國 立 交 通 大 學

電信工程學系

碩 士 論 文

多頻段平面倒 F 型天線之微小化研究

The Miniaturization of Multi-Band Planar Inverted-F Antenna

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國 立 交 通 大 學

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多頻段平面倒 F 型手機天線之微小化研究

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摘要

為了滿足多頻通訊系統的發展，手機天線不僅要小尺寸還要具有多頻帶的特性。意謂著天線要在有限尺寸下具有多重的共振路徑，由於每個頻帶的輻射單元被縮小，導致輻射效率變低。市面上的手機多頻微小天線，大都是利用 PIFA (planar inverted-F antenna) 結構來減小天線的物理長度。對傳統的 PIFA 來說，有兩個方法可達到多頻帶的需求，利用寄生輻射單元，增加天線的共振模態，但單元間偶合複雜，難以設計且增加天線面積；另一種方法是利用 U 型狹縫在主輻射體切割出多重共振路徑，但此方法會導致頻寬和輻射效率降低。本論文提出一種能讓 PIFA 維持小尺寸且具有多頻段的技術，使其每個頻帶重覆使用相同的輻射單元，不僅維持小尺寸且輻射效能也能保持一定的水準。改良短路棒在傳統式 PIFA 中的功用，不再是靠近饋入點的電容性負載，而是等效成短路式負載接在天線的末端，再配合接地板的特殊設計，使得天線等效成短路式半波長阻抗轉換器。為了滿足多頻帶的需求，在天線中引進寄生轉折單元來增加共振路徑。隨著頻率的改變，等效阻抗轉換器會利用短路附載來切換共振電流路徑，逕而輻射。同時，利用輻射阻抗來做阻抗匹配。由於此設計中，短路棒作為短路式負載且輻射單元重複使用使得天線體積縮小至 30mm×20mm×4mm 且接地板只需要

30mm×43mm，覆蓋頻帶為 GSM900、DCS、PCS、UMTS、Bluetooth/WiFi、WiMAX、HiperLAN/2 and additional band (4600~4800MHz)。天線輻射場型近似全向性且具有合理的增益值，量測各頻帶最大值介於 1dBi ~ 4.8dBi 之間。

A Novel Technique of Miniaturization in Multi-Band Planar Inverted-F Antenna of the Handset

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Abstract

For the multisystem applications, the antenna of a handset not only needs small size but also covers multi bands, which means that the antenna must have multi-resonating paths in a limitary size. Due to each radiating element of each frequency band is reduced such that the radiation efficiency is not good and the bandwidth is narrow. These critical parameters are trade-off one another, therefore, it is difficult to keep good performance in a compact antenna of multi-band. PIFA

(planar inverted-F antenna) is the popular type of antenna in the mobile phone market. PIFA can reduce effectively physical length of the antenna with a shorted pin which acts capacitance load and is near the feed. In conventional PIFA design, there are two popular techniques for the requirement of multi-band. Firstly, use parasitic element to increase the resonating modes, but this way would to increase the area of the antenna. Secondly, use the embedded U-shaped slits to create multi-resonating paths in main radiating element, but the radiating element is reduced, so the radiation efficiency is not good. In this paper, a novel miniaturization technique of multi-band PIFA is proposed, which makes the antenna to reuse the radiating element to radiate every frequency band. It not only reaches multi-band but also keeps good performances and small size. The modification is that the shorted pin acts short-circuit load and locates at the end of antenna instead of the function of the shorted pin in conventional PIFA. The proposed PIFA can be modeled by a half-wave transmission line impedance transformer (TILT) of short-circuited load form. For the requirement of multi-band, it adds parasitic folded branches to increase resonating current paths. Therefore, the antenna is equivalent to the parallel multi-TLITs. With changing resonate frequency, the parallel multi-TLIT is similar as a current switch to change the current path with the short-circuited load and radiate. The size of the proposed PIFA and the ground plane are 30mm×20mm×4mm and 30mm×43mm. The covered frequency bands included GSM900, DCS, PCS, UMTS, Bluetooth/WLAN, WiMAX, HiperLAN/2 bands, and an additional band (4600~4800MHz). Moreover, the antenna has a nearly omni-directional radiation pattern and a reasonable peak gain of 1dBi to 4.8dBi.

誌　　　謝

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游雅仲　誌予

九十七年六月

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Chapter 1 *Introduction*

1.1 Background and Problems

In the design of mobile phone antenna, the printed antenna on PCB and PIFA (planar inverted-F antenna) are popular for multi-band solutions. It is due to their advantages of small size, low-cost, and direct integration with microwave circuit. It is also well known that antenna size, bandwidth, and antenna gain are trade-off factors with one another, which increases design difficulty of the printed antenna and PIFA. In this paper, the proposed novel modified PIFA can achieve requirements of multi-band, small size, antenna pattern and gain.

1.2 Related Works

In the past, most of multi-band antennas had been proposed [1]~[4]. The design type is mainly based on a PIFA structure to cover 3~5 frequency bands. It is because that the PIFA can reduce physical length of antenna effectively and creates multi-resonating current paths by adding some parasitic elements. The printed antenna is difficult to reach multi-band in small size, which is due to the constraint of radiating parasitic elements allocated on the same plane.

In [1], the antenna contains a main radiating patch with a U-shaped slot and a parasitic patch, with each patch connected to the ground plane with a shorted pin. This design is equivalent to a tri-PIFA that covers GSM, PCS and UMTS bands. In [2], a meandered multi-band antenna with coplanar parasitic patches was proposed; the patch end is folded to connect with the ground plane, this way would reduce the physical length of the antenna. The antenna is equivalent to a four-PIFA and covers GSM, DCS, PCS and Bluetooth bands. In the both examples, difficult to determine the distance of each patch and the position of the shorted pin of the main patch are the main drawbacks, which is mainly due to the series coupling among multi-shorted pins or plates.

In [3], the proposed PIFA covers five bands. Firstly, the part covers three frequency bands has the structure of two folded strips on the same plane, which share the same shorted pin. Secondly, two new radiating strips are added and located at a plane perpendicular to the ground plane and the main tri-PIFA, which creates another two frequencies. These two strips connect directly with the feed strip. The new radiating strips and the original folded strips share the same shorted pin. It is called panta-PIFAs to cover five frequency bands. Although the way to reduce the antenna area is effective, but the radiation patterns due to the added strips are easily interfered by the original strips.

In [4], four frequency bands are achieved by adding a parasitic patch to a dual-PIFA, which connects to the ground plane. The added parasitic ground patch acts a ground resonator, and increases resonating paths to cover six frequency bands. To create a more balance system, a double layers PIFA was produced with a replica of the equivalent structure being etched on the underside of substrate. Although the final design covers six frequency bands, the coupling among radiating elements is serious, which leads to a poor radiation efficiency.

1.3 Thesis Organization

There are five chapters of the thesis. Chapter 2 presents the basics of the PIFA, including mechanisms and some popular dual-band PIFA designs. Chapter 3 describes some multi-band techniques of the PIFA. Chapter 4 shows our design concept, circuit modeling, simulated and measured results, and their comparison. Chapter 5 is conclusion.

Chapter 2 *Basics of Planar Inverted-F Antenna*

2.1 Introduction of Planar Inverted-F Antenna (PIFA)

In general, a planar inverted-F antenna is achieved by short-circuiting its radiating patches or grounding the antenna with a shorted pin or a plate. With a proper ground plane, the antenna size may be reduced. In recent years, for fulfilling the requirements of compact size and multi-band, PIFA is always applied to the mobile phone. Some basic and mechanism of PIFA are described in detail as followings.

2.2 Basics of PIFA

Fig. 2.1(a) shows the structure layout of a half-wavelength patch antenna. Since the voltage along the patch center line is zero as shown in Fig. 2.1(b), a grounded conducting plate is inserted along the center line as shown in Fig. 2.1(c), which can reduce the antenna length to a quarter-wavelength and forms a quarter-wavelength PIFA. It is noted that the boundary conditions are the same for the cases of Figs. 2.1(a) and 2.1(c).

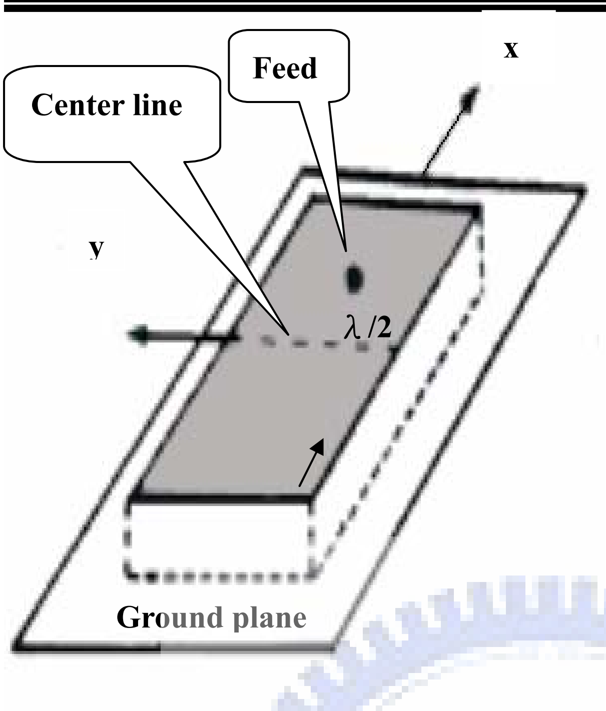

Fig. 2.1 (a) A patch antenna

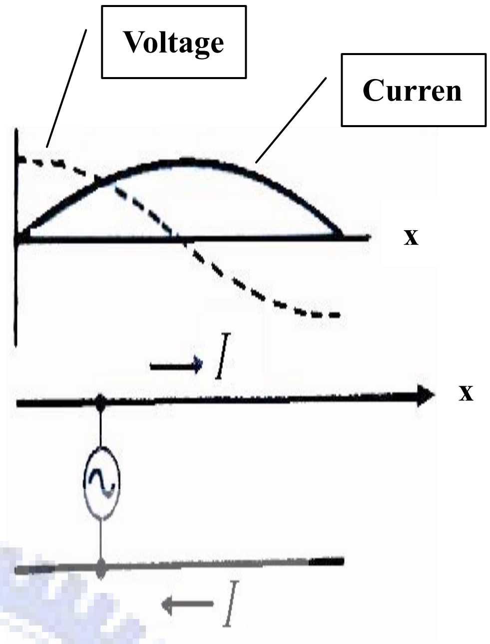

Fig. 2.1(b) Distributions of current and voltage along x-axis.

To reduce the length of quarter-wavelength PIFA further, the patch is folded to connect the ground plane as shown in Fig. 2.1(d). The corner of the folded patch would accumulate charges and yields a strong electric field, which is equivalent to a capacitance load. To reach L-C resonance, the conducting plate of the center line is replaced by a conducting strip. The strip acts as an inductance load in impedance matching since strong magnetic fields are induced by a mass current flowing to the ground plane through the strip. Although the quarter-wavelength PIFA can be reduced to a 1/8 wavelength PIFA, the radiating efficiency is also degraded due the antenna size reduction.

