行政院國家科學委員會專題研究計畫 成果報告

應用於多種無線通訊系統之寬頻天線陣列
研究成果報告(精簡版)

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出席國際會議研究心得報告及發表論文

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中 華 民 國 96 年 08 月 23 日

應用於多種無線通訊系統之多頻段天線陣列
A multi-band antenna array for multiple wireless communication systems

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主持人：鄭士康　台大電信工程研究所
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中文摘要

近年來無線通訊產品大量湧現在生活週遭的每一個角落，慢慢地成為人們生活中不可或缺的物品。為達到更優質的通訊，各式各樣的基地台和橋接器的需求逐漸增加。如果每一個通訊系統都使用各自的基地台或橋接點，週遭環境中所需安裝的天線數目將大量增加，眾多天線的架設亦有礙觀瞻。本研究計畫設計完成一個適用於各種通訊系統、價廉、精巧的多功能寬頻相位陣列天線系統。該架構由兩個四天線元件的陣列所組成。鑒於大部分的無線通訊使用的頻譜分布在 2.0GHz 到 6.0GHz 之間，因此我們設計一個工作於此頻帶範圍之陣列天線作為範例。量測結果顯示：除 3GHz 以下範圍，由於天線耦合較強，場型不如預期外，其餘頻段測得結果均與設計相符。

關鍵字：陣列天線

Abstract

In this project a new wideband array antenna system for multiple wireless applications is developed. It is composed of two equispaced four-element arrays, phase shifters, diplexers, and power dividers. The two arrays are interleaved and connected to diplexers and power dividers. The proposed antenna system associated with feeding network and antenna elements can be integrated on a single substrate. Consequently, such a design is with low fabrication and assembly cost and compact size. A wideband antenna array with bandwidth from 2.0GHz to 6.0GHz and main beam pointing to 20 degrees is designed and measured as an example. The radiation patterns below 3.0GHz deforms drastically, suffering from mutual couplings between antenna elements. The performance for other frequencies seems to agree with our design.

Keywords: array antenna.

I. Introduction

Recently wireless communication products emerge in large number and gradually become living essentials. The demand of various base stations and access points for different communication standards increases in order to pursue better service quality. As the number of base stations and access points goes up, the number of antennas increases dramatically. Technically, it results in serious couplings between antennas of different communication systems and occupies a large space. For the public, it arouses concerns about their excessive electromagnetic radiation. Thus, a compact multifunctional array antenna to provide a wide variety of wireless services is highly desired.

Consider an equispaced array of 4 elements, a uniform progressive phase factor δ can be introduced to position the main beam to angles θ_0 and π-θ_0 [1]. If δ is a linear function of frequency, the direction of main beam still points at θ_0 and π-θ_0, but the main beam deforms and the level of side lobe degrades as frequency sweeps. The digital signal processing technique, digital beamforming, can provide a frequency-invariant beam pattern over an arbitrary bandwidth [2]. This approach is very powerful, but for an n-element array each antenna requires an RF transceiver and A/D converter, resulting in high fabrication cost. Consequently, designing an array with lower cost and beam pattern not sensitive to frequency sweeping is in great demand for future wireless applications.

Here we propose a new wideband array antenna system which is composed of two equispaced four-element arrays, phase shifters, diplexers and power dividers. The two arrays are interleaved and connected to diplexers and

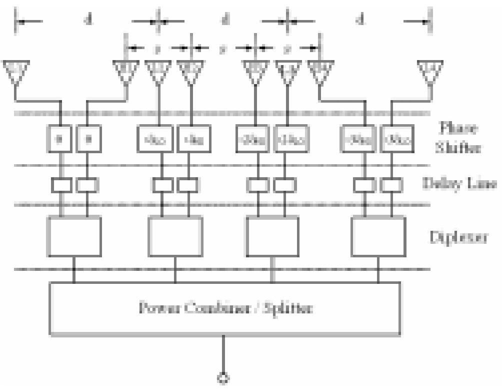

Fig.1. Proposed System Architecture.

