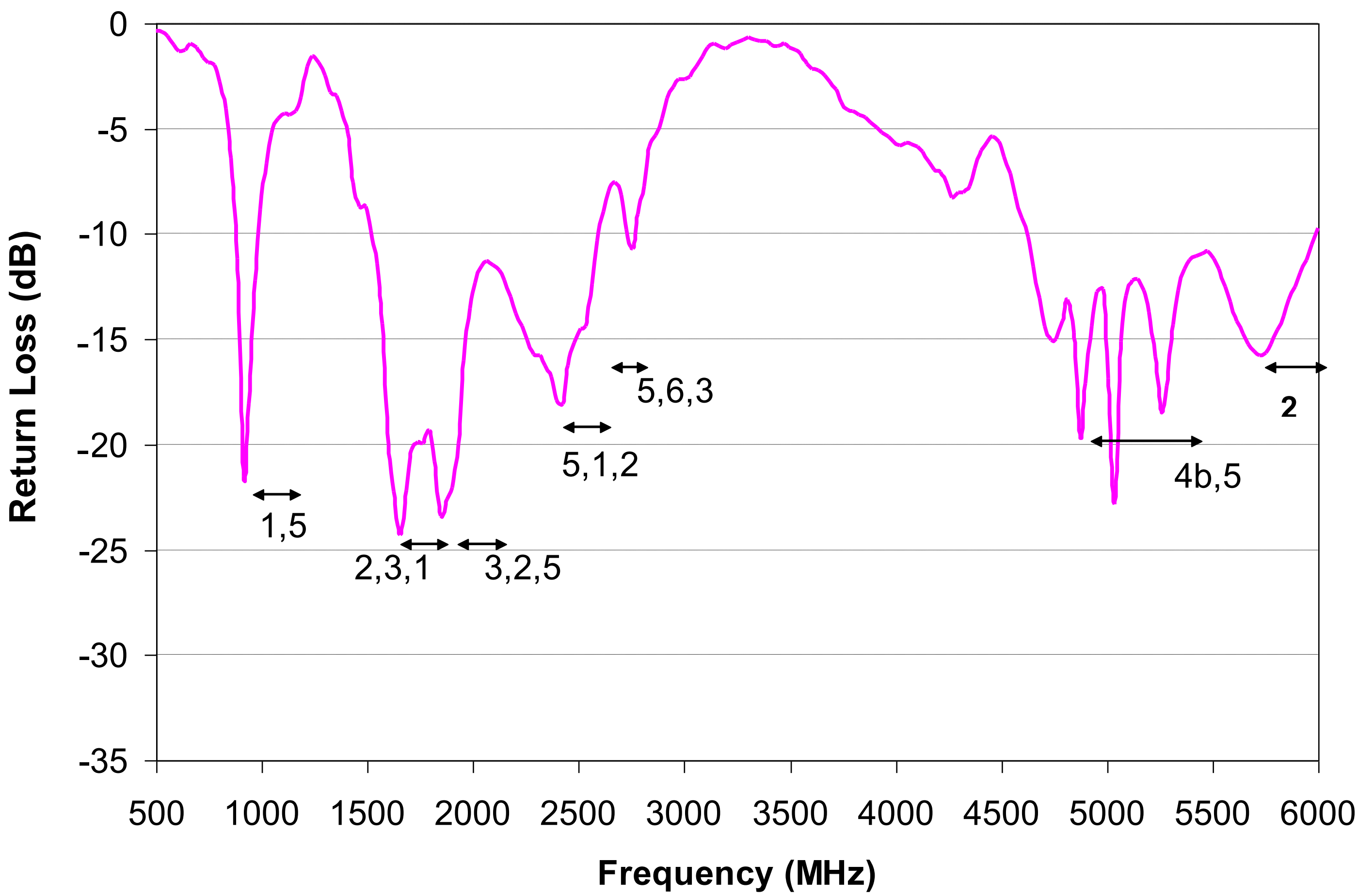