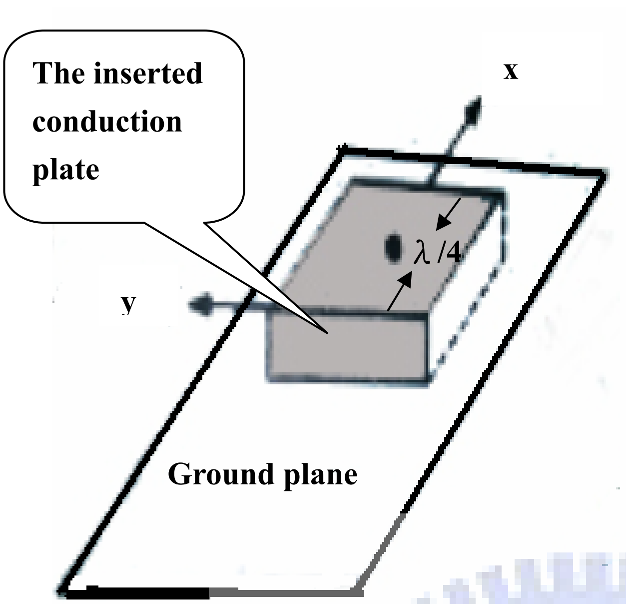

Fig. 2.1(c) A λ/4 PIFA.

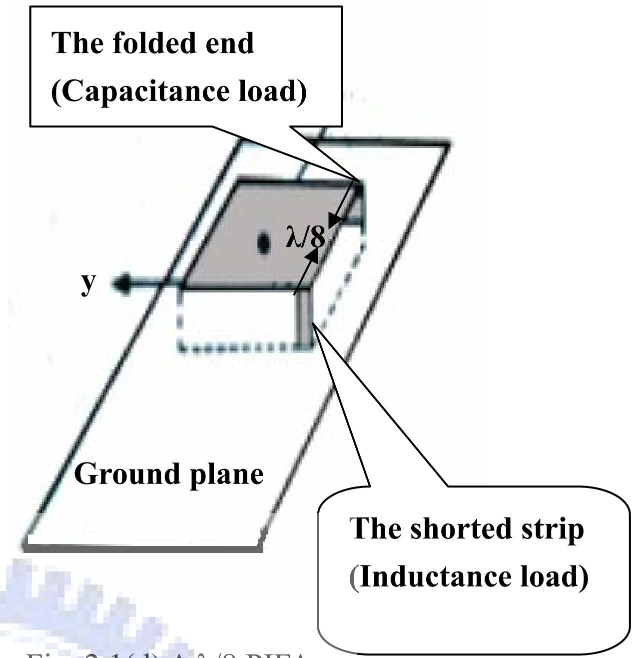

Fig. 2.1(d) A λ/8 PIFA.

Fig. 2.2 shows the evolution of the inverted-F antenna. #1 is similar as a monopole antenna and #2~#4 are the inverted-F structure of quarter-wavelength.

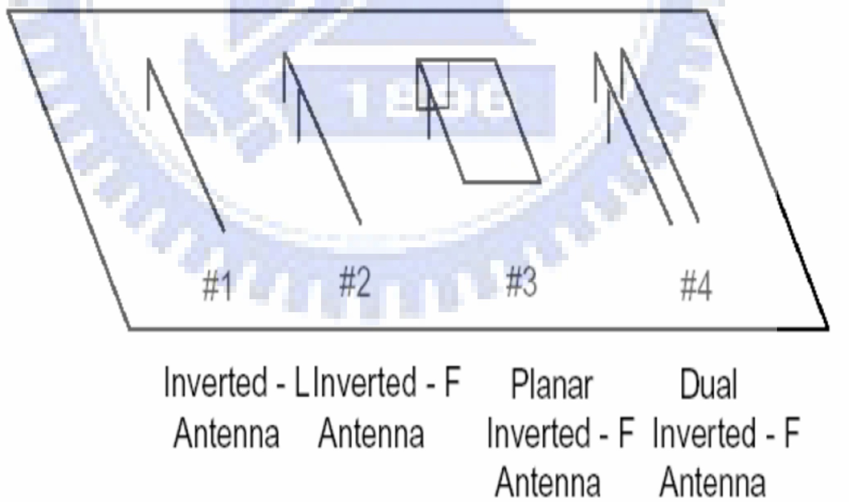

Fig. 2.2 Evolution of the inverted-F antenna from #1 to #4.

2.3 The Characteristics and Limitations of PIFA

PIFA provides the most popular characteristics such as

- compact size,
- fabricate easily, and
- low cost.

With changing the boundary condition, mentioned at section 2.2, of the antenna, the physical size can be reduced to quarter-wavelength and radiate the same frequency. Due to size reduction, the radiation efficiency is not good, therefore, the PIFA always needs a large ground plane under the radiation element to reflect and increase the electromagnetic energy. The general solution is to integrate the ground planes of system and antenna, therefore, PIFA only needs a radiating element with a shorted pin, which is fabricated easily with low cost.

Some limitations of the PIFA are that

- high quality factor
- narrow bandwidth
- bad radiation efficiency

Because the problems of coupling are serious between antenna and the ground plane, the PIFA has a high quality factor and. It is well-known that the quality factor (Q), bandwidth, and radiation efficiency of the antenna are trade-off each other. Therefore, the conventional PIFA has to reduce the value of Q and enhance bandwidth with increasing the length of the shorted pin (7~10mm) to reduce the coupling between antenna and the ground plane. The technique is difficult to apply in a compact mobile phone.

2.4 A Simple and Popular Dual-band PIFA

When a U-shaped slit is created in a main patch as shown in Fig.2.3, the resulted PIFA can radiate dual frequencies as shown in Fig. 2.4. The radiating path L1 + W1 creates 900 MHz band. The radiating frequency is approximately determined by

$$f_{900} \cong \frac{c}{4(L_1 + W_1)}$$

The U-shaped slit creates a shorter resonating current path L2+W2, which induces 1800 MHz band:

$$f_{1800} \cong \frac{c}{4(L_2 + W_2)}.$$

Since the two radiating elements share the same shorted pin, the antenna can be treated as a dual-PIFA without altering the outer shape. However, the coupling effects of these two resonating frequencies may lead to bad radiation efficiency. This phenomenon is more serious in the case of multi-band (more than tri-band).

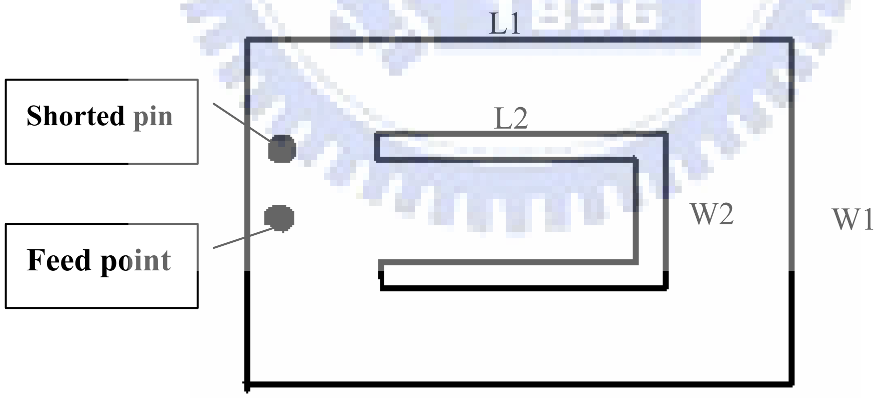

Fig. 2.3 A simple dual-band PIFA with a U-shaped slit

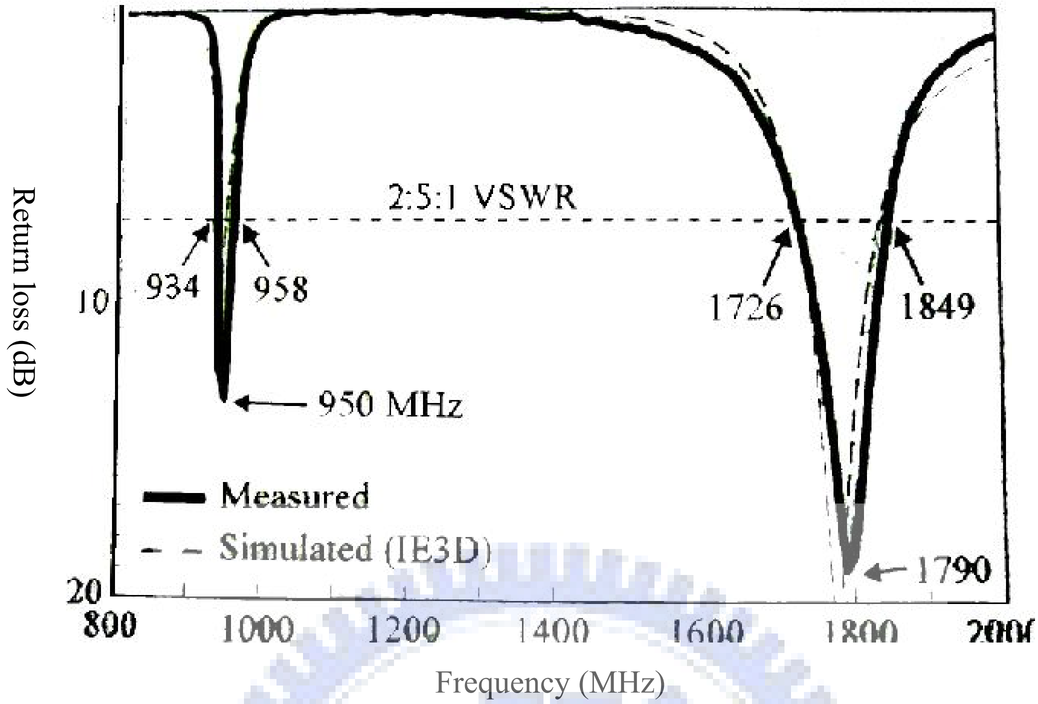

Fig. 2.4 The return loss of the dual-band PIFA

Chapter 3 *Review of Multi-band PIFA Design Methods*

3.1 Introduction

In general, the traditional PIFA can cover dual-bands easily with some simple slits. With the requirements of the multi-band handset or CPEs, the multi-band and compact PIFA have recently received much attention and many techniques have been reported to reach multi-band and antenna size reduction such as [5]~[10]. Popular PIFA design methods include multi-embedded slits [5], shorted-parasitic elements [6][7], and ground-parasitic resonator. The first method already introduced in section 2.4.

3.2 Embedded Slits Technique

Main radiating elements create multi-resonating paths with some embedded slits. The shape and size of the embedded slot are mainly determined by the position of the shorted pin. A single feed and compact quad-band PIFA was proposed in [5]. In Fig. 3.1, three embedded U-shaped slits are added with proper dimensions and positions for creating four target frequency bands as shown in Fig. 3.2. For impedance matching, one end of the antenna is folded and connected to the ground plane, which yields a capacitive load to eliminate the inductive imagery impedance. Further reduction of 15% is achieved by adding a capacitor plate as shown in Fig.3.1.