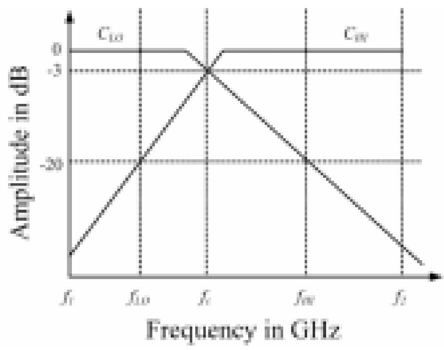

Fig. 2. Specification of the diplexer.

power dividers. The proposed antenna system associated with feeding network and antenna elements can be integrated on a single substrate, offering lower fabrication and assembly cost and more compact size than the conventional solutions. A wideband antenna array with bandwidth from 2.0 GHz to 6.0 GHz and main beam pointing to 20 degrees is designed and measured as an example.

II. Design Concept

The structure of the proposed system is depicted in Fig. 1. The phase shifters are designed to position the main beam to a specific direction. The use of the diplexers is to switch the two arrays as frequency sweeps. Assume that f_1 and f_2 are the lowest and the highest frequencies of the desired band, choose

$$f_c = \sqrt{f_1 f_2} \tag{1}$$

$$f_{LO} = \frac{(f_1 + f_c)}{2} \tag{2}$$

$$f_{HI} = \frac{(f_2 + f_c)}{2} \tag{3}$$

Such a choice makes the low- and high-bands of the diplexer have the same fractional bandwidth. The frequency response of the diplexer is plotted in Fig. 2. The delay lines in Fig.1 are designed so that the outputs of the diplexer are with the same phase at f_c. Finally, the diplexers are fed using wideband power dividers.

The array factor of the proposed system can be expressed in the form

$$AF(f,\theta) = C_{LO}(f)\sum_{n=1}^{4} e^{jn(k_0 d\sin\theta - \delta_{LO})} + C_{HI}(f)\cdot A\cdot\sum_{n=1}^{4} e^{jn(k_0 s\sin\theta - \delta_{HI})} \tag{4}$$

$$\delta_{LO,HI} = \delta\frac{f}{f_{LO,HI}} \tag{5}$$

$$A = e^{j\frac{3}{2}k_0(d-s)\sin\theta} \tag{6}$$

where

k_0	wave number in free space;
d and s	half-wavelengths in free space at frequencies f_{LO} and f_{HI}, respectively;
C_{LO} and C_{HI}	frequency responses of the low-band and the high-band of the diplexer, respectively;
δ	system progressive phase factor, a constant;
δ_{LO} and δ_{HI}	progressive phase factors of array with spacing d and s, respectively.

C_{LO} and C_{HI} are similar to the responses of bandpass filters with center frequencies at f_{LO} and f_{HI}, respectively. The array with spacing d works as frequency being around f_{LO} , and the array with spacing s works as frequency being around f_{HI} . By introducing the diplexers, the deformation of the main beam due to frequency sweep can be relieved.

III. Simulation and Measurement Results

A. Simulation Results

A 2.0 GHz to 6.0 GHz wideband antenna array with mainbeam pointing to 20 degrees is designed to validate the proposed concept. According to the equations in Section II, δ=61 degrees, f_c=3.46 GHz, f_{LO}=2.73 GHz and f_{HI}=4.73 GHz. The spacings d and s are 54.9 mm and 31.7 mm, respectively. The minimal spacing between two antenna elements is 11.6 mm, corresponding to $0.13\lambda_0$ at f_c. Assume that the mutual couplings between antenna elements can be neglected, the simulated array factors are plotted in Fig. 3, and the side lobe level against frequency and the 3dB beamwidth against frequency are shown in Fig. 4. It is seen that the main beam points to 20 degrees over 2.0 GHz to 6.0 GHz, the 3dB beamwidth is between 22^{o} and 38^{o}, and the side lobe level is larger than 10 dB from 2.0 GHz to 5.7 GHz.