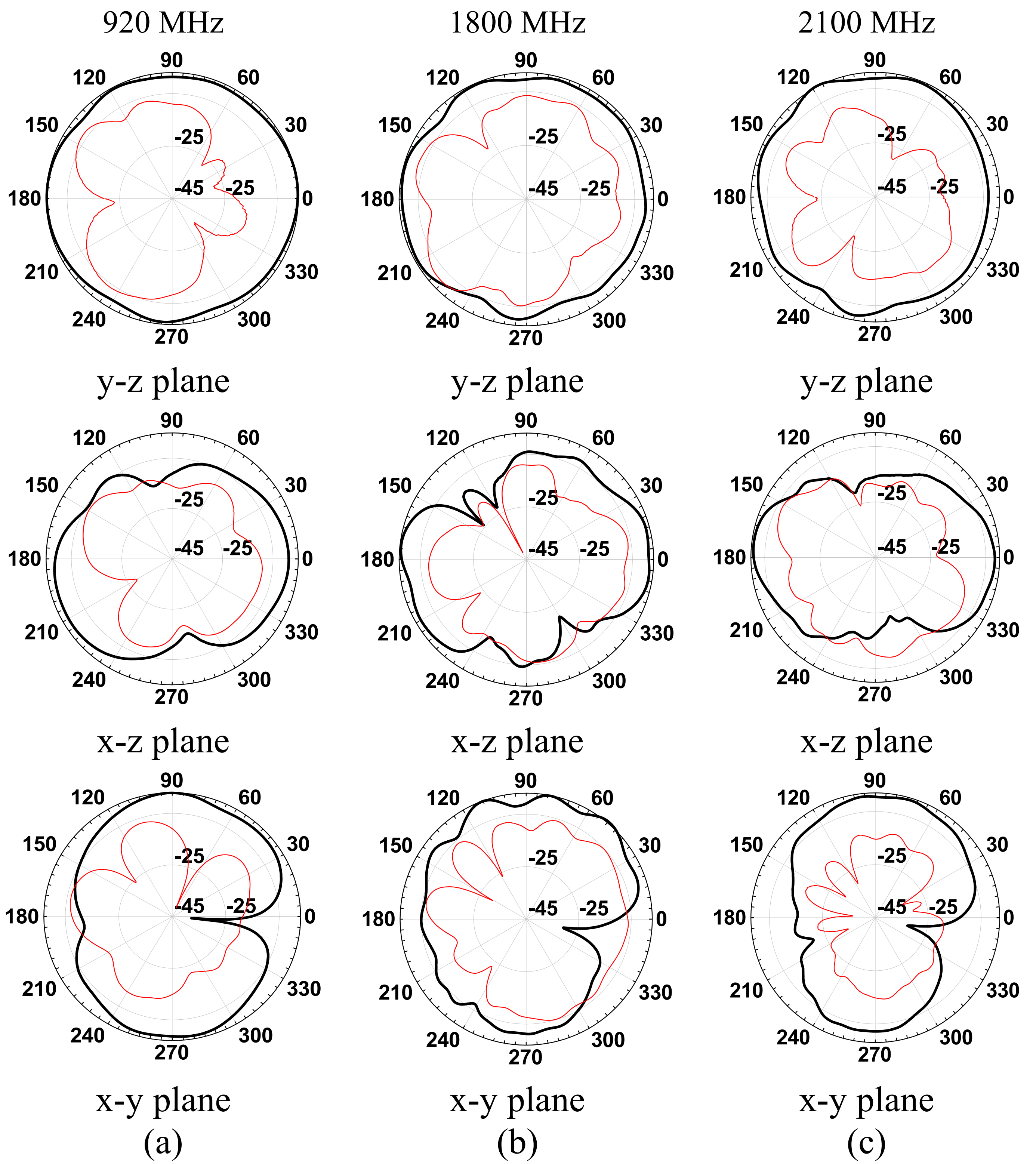