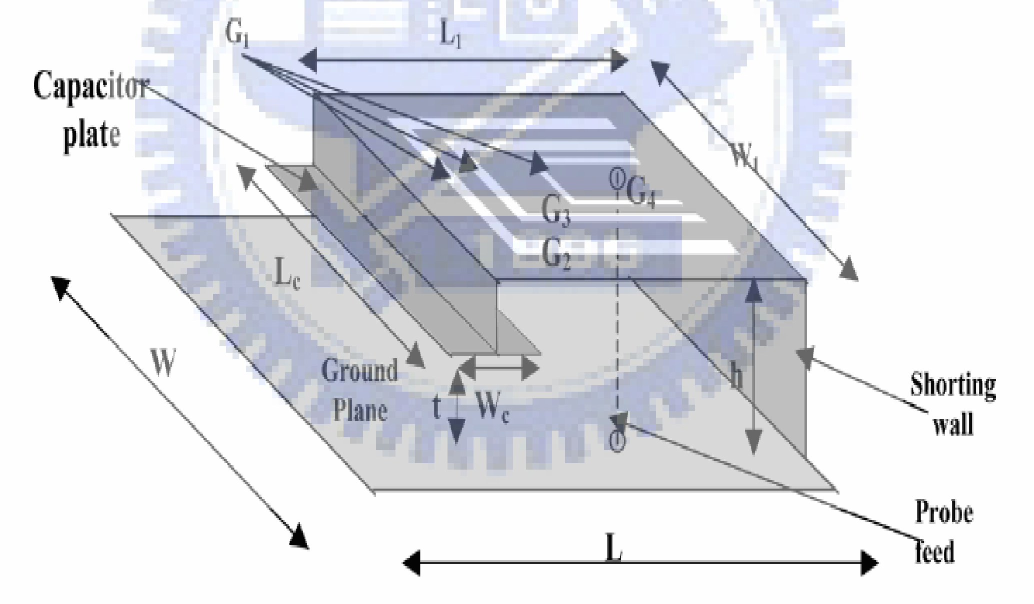

Fig. 3.1 The configuration of the quad-band PIFA with U-shaped slits

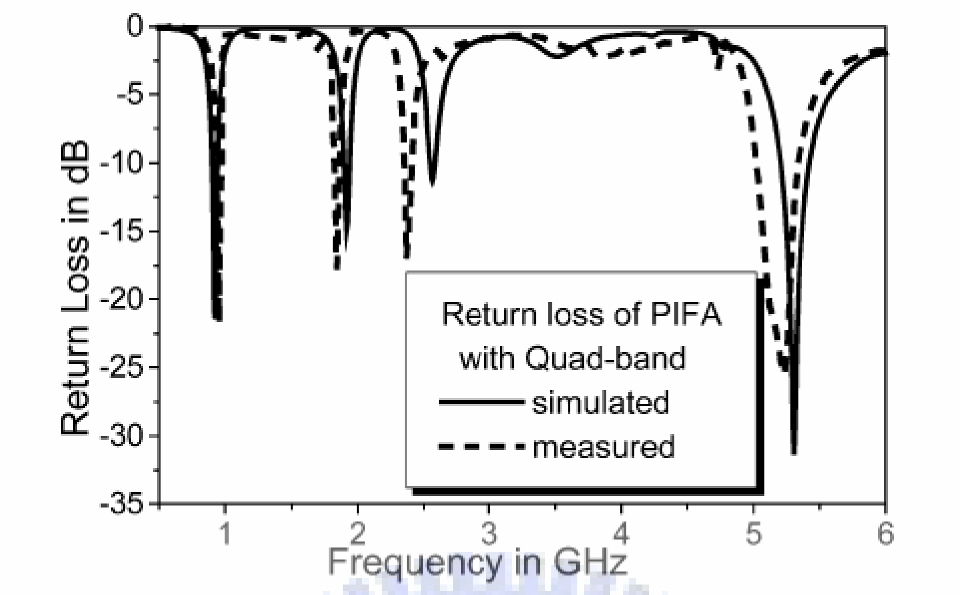

Fig. 3.2 The return loss of the quad-band PIFA with U-shaped slits

Shorted-parasitic Element Technique

The technique employs parasitic radiating elements to surround the main radiator of the original PIFA. Each parasitic element connects the ground plane with a shorted pin. The antenna is equivalent to a multi-PIFA to create multi-frequency. In [6], a tri-band PIFA as shown in Fig. 3.3 that consists of a main radiating element and a shorted-parasitic element [6]. Both elements are on the same plane but disconnected. A L-shaped slit is created in the main element to create two resonating paths to induce GSM900 and DCS1800 bands. The shorted-parasitic element provides the UMTS band, but it increases the area of the antenna. The frequency response of the antenna is shown in Fig. 3.4.

The energy couples to the additional shorted-parasitic element from the main radiating element. Due to the two shorted pin both act capacitance load and yield strong electric field, they need enough long length to decrease the capacitance for impedance matching, and increase the thickness of the antenna.

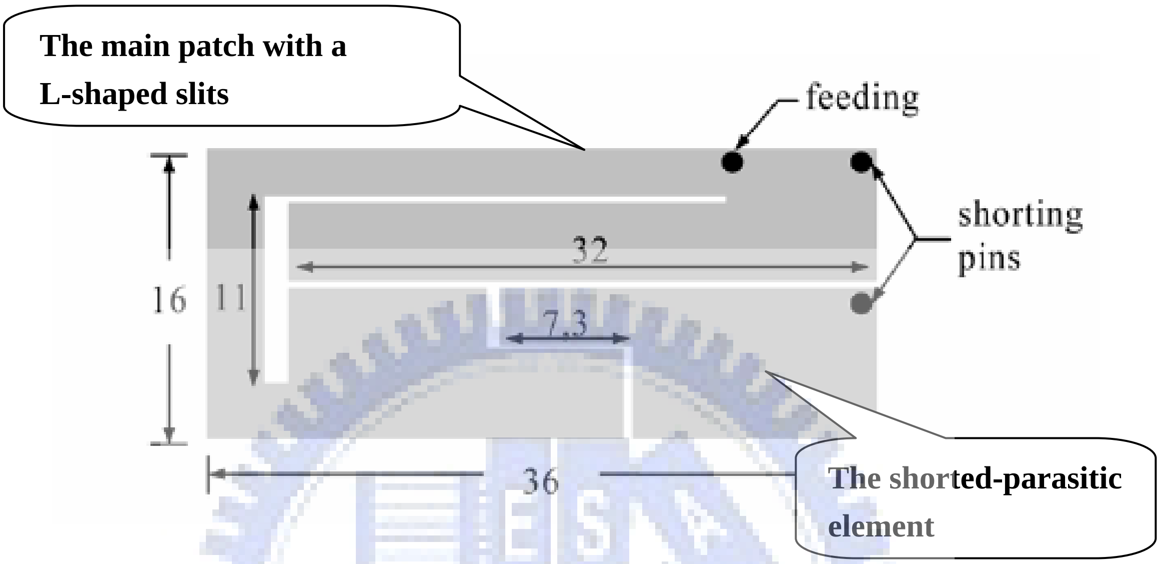

Fig. 3.3 The tri-band PIFA with a shorted-parasitic element

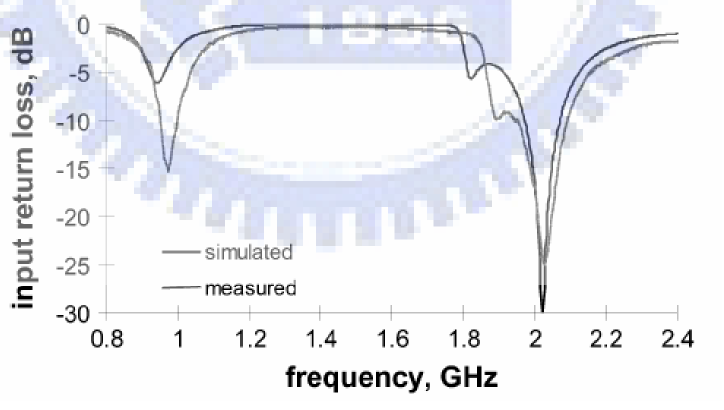

Fig. 3.4 The measured and simulated return loss of the tri-band PIFA

In [7], three parasitic elements have to be added to the main patch to achieve multi-band, shown in Fig. 3.5. They are chosen to quarter-wavelength type, each connected to the ground plane by shorted strips and located near the main patch in order to be correctly electromagnetically excited. The PIFA also covers GSM900, DCS, PCS, and UMTS bands. Fig. 3.6 shows the VSWR of the main patch with and without shorted-parasitic patches no.2 and no.3.

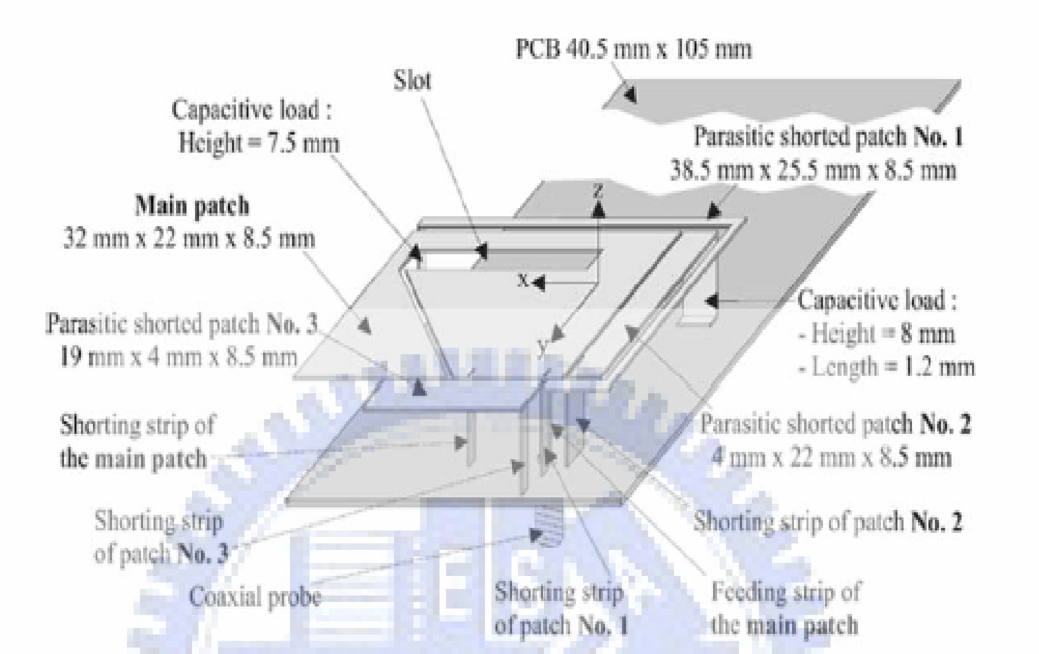

Fig. 3.5 The quad-band PIFA with three shorted-parasitic elements

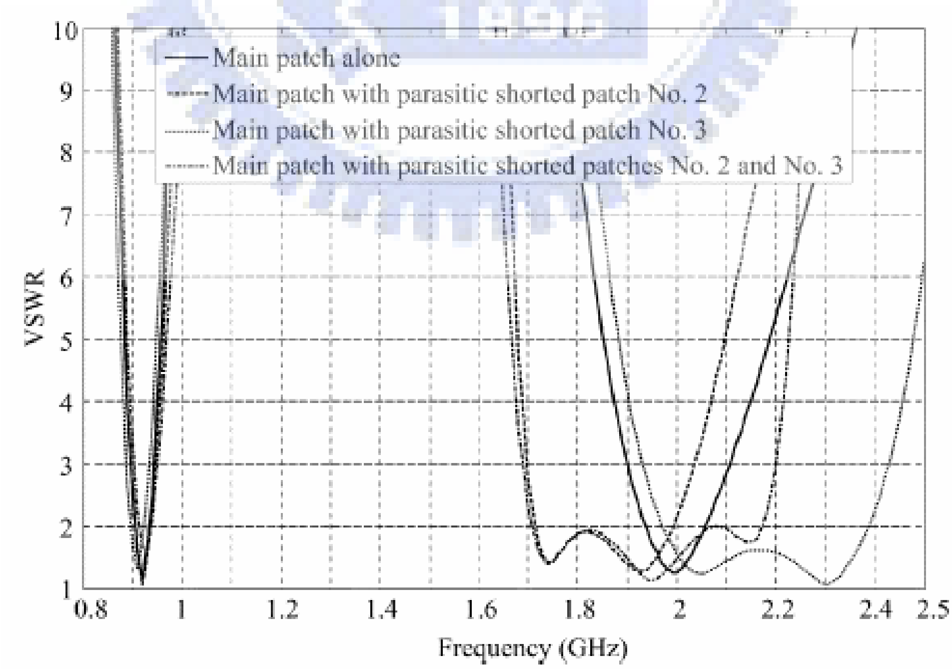

Fig. 3.6 The VSWR of the main patch with and without shorted-parasitic patches no.2 and no.3

3.4 Direct-connected Resonator Technique

In the example of the section 3.3, multi-short pins are needed for disconnected radiating elements, which may create complicated coupling effects, which causes the difficulty of impedance matching. For avoiding using multi-shorted pins in multi-band PIFA design, the direct-connected strip technique is proposed [8]. It uses additional resonators to connect directly with the feed strip of the original PIFA, at the same time, these additional resonators are quarter-wavelength type, and share the same shorted pin with the original PIFA. It also be equivalent to multi-PIFAs and does not increase the antenna size. But these additional resonators are under the antenna surface, the radiation pattern would be interfered by the original structure. The configuration of the original dual-band PIFA is shown in Fig. 3.7, it has two resonating paths with two patches, covered GSM900 and DCS band. With this technique, it adds a additional L-shaped resonator to connect with the feed strip, shown in Fig. 3.8, which creates UMTS band. In Fig. 3.9, it adds two additional resonators, covering five frequency bands.