B. Components Design

The substrate used is an RO4003 with

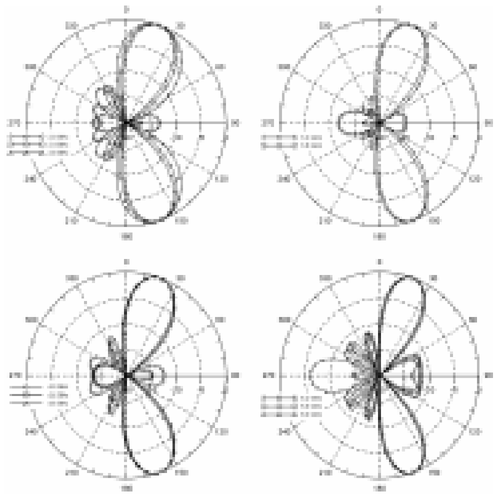

Fig.3. Simulated array factors of the proposed array system.

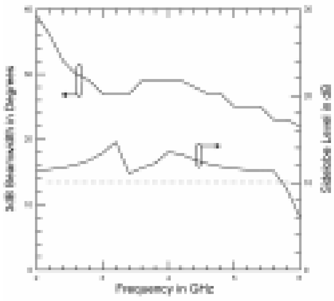

Fig.4. Side lobe level and 3dB beamwidth against frequency.

thickness 0.508 mm and relative dielectric constant 3.38. As discussed previously, the minimal spacing between two antennas is 11.6 mm. As a result, an antenna element with a width smaller than 11.6 mm is needed. However, the design of such a planar antenna with a bandwidth from 2.0 GHz to 6.0 GHz presents many difficulties. One of possible solutions is a loaded monopole antenna, offering a compact size and excellent pattern characteristics over a wide bandwidth. The resultant antenna element is shown in Fig. 5. The antenna gain between 2.0GHz to 6.0 GHz is 1.0dBi in average. Figure 6 presents the couplings between antenna elements, showing that the maximum coupling is -6 dB.

For the diplexer, we connect two broadband bandpass filters based on stub-line filters [3]-[7] together to form the desired diplexer; nevertheless, some unwanted interactions between the filters cause serious performance degradation. As a result, we develop a Matlab program based on *fmins* subroutine to optimize the designed parameters to meet the desired specifications. Figure 7 presents the layout and

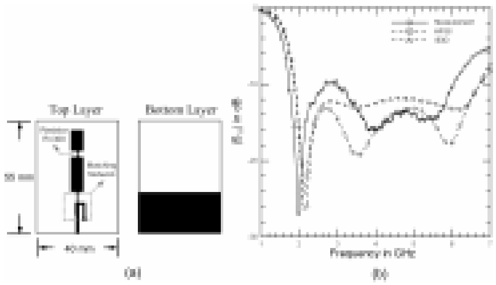

Fig.5. Antenna element. (a) Geometry. (b) Amplitude of S_{11}..

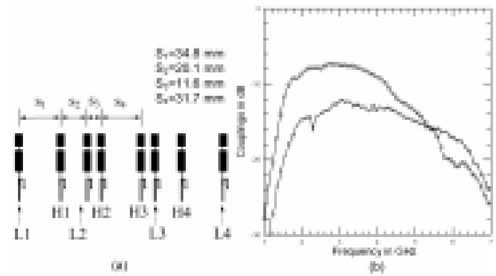

Fig.6. Couplings between antenna elements.

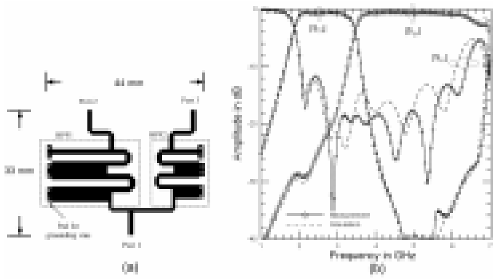

Fig.7. Frequency responses of the diplexer used in the array system.

scattering parameters of the designed diplexer. The losses at 2.0 GHz and 6.0 GHz are 0.3 dB and 0.8 dB, respectively. The measured cutoff frequency is at 3.45 GHz, which is almost identical to the simulated one. The measured and simulated phase differences at 3.45 GHz is 32 and 20.7 degrees, respectively. The discrepancy is contributed by the imperfection of the manually soldered SMA connectors at the output ports.