Fig.9. Measured return loss of double sided PIFA design 2 indicating predominant tuning elements as identified in Fig.5.


920 MHz
1800 MHz
2100 MHz
y-z plane
y-z plane
y-z plane
x-z plane
x-z plane
x-z plane
x-y plane
x-y plane
x-y plane
(a)
(b)
(c)

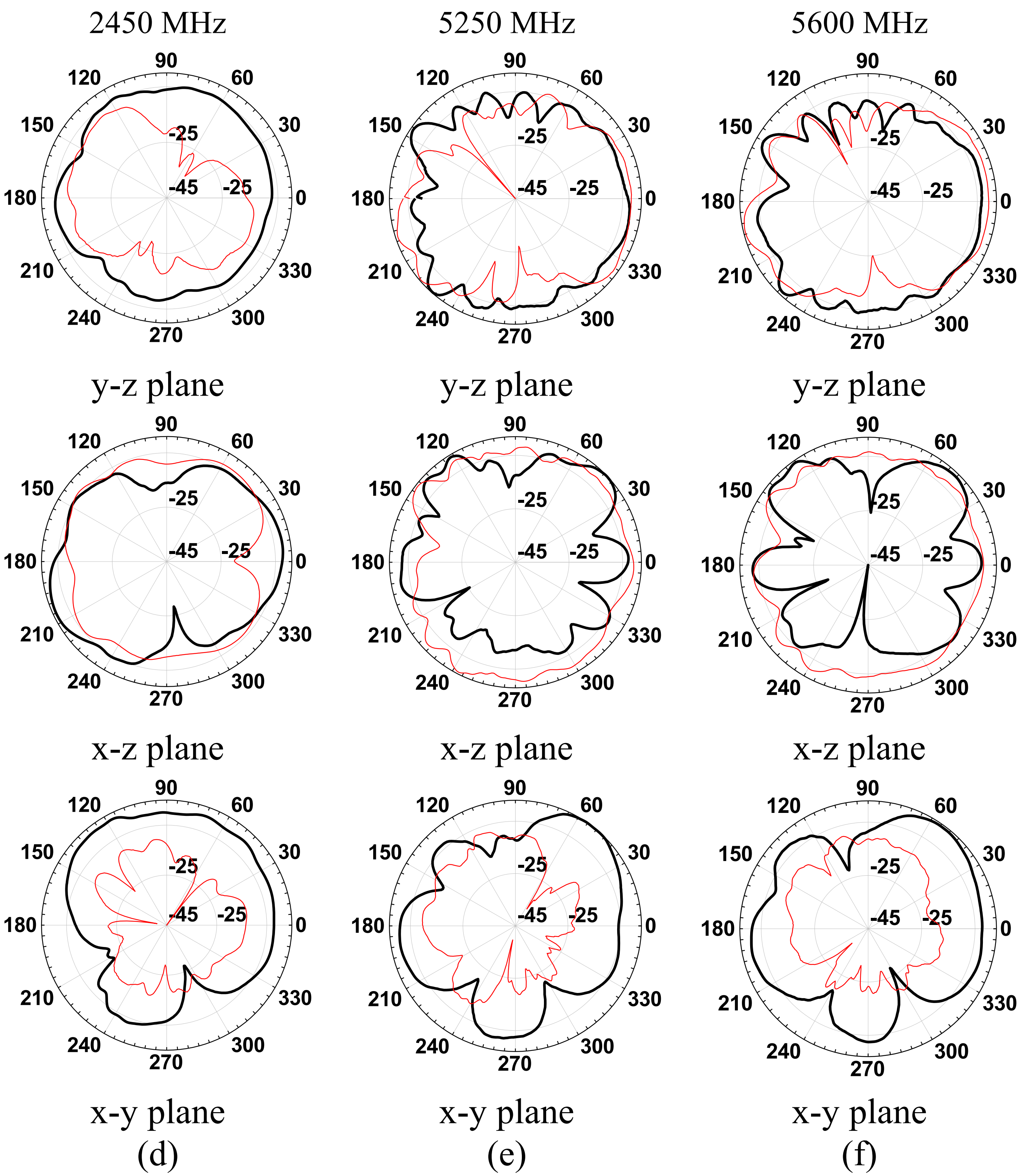


Fig.10. Measured PIFA radiation patterns. (a) 920MHz; (b) 1800MHz; (c) 2100MHz; (d) 2450MHz; (e) 5250MHz; (f) 5600MHz.