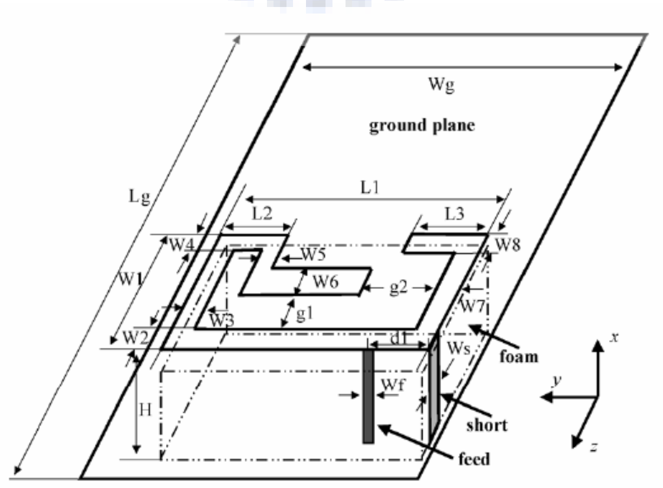

Fig. 3.7 The original dual-band PIFA

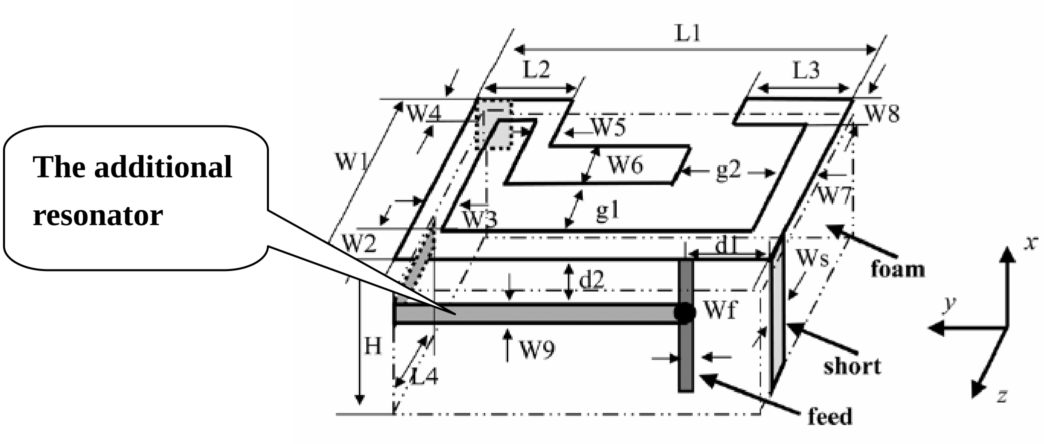

Fig. 3.8 The tri-band PIFA with a direct-connected resonator

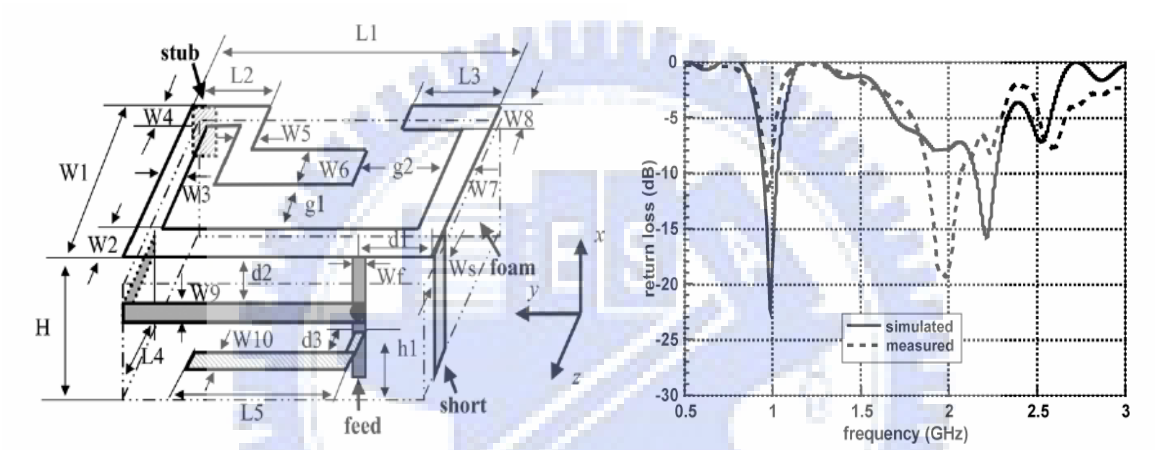

Fig. 3.9 The five-band PIFA with two direct-connected resonators and its return loss

3.5 Ground-resonator Technique

This technique is that the original PIFA adds the additional parasitic elements in the ground plane, increasing the resonating modes with the coupling between the antenna and ground plane. In the condition of a limitary space, this way can yields more bands than the shorted-parasitic element technique. In [9], a five- band PIFA with ground resonator technique. Fig. 3.10 shows the configuration of the PIFA, the feed probe is connected to the top inner patch element A and the two symmetrical top outer patches of element B connect with the ground plane C with two shorted pins. The added parasitic element D at the bottom plane is not electrically connected to the ground plane. Element A and C provide the GSM900 band and Element B and C operate the DCS band. Element D is the additional parasitic element that provides the PCS and

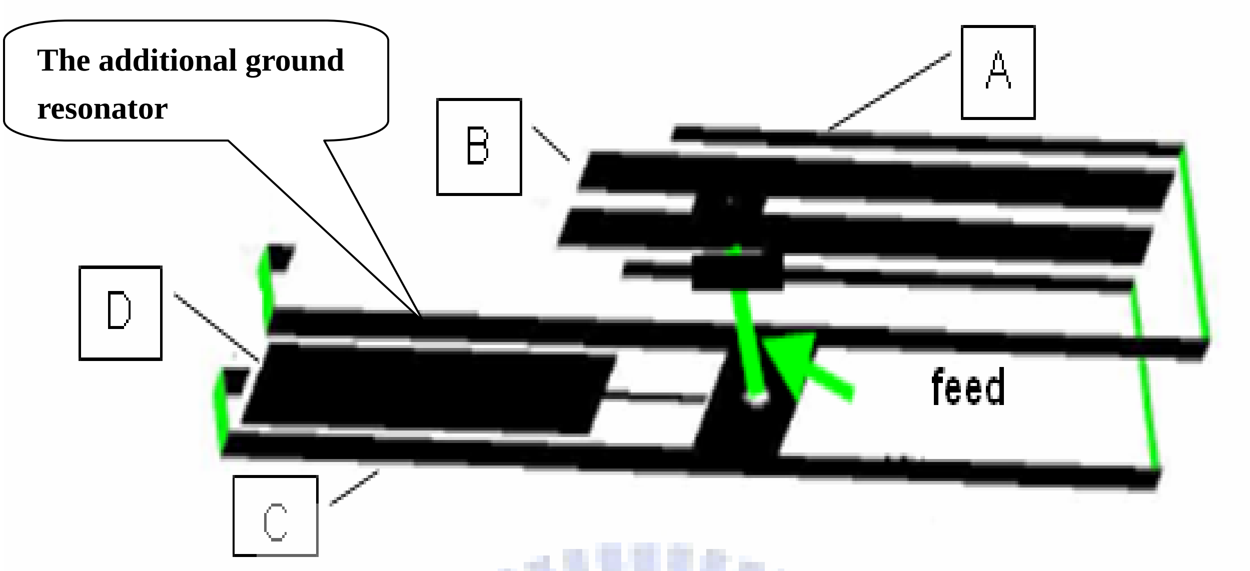

Fig. 3.10 The configuration of the five-band PIFA with an additional parasitic-ground resonator

UMTS bands in association with element A and C. Because the inductance of the long narrow feed line between element D and ground plane C is tuned by a capacitance air gap and a broadband match is achieved for the upper frequencies of operation.

It has been shown that the mentioned above five-band PIFA can be successfully implemented in the planar form [10]. The Fig. 3.11 graphically illustrates how the original PIFA was transformed into an equivalent planar design. The final geometry is printed onto FR4 substrate. Due to the unbalance mode, it is difficult to reach impedance matching. To create a more balanced system, a double layer PIFA is produced where an exact replica of the transformed plane form was etched on the underside of the substrate. The feed connection is shown in Fig. 3.12. Due to the additional coupling effect between two layer PIFAs, the final planar PIFA covers six frequency bands, which shown in Fig. 3.13. This transformation increases effectively the covered frequency bands of three dimensional PIFA with the ground resonators. But the final planar form consists of 6 elements; therefore the mutual interactions between these tightly coupled elements make the antenna difficult to find optimum physical parameters. So far, the planar- transformed technique of 3D PIFA with ground resonator covers at most frequency bands in PIFA design.