C. Feeding Network

The layout of the feeding network is shown in Fig. 8. Its size is 200 mm by 90mm. The 4-way power divider [8] and the four diplexers are connected together. The delay lines are used to make the outputs of the diplexers have the same phase at the cutoff frequency. The serpentine lines are designed to implement the phase shifters, making the differences between Ports L_i and L_{i+1} at 2.73 GHz and between Ports H_i and H_{i+1} at 4.73 GHz be 61 degrees, respectively. Figure 9 presents the measured reflection coefficients and the insertion losses at output ports of the feed network. Ideally, the

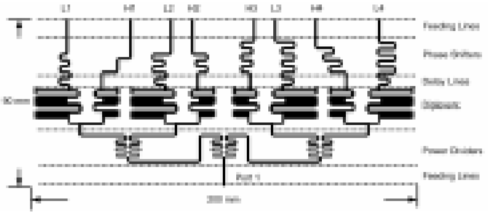

Fig.8. Layout of the feeding network.

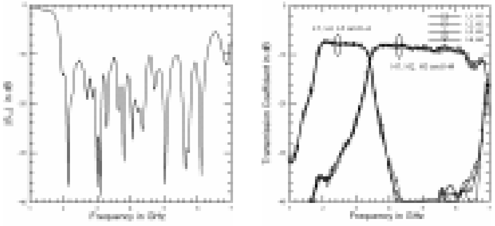

Fig.9. Measured reflection coefficient and the insertion losses at the output ports of the feeding network.

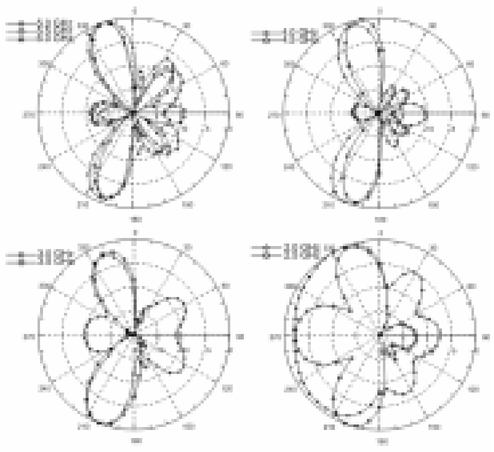

Fig.10. Measured radiation patterns of the designed antenna array.

insertion losses at the output ports are -6dB. The additional losses at 2.0 GHz and 6.0GHz are 0.5 dB and 1.5dB, respectively, which are contributed by the 4-Way power divider and diplexers.

Table I summaries the measured phases at the output ports and phase differences between output ports at frequencies 2.73 GHz, 3.45 GHz, and 4.73 GHz. The numbers in brackets represent the ideal value. At the column of 3.45 GHz, the ideal phase shift between Ports L_i and H_i can be determined by Eq. (7). It can be seen that the measured phase shifts agree well with the designed ones.

$$\Delta_{L_i,H_i} = i \cdot \delta \cdot \left(\frac{1}{f_{LO}} - \frac{1}{f_{HI}} \right) \qquad (7)$$

D. Antenna Array

Figure 10 shows the radiation patterns in the *xy*-plane at different frequencies. The radiation patterns below 3.0 GHz deform dramatically,

TABLE I. Measured phases at the output ports

	Phase (Degrees)					
Port	2.73GHz		4.73GHz		3.45 GHz	
L1	-112.3		-		65.9	3.1 (0)
H2	-	61.4 (61)	-58.1		62.8	
L2	-173.7		-	64.2 (61)	-12.1	26.7 (30.7)
H2	-	61.8 (61)	64.2		14.6	
H3	-		176.6	61.1 (61)	-26.2	66.2 (61.3)
L3	124.5		-	58.9 (61)	-92.4	
H4	-	64.3 (61)	117.7		-66.2	110.0 (92.0)
L4	60.2		-		-176.2	

suffering from mutual couplings between antenna elements.