——— Co-polarization, – – – – Cross-polarization

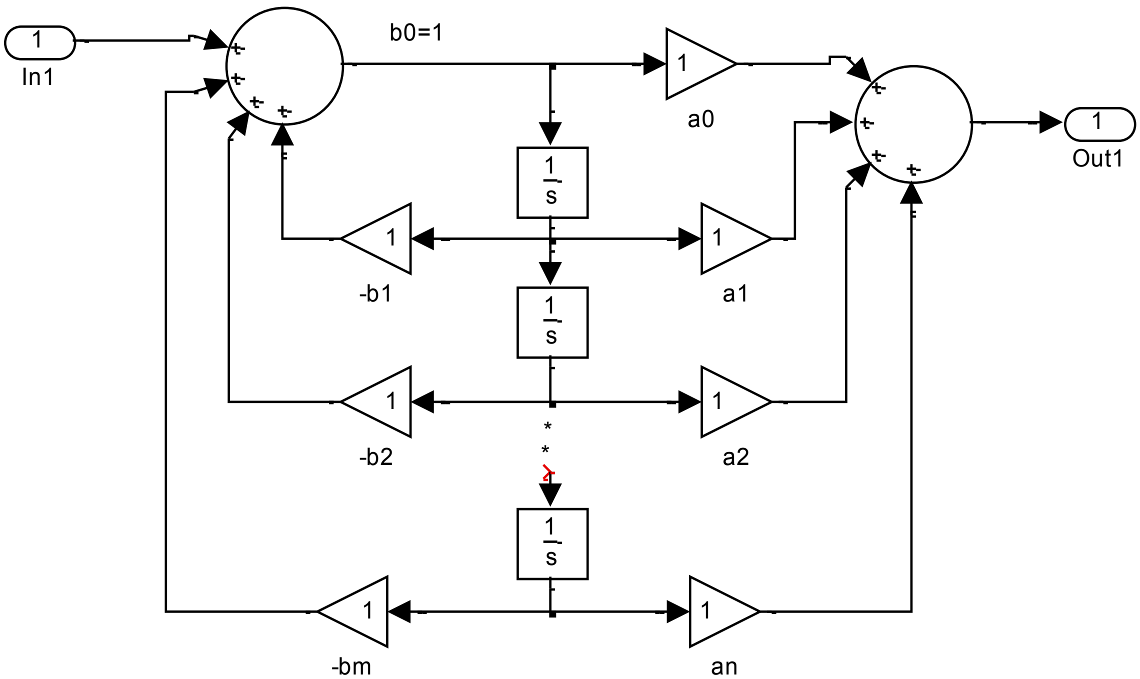


Fig. 11. System model of multiband antenna

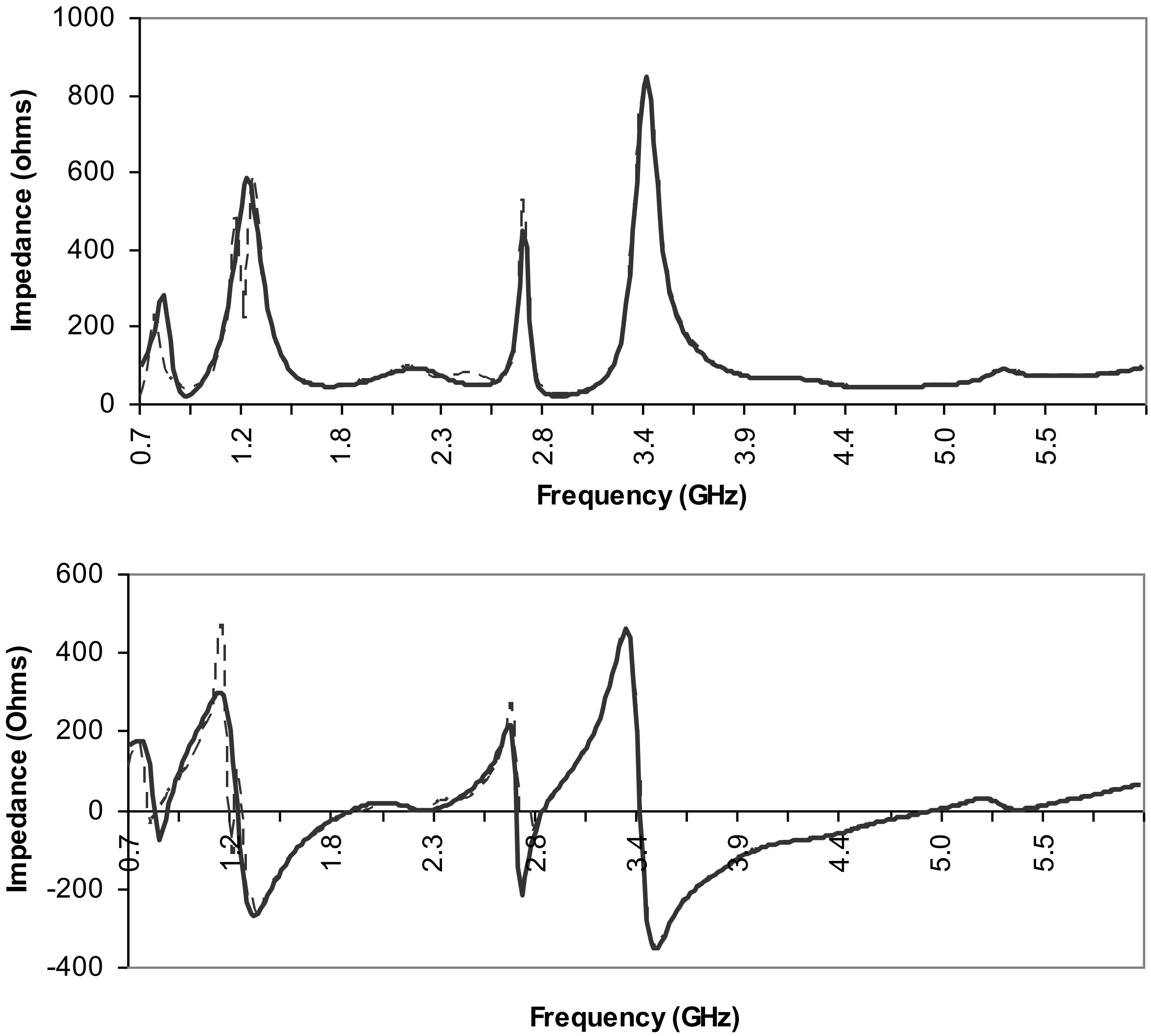


Fig. 12. Simulated and System modeled input impedance of multiband antenna.
Simulation System Model