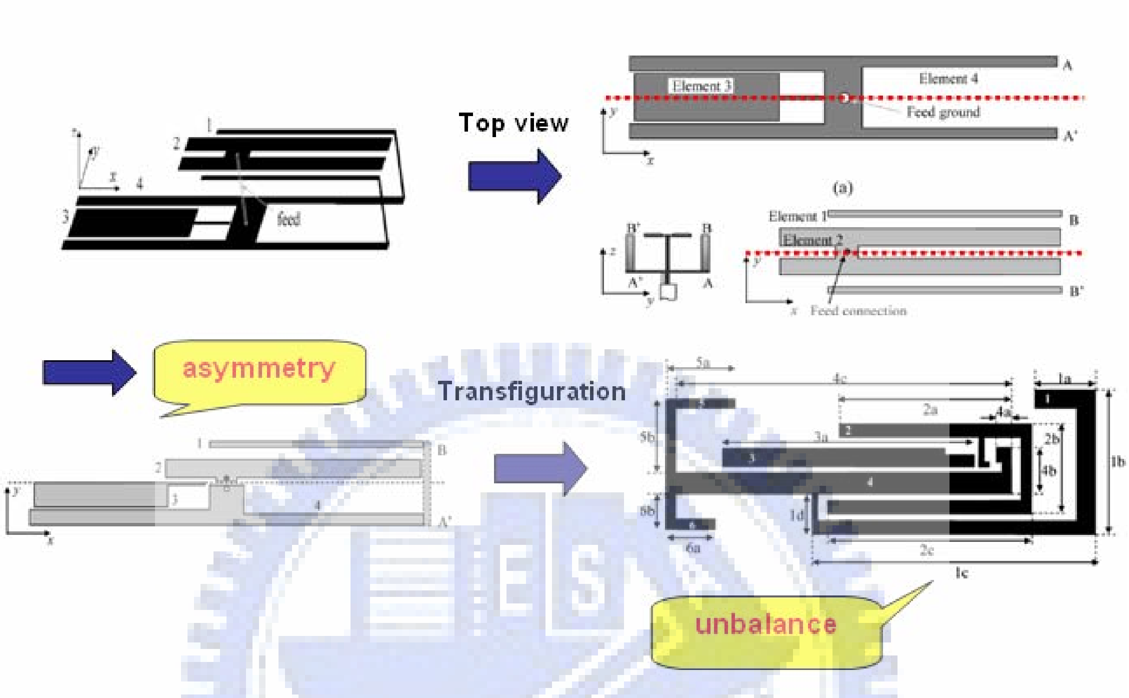

Fig. 3.11 The process of the PIFA transformation to planar form

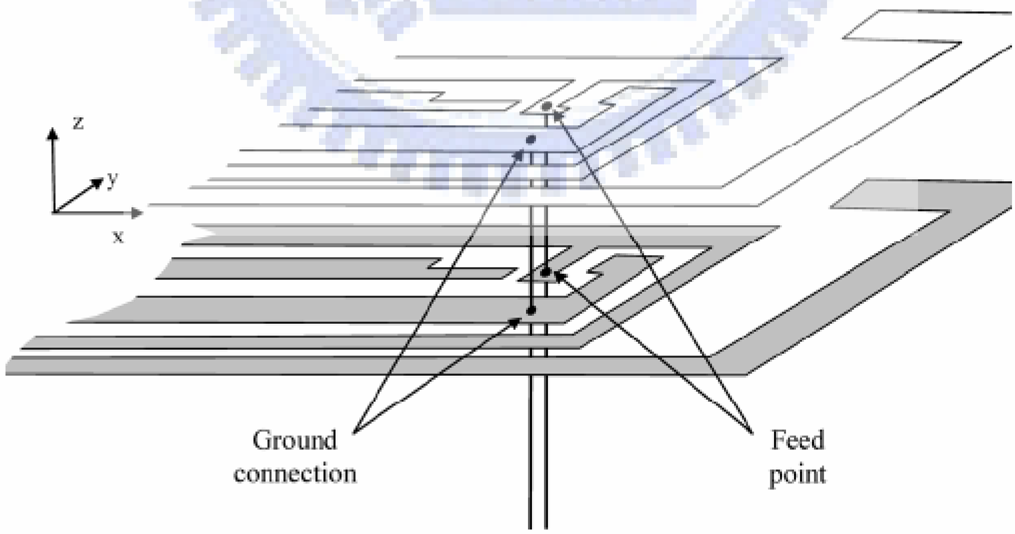

Fig. 3.12 The feed position of the double layer PIFA

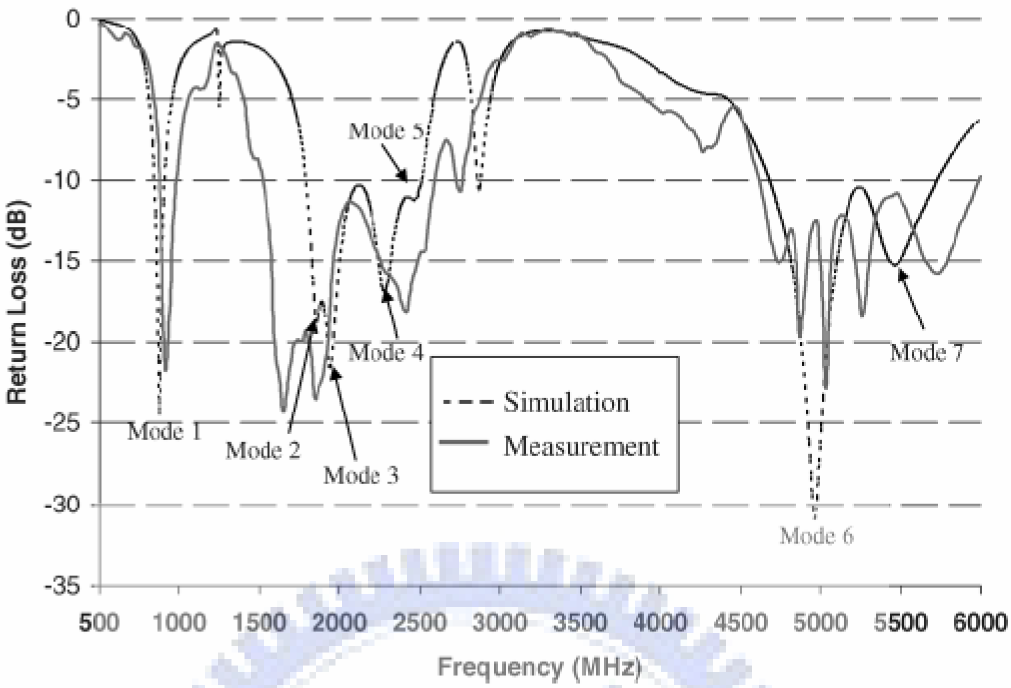

Fig. 3.13 The simulated and measured return loss of the double layer PIFA

Chapter 4 *The Proposed Compact Multi-Band PIFA*

4.1 Design Concept

In PIFA design, multi-resonating paths are needed for multi-band. When the size of the antenna is miniaturized, these resonating paths may heavily interfere to one another, which degrades the radiating efficiency. Increasing antenna common part of multi-band radiation is our major approach, which can reduce effectively the interferences among radiation elements and the antenna size.

4.2 Design Procedure and Method

4.2.1 Control Resonating Paths Using the Shorted Pin

Most time the shorted pin acts as a capacitor load and is near the feed only for impedance matching purpose, which may yield a large ground plane, narrow bandwidth and a long shorted pin (large antenna volume) to provide enough capacitance. Here, the shorted pin is moved away from the feed and just acts as a short-circuited load, which is an effective way to control the current resonant paths and reuses the radiating elements.

4.2.2 Create Multi-resonating Path

To increase number of effective resonating-paths, two connected parasitic-folded branches are added. The target frequency bands can be achieved by adjusting the length and width of each parasitic-folded branch.

4.3 The Proposed Multi-band PIFA

4.3.1 Multi-band Antenna Design and Result

The front view and the 3-D view of the proposed antenna are shown in Figs. 4.1 (a) and (b), respectively. The front view shows that the antenna is composed by an inverted-F structure and an inverted-E structure. The radius and length of the shorted pin shown in Fig. 4.1(b) are 0.8 mm and of 4 mm, respectively, which is far away from the feed and acts a short-circuited load. Two parasitic- folded branches behind the inverted-F structure with proper dimensions as shown in Fig. 4.1(b) and the shorted pin positioned far away from the feed create the required resonating paths of the six higher bands, which is validated by the simulation result of frequency response shown in Fig. 4.2, which shows the comparison of the computed and measured return losses. It is found that the measured frequency response (less than 10 dB) and impedance matching are better than the simulation ones, especially in the UMTS band. It is noted that the lowest frequency bands, GSM 900 MHz and DCS 1800 MHz are created by the inverted-E structure with a fold patch behind. modified PIFA covers more bands with a smaller size 30 mm × 20 mm × 4 mm and a smaller ground plane size 30 mm × 43 mm. Additionally, our structure is simple and is easy to fabricate. To optimize the return loss over the covered spectrum, the probe feed is located at the join of the inverted-F and E structures.

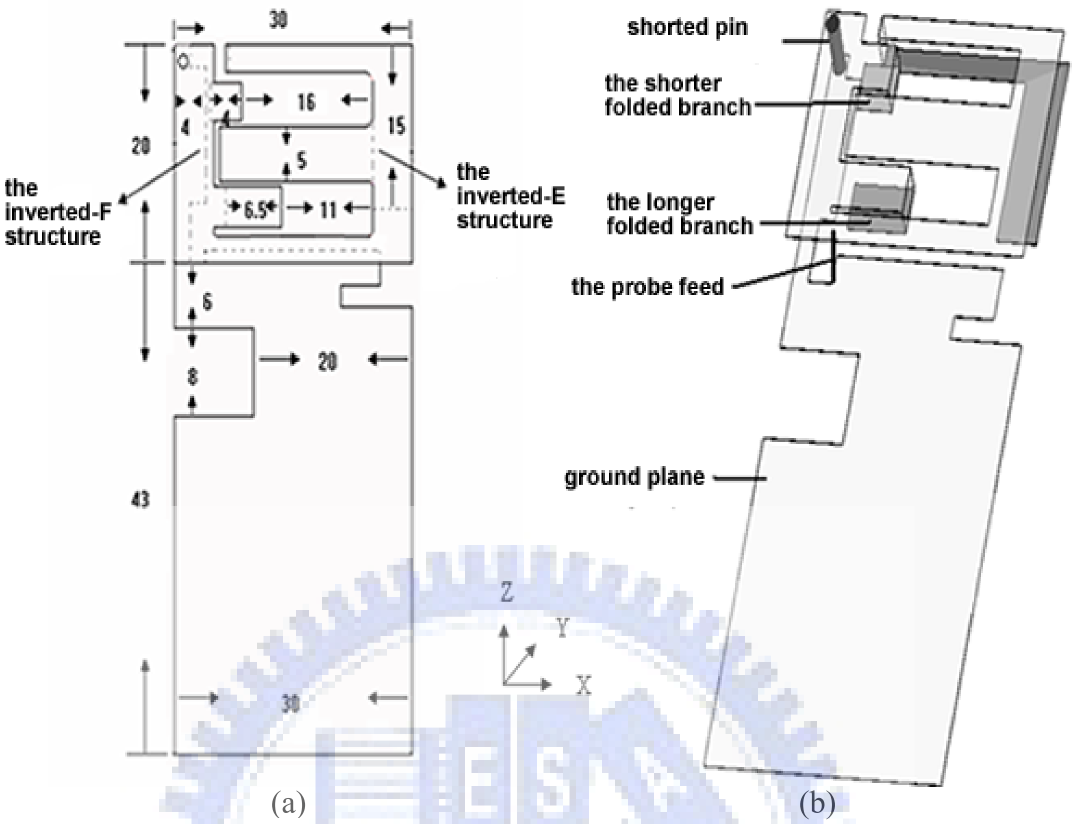

Fig. 4.1 (a) Front view of the antenna (mm) , and the dot-line portion represents the structure behind the antenna surface; (b) 3-D view of the antenna