V. Conclusions

A new wideband planar antenna array has been proposed in this paper. This antenna system associated with feeding network and antenna elements can be integrated in a single substrate. Consequently, such a design is with low fabrication and assembly cost and compact size. So far, the prototype of the array antenna has been completed. Suffering from the strong mutual coupling between antenna elements, the radiation patterns below 3 GHz deform dramatically. The overall system will be improved in the future.

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參加
2007 IEEE
天線與傳播學會
國際研討會
（2007 IEEE Antennas and Propagation Society International Symposium）
報告

鄭士康
台大電機系/電信研究所
中華民國九十六年八月廿三日

一、引言

此次獲國科會補助，參加 2007 年 IEEE 天線與傳播學會國際研討會(2007 IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting)，由敝人及博士班學生賴明佑各宣讀論文一篇，碩士班學生巫宗佑宣讀論文兩篇。此一研討會爲世界電磁研究人員一年一度，規模最大之盛會之一，重要論文常於此發表。

本屆會議於六月十一至十四日於美國夏威夷州檀香山市(Honolulu)舉行。敝人於六月十日星期日下午出發，搭乘華航直飛班機，同機尙有交大林育德教授、鍾世忠教授、台科大楊成發教授、中山大學郭志文教授、本系瞿大雄教授、林怡成教授等多人。因時差十八小時，同日早晨抵達，由先到之台科大馬自莊教授載林怡成與我到會場旅館 Sheraton Waikiki。Check in 後與林教授同住一房，下午報到，並演練口頭報告。十一日至十二日參加大會，因台灣尙有要務，故於十三日上午即搭機經東京返國，於十四日星期四下午返抵台北。

此次台灣各大學參加會議人數眾多，除教授外，亦有多位研究生，足見後生可畏。敝人認爲，台灣研究生較缺國際觀，政府應多鼓勵國內研究生參與國際研討會，培育下一代研發人才，此次多位研究生之參與，正是良好之典範。

二、會議經過

報到

六月十日會場報到後，領到資料袋及論文集光碟片。大會每人發放上有標誌之夏威夷衫一件作爲紀念品，惜尺碼略大。會議分十四個口頭發表場地，同時進行。進行四天，一共有 126 個口頭發表場次(Session)；另外前三天中午於午餐時間有壁報論文發表(稱爲互動論壇，Interactive Forum，以論文主題而非論文評審成績分配)，共 49 場次：口頭與壁報共計發表論文 1700 餘篇，參加人數預估在兩三千人之譜。與前幾年參加相同會議之經驗相較，場次減少，但論文篇數差不多，可能是場地分配的問題。

參加會議與發表論文

此次敝人與學生共發表四篇論文，主題分別爲場型可調式天線設計、時域混合計算格網誤差分析、多層印刷電路板 RFID 天線設計、波束方向可切換之智慧型天線設計等，聽眾反應均甚良好。尤其多層印刷電路板 RFID 天線設計論文發表後，聽衆討論特別熱烈；主因是之前的 RFID 天線文獻均未深入考慮應用於印