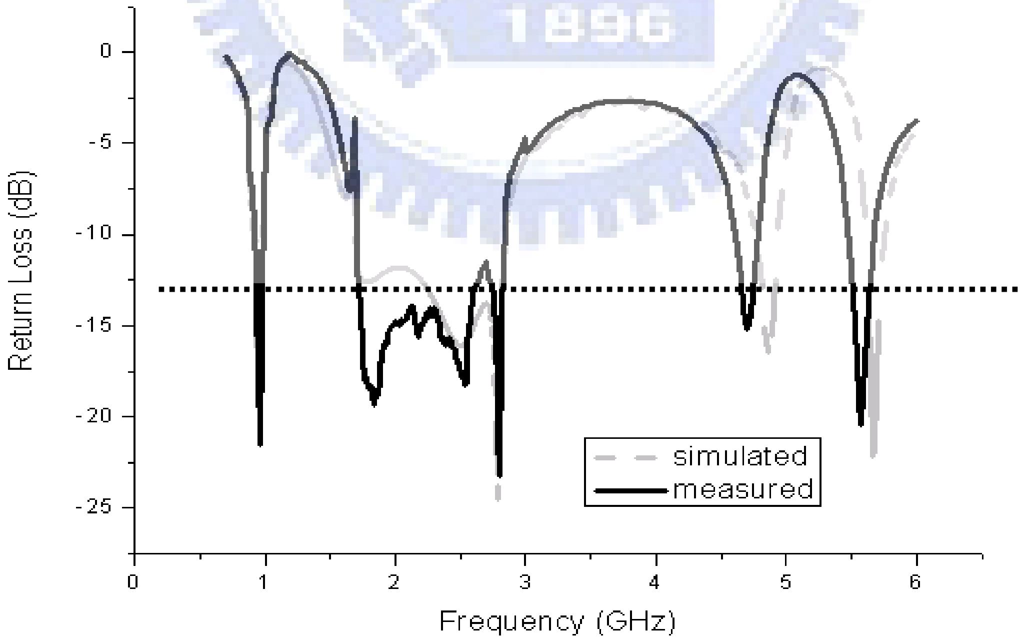

Fig. 4.2 The measured and simulated return loss of the multi-band PIFA

4.3.3 Modeling of the Proposed Multi-band PIFA

The circuit model of an antenna is always obtained by rational function and vector fitting method [11]. It needs the data of the measured antenna impedance to compute the coefficients of the polar and zero point in rational function with vector fitting method. With the increasing of the covered frequency bands, the computation is more complicated. As far as a designer concerned, the result would help to know the equivalent model in system view, but it does not provide the effects yielded by the structure of the antenna directly. In this paper, the multi-band PIFA with the proposed technique can obtain the circuit model directly through antenna structure without complicated computation.

According to the descriptions of the section 4.1.1 and 4.1.2, the equivalent circuit model of the multi-band PIFA has been shown in Fig. 4.3. The circuit to cover from PCS band to HiperLAN/2 is modeled by 6 parallel transmission lines of different lengths. Each resonant path is modeled by a parallel transmission line of a half wavelength. It is because that the coupling effects among these six frequency components are minimized due to the parasitic-folded structures forming as one radiator. It is noted that the GSM 900 or DCS 1800 band is simply described by a radiating resistance since they both have a monopole structure.

In the fig. 4.3, Z_{Ln} is the short-circuited load of nth transmission line due to the shorted pin, and Z_{Rn} is the radiation impedance in each band. The Z_{Ro} is the radiating resistance of the GSM900 or DCS1800 band.

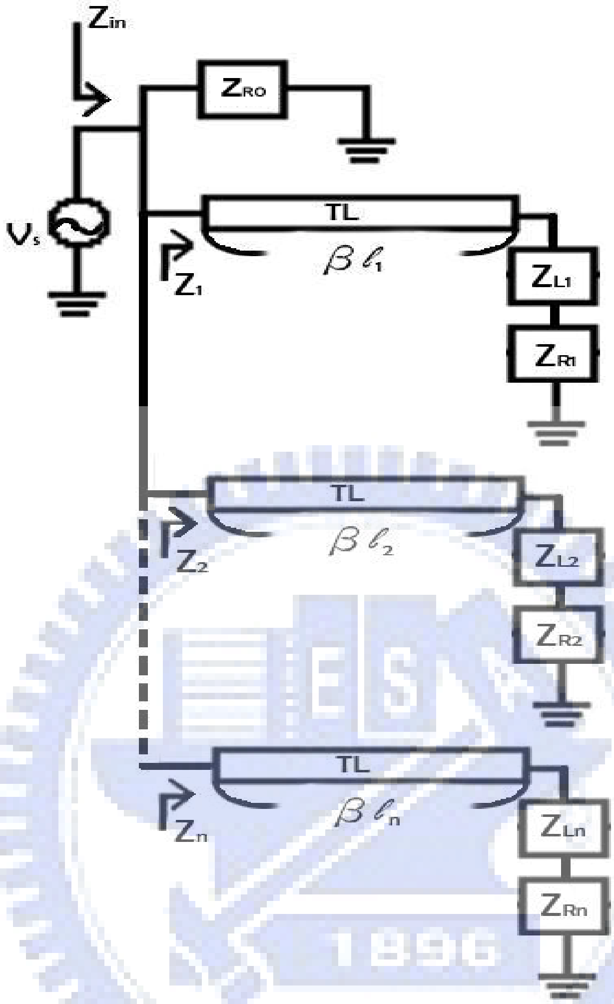

Fig. 4.3 The equivalent circuit model of the proposed antenna. The circuit to cover from PCS band to HiperLAN/2 is modeled by 6 parallel transmission lines of different lengths. Beta is the characteristic impedance of the transmission line. The GSM 900 or DCS 1800 band is simply described by a radiating resistance since they both have a monopole structure.

The input impedance is approximately to

$$Z_{in} = Z_1 \Delta U^{-1}(w_1) // Z_2 \Delta U^{-1}(w_2) // \ldots // Z_n \Delta U^{-1}(w_n) // Z_{Ro}$$

$$= \frac{Z_{Ro}\prod_{i=1}^{n} Z_i}{\prod_{i=1}^{n} Z_i + Z_{Ro}\sum_{i=1}^{n}[(\prod_{k=1}^{n} Z_k)\frac{\Delta U(w_i)}{Z_i}]} \qquad (4.3)$$

the Zi (i=1~n) is the impedance of each half wavelength transmission line transformer of short-circuited type.

$$Z_i = Z_0 \frac{Z_{Li} + Z_{Ri} + jZ_0 \tan(\beta_i \ell_i)}{Z_0 + j(Z_{Li} + Z_{Ri})\tan(\beta_i \ell_i)} \qquad (4.4)$$

The U(x) is the step function, and we define

$$\Delta U(w_m) = U(w - w_l) - U(w - w_u) \qquad (4.5)$$

When resonating happens at frequency wm, the formula will simplify to

$$Z_{in} = Z_{Rm} \qquad (4.6)$$

Z_{Ln} : the short-circuited load of the nth transmission line.

Z_{Rn} : the radiation impedance in each band.

Z_{Ro} : the radiating resistance of the GSM900 orDCS1800 band.

ℓ_n : the half-wavelength transmission line of the nth frequency band.

It can be found that the input impedance equals approximately to the radiation impedance from (4.6), in the system view, the radiation impedance can replace with the input impedance of antenna, and the design concept would decrease the complication of the circuit model of a multi-band antenna. This result is similar as the half-wavelength dipole antenna, because the effective electrical resonating path is also half-wavelength of the center frequency of each band. Fig. 4.4 shows the comparison of the input impedance of the proposed PIFA and half-wavelength dipole antenna.

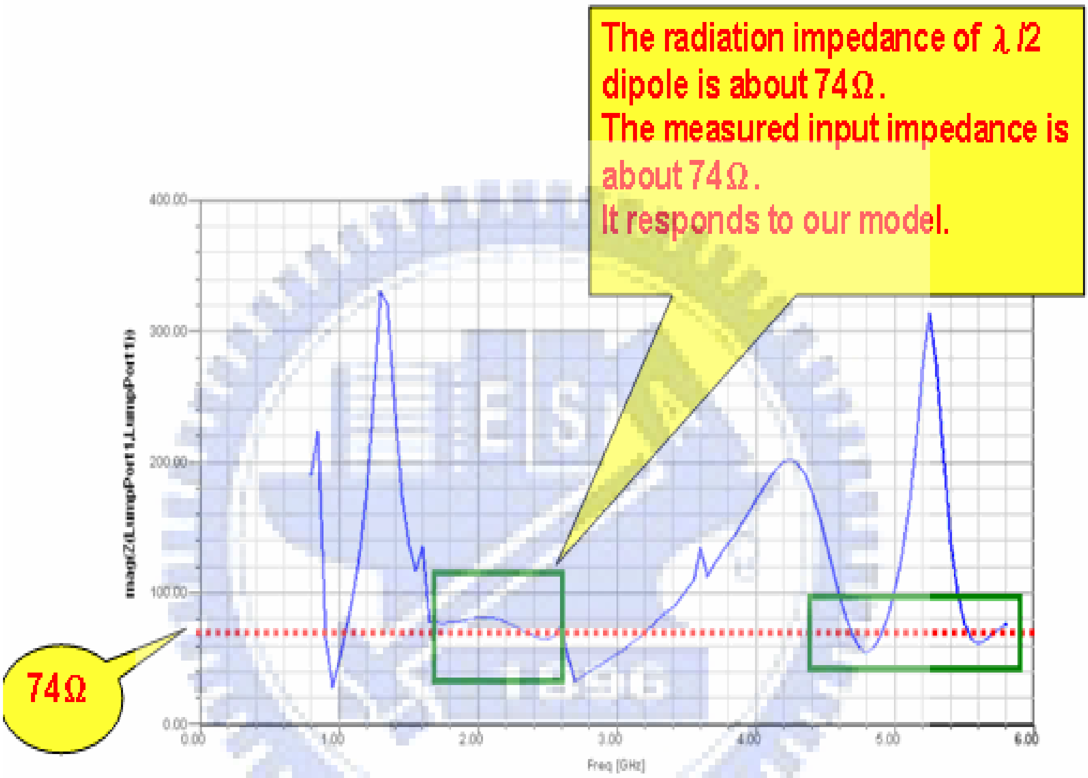

Fig. 4.4 The comparison of the impedance of the proposed PIFA and λ/2 dipole

4.3.4 The Current Distribution

The simulations of the current flow distribution of WMAX and HiperLAN/2 bands are shown in Fig. 4.5 (a) and (b), respectively. From Fig. 4.5(a), the current flows through the longer folded branch, then is blocked at the edge of the shorter folded branch of the inverted-F structure, and finally, returns to the ground plane through the shorted pin. The equivalent circuit model of the current flow-path is described by a short-circuited TLIT of a half-wavelength length, which corresponds to the center frequency of the WiMAX band. Fig. 4.5(b) shows that the current is blocked by the longer folded branch of the inverted-F structure and moves to the shorter folded branch and then returns to the ground plane through the shorted pin. Similarly, the equivalent circuit model of the current flow-path is described by a short-circuited TLIT of a half-wavelength length, which corresponds to the center frequency of the HiperLAN/2 band. From the simulation result as shown in Fig. 4.5, it is observed that flow current are accumulated at the folded edge to produce a high potential zone and an inversed electrical field, which changes the current direction.

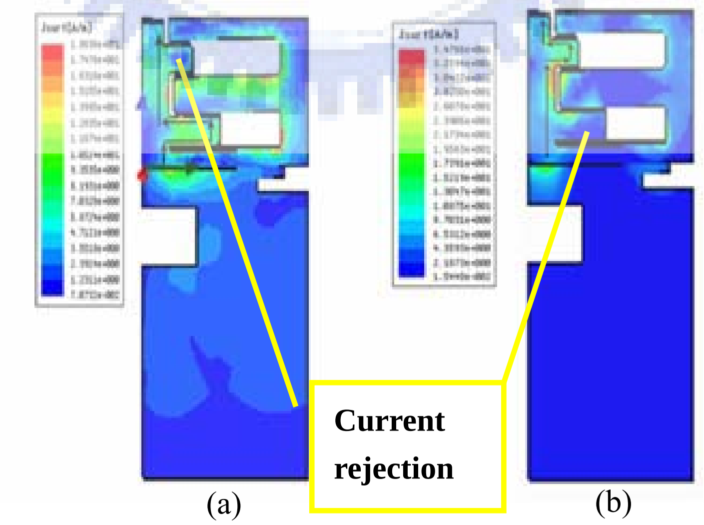

Fig. 4.5 The current flow paths of WiMAX and HiperLAN/2 are path no.1 and path no.2

4.3.5 The Radiation Pattern

Fig. 4.6~4.13 shows the measured and simulated radiation patterns of the GSM900 band to Hiper-LAN/2 band. It is found that all the simulation results agree with the measured ones, and they are nearly omni-directional. The peak gains of the GSM900, DCS, PCS, UMTS, Bluetooth, WiMAX, HiperLAN/2, and the additional 4GHz band are 2.4, 3.9, 4.3, 4.2, 4.3, 4.3, 4, and 3.7 dBi, respectively.

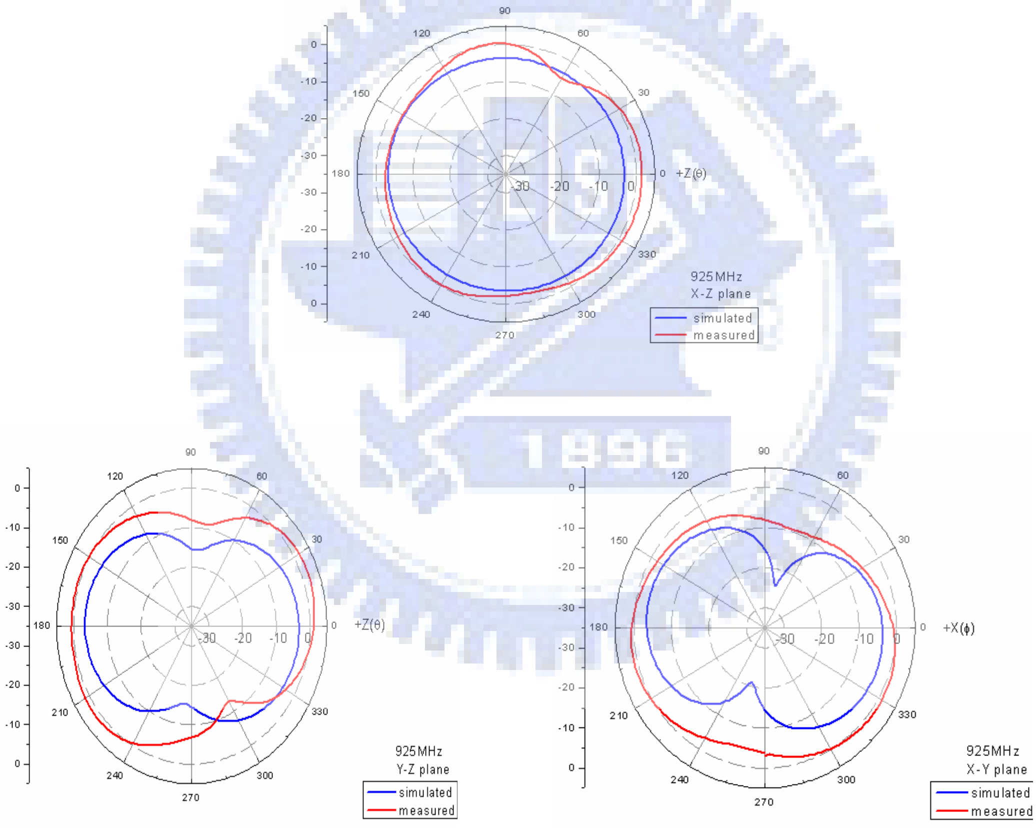

Fig. 4.6 The radiation patterns of the GSM900 band

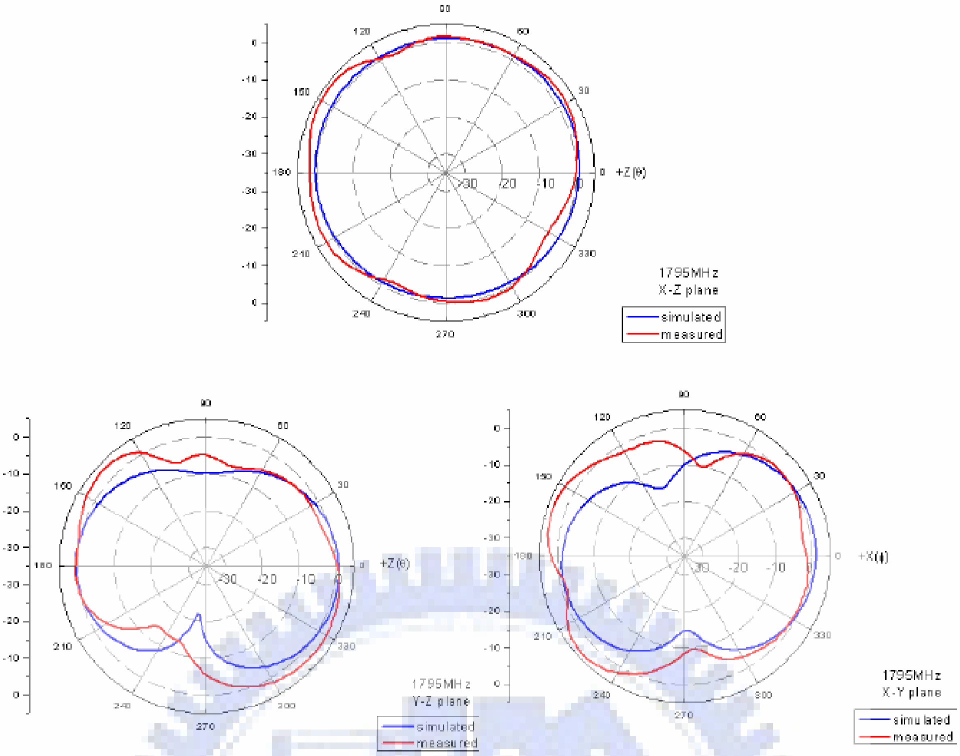

Fig. 4.7 The radiation patterns of the DCS band

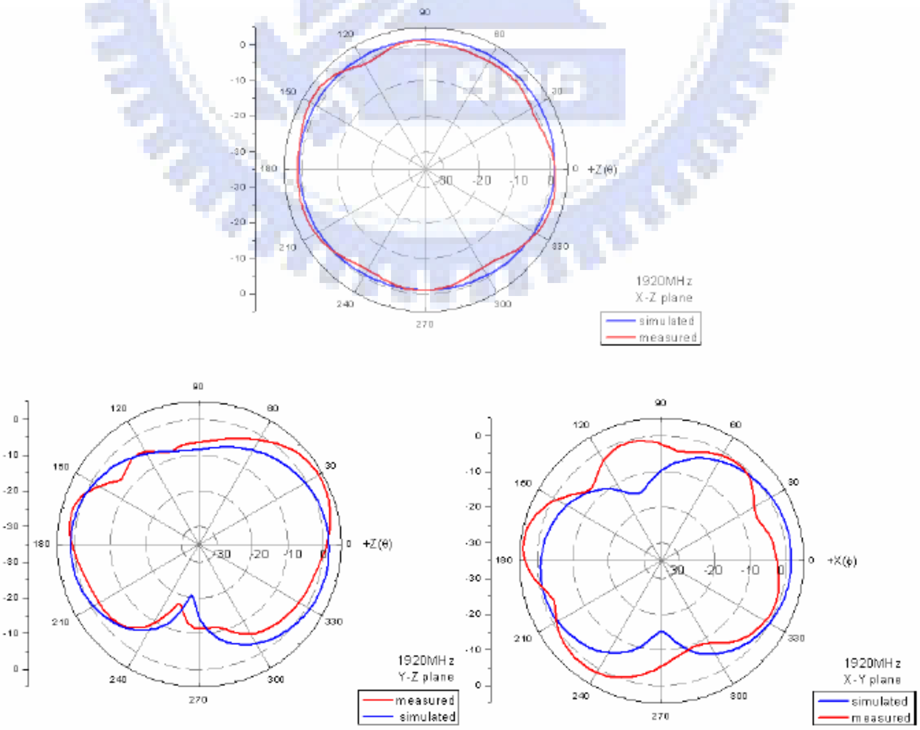

Fig. 4.8 The radiation patterns of the PCS band

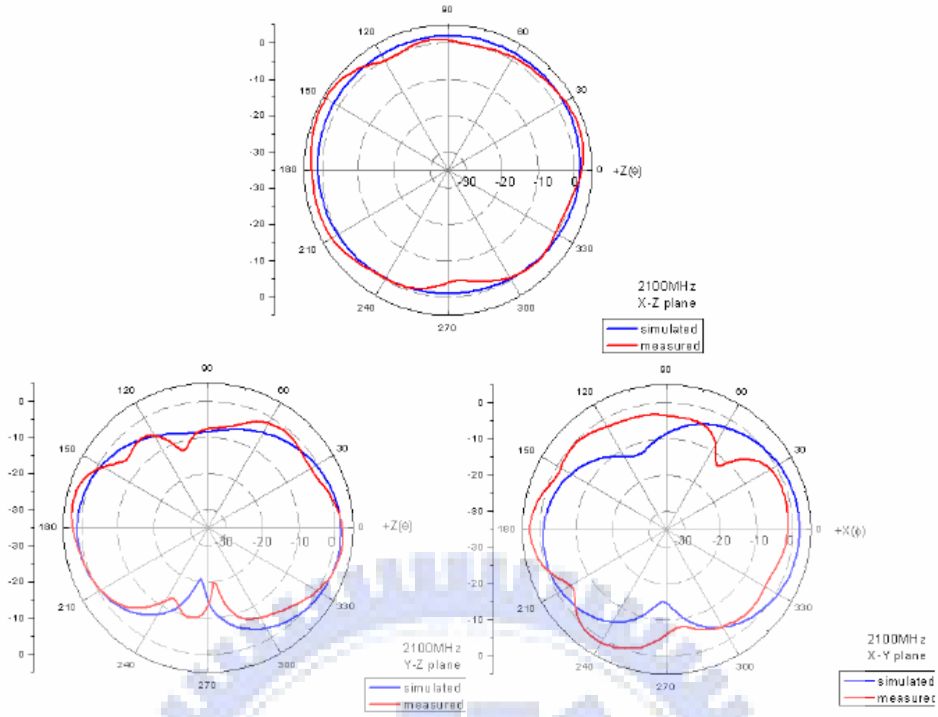

Fig. 4.9 The radiation patterns of the UMTS band

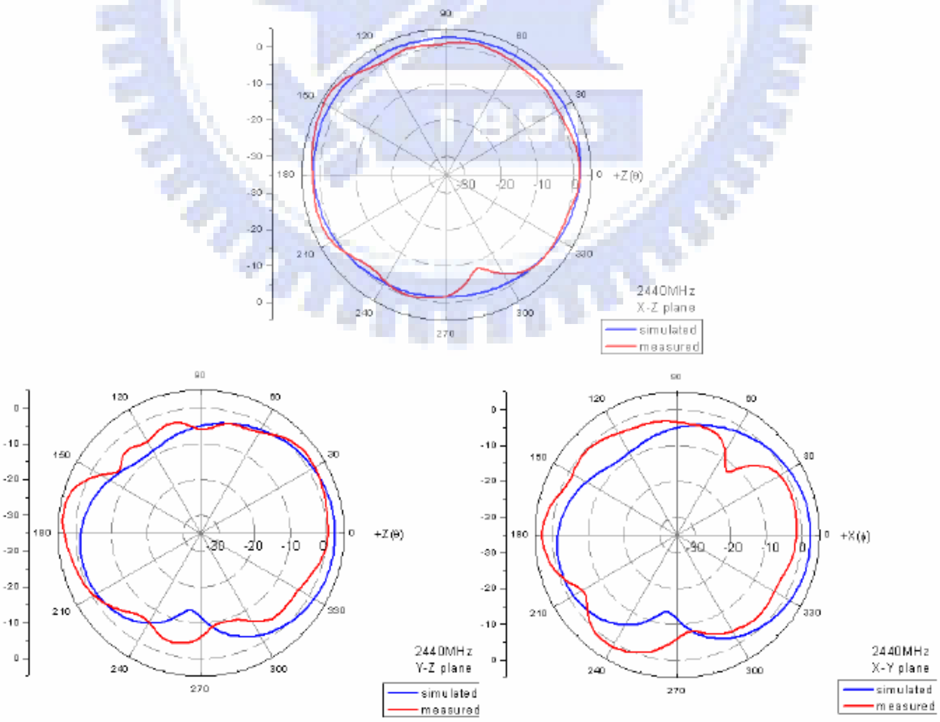

Fig. 4.10 The radiation patterns of Bluetooth band

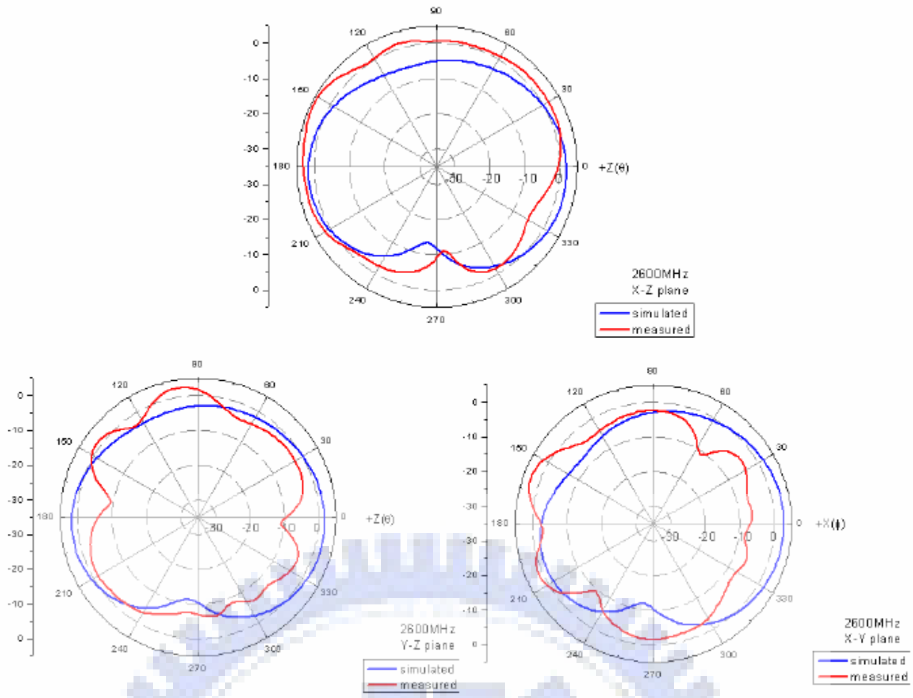

Fig. 4.11 The radiation patterns of the WiMAX band

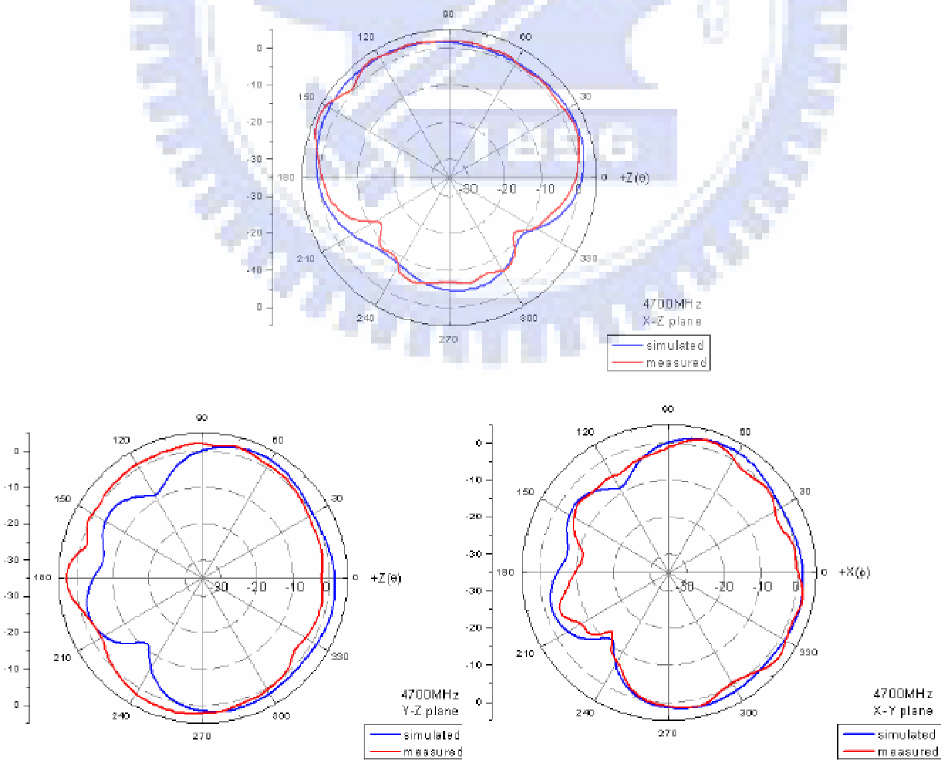

Fig. 4.12 The radiation patterns of the additional band

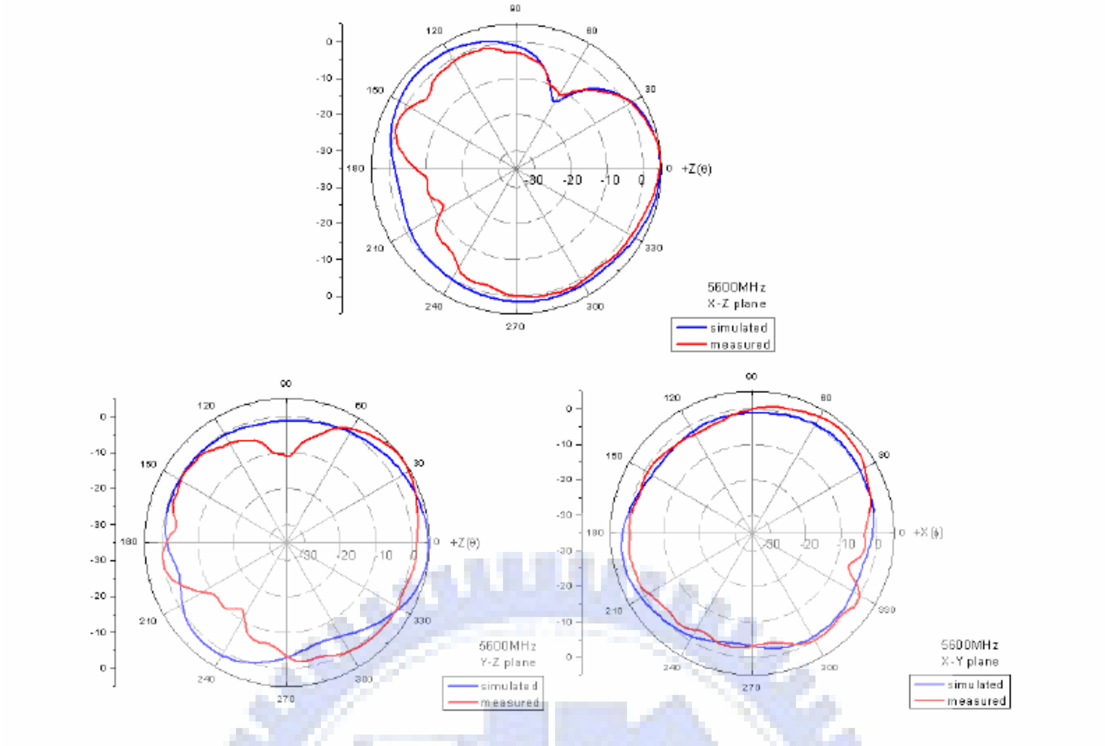

Fig. 4.13 The radiation patterns of the HiperLAN/2 band

4.4 Summary Innovation

Table. 4.1 Innovation

	Conventional multi-band PIFA	**Modified multi-band PIFA**
The function of the shorted pin	Act as a capacitance load	Act as a short-circuited load
Position	Near the feed point	Far the feed point
Operation mechanism	Decrease the inductive impedance to reach impedance matching	Resonating current must flow half-wavelength path and return to ground plane with short-circuited load.
Advantage & Drawbcak	Increase antenna size. The effect of the position is sensitive to input impedance.	Decrease antenna size and ground plane size. Control the current path.
The method of creating multi-band	Use multi-shorted pins to yield multi-PIFAs. Add radiating elements to increase resonating paths.	Use the parasitic folded branch to increase current paths. Different mode can reuse the folded branch.
Modeling of antenna	In general, the model can obtain through the measured impedance with vector fitting method.	Combine the two technique, the antenna can be equivalent to parallel impedance transformers of short-circuited load form.
Advantage & Drawbcak	Increase the antenna size. Difficult to tune the optimal parameter. Complex computation.	Reuse radiating element to reduce antenna size. The model can connect with real structure directly.

4.5 The Comparison to Other Published Multi-band PIFA

Table. 4.2 Comparison

Ref.	Antenna dimension (mm^2)	Ground dimension (mm^2)	The number of covered frequency band	Peak gain range (dBi)
Proposed PIFA	2400	1290	8	1.2~4.8
[6]	5184	3600	4	-1~3.3
[7]	8181	4200	3	-1~3
[8]	4608	2880	4	-1.5~3
[9]	15280	1608	5	1.3~2.5
[10]	2726	2018	6	2

Chapter 5 *Conclusions*

In this report, a novel technique of miniaturization of multi-band PIFA is proposed, the shorted pin just acts a short-circuited load, which is an effective way to control the current resonant paths. With the properly positioned shorting pin and only few parasitic-folded branches, resonating paths are created easily to fulfill multi-band requirement. With our approach, antenna analysis is simplified since the circuit is modeled by using the transmission line impedance transformer (TLIT) method to yield the analytical result of the antenna input impedance. This method is much simpler to compare with the conventional vector fitting method, which helps us to determine antenna dimension easily. In the mentioned example, the inverted-F structure is shared as a common component for all resonating paths, and covers the PCS (1850~1990 MHz), UMTS (1920~2170 MHz), Bluetooth/WLAN (2400~2480 MHz), WiMAX (2500~2690 MHz), HiperLAN/2 (5470~5725 MHz) and an additional band (4600~4800 MHz). Our design can also reduce the antenna size effectively. Compared the simulation result with the measurement ones, the return loss and radiation pattern are in agreement. In addition, the multi-band antenna is small with good radiation patterns.

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