刷電路板的情形，而我們的研究顯示一般 RFID 天線用於印刷電路板會發生短路，無法運作；我們在電路板上的狹縫天線設計，則可解決此一問題，效能甚佳。

在所聽的論文發表方面，由於個人對時域數值方法的理論特別有興趣，因此印象較深刻的論文主題大多屬之。以下簡單介紹幾篇：

1. 韓國Piljun Park 等人的3D次網格FDTD技術，可以使粗細網格大小間的比例為任意奇數，並完成比例為17的天線分析，相當特別，但缺乏誤差及穩定性的理論分析。
2. 法國J. Gazave等人也提出3D次網格FDTD技術，粗細網格大小間的比例為任意整數，並完成比例為12的自由空間傳播計算，同樣也缺少誤差及穩定性的理論分析。
3. 美國OSU的Ryan A, Chilton與Robert Lee研發出具有穩定性與守恆性的3D FDTD次網格架構，應用較抽象的數學觀念討論，決定各次網格內插權重。粗細網格大小間的比例也可以為任意整數，並以導波管的不連續問題驗證其理論，但未完成誤差之理論分析，僅以實例計算說明其粗細網格交界之反射甚低。兩位作者並且稱合宜的次網格FDTD技術為許多研究者尋找的「聖杯」，其困難與重要性可見一斑。
4. 英國Costa等人利用Huygence次網格FDTD技術，加上Debye模型，可處理UWB超寬頻訊號通過頻率相關媒質的問題。
5. 法國Pascaud等人針對MIMO天線，發展雙網格FDTD技術，以較細網格計算天線單元之近場，再以之為等效入射場，用正常大小網格計算其輻射場。
6. 巴西de Sousa等人運用TLM技術，將電磁問題區域分成小塊，以電路元件表示，並與SPICE結合，可分析不少問題。
7. 新竹交大陳富強教授指導學生發展出應用於ADI-FDTD的PML結構，並有理論分析，為可用於高Courant數之ADI-FDTD方法拓展應用範圍。

三、整體印象及心得

今年再度參與此一 IEEE 天線與傳播學會國際研討會，除了發現生面孔很多之外，熟識友人又有數人獲選為 IEEE Fellow，足見台諺「戲棚下站久就是你的」之真確。此外，平行場次之多，使聽眾常有分身乏術之嘆。壁報論文可使論文作者與有興趣之觀眾互動增加，不失為一種良好的發表方式。另外，因過去英文口頭報告訓練不夠，國際會議報告常不能令人滿意。去年遂以十餘小時反覆修改背誦全部講稿，效果甚佳。今年同樣花費甚多時間背誦，自覺表現與去年差不多，均較以往進步；且因 Session 較晚開始，遭主持人要求提前三分鐘結束，而仍能臨時彈性調整內容，順利完成演講，皆是熟背講稿之功。此一心得或許可供國內

研究生參加國際會議時參考。

在探討主題方面，翻開議程手冊，即可發現天線與無線通訊技術場次增加許多，反應無線通信熱潮。數值電磁計算場次仍多，大多可歸類於時域有限差分法及有限元素法，頻域快速多極演算法偶而可見，所解之問題也已多爲實際三維問題，進步不可謂不大，然而基本方法上的創新則極爲少見，一般均在計算之過程修改，或充分利用快速之電腦設備，以便提高計算效率。天線方面之論文逐漸以應用爲導向，如 UWB 天線設計、MIMO 天線設計、RFID 天線設計等均是；另一趨勢則是天線設計中無線通訊理論及通訊規約標準的引用漸多，研究天線的學者最好也能涉獵相關書籍；也有新材料如 Metamaterial 及非線性元件的導入等，形成新的研究主流。若干新主題，如奈米電磁學也開始出現，由於奈米科技漸受重視，而其電磁現象研討爲其理論基礎，相關研究未來可能會有很好的發展，值得注意。

四、結語

感謝國科會於計劃中補助敝人參與此一會議，一方面得以發表一己及指導學生之研究所得，一方面亦得以了解世界電磁研究之最新情況。明年此一會議將在美國加州聖地牙哥市(San Diego)舉行，預料盛況當不遜今年，希望能再有機會參加。

參加
2007 IEEE
天線與傳播學會
國際研討會
（2007 IEEE Antennas and Propagation Society International Symposium）
報告

鄭士康
台大電機系/電信研究所
中華民國九十六年八月廿三日

一、引言

此次獲國科會補助，參加 2007 年 IEEE 天線與傳播學會國際研討會(2007 IEEE AP-S International Symposium and USNC/URSI National Radio Science Meeting)，由敝人及博士班學生賴明佑各宣讀論文一篇，碩士班學生巫宗佑宣讀論文兩篇。此一研討會為世界電磁研究人員一年一度，規模最大之盛會之一，重要論文常於此發表。

本屆會議於六月十一至十四日於美國夏威夷州檀香山市(Honolulu)舉行。敝人於六月十日星期日下午出發，搭乘華航直飛班機，同機尚有交大林育德教授、鍾世忠教授、台科大楊成發教授、中山大學郭志文教授、本系瞿大雄教授、林怡成教授等多人。因時差十八小時，同日早晨抵達，由先到之台科大馬自莊教授載林怡成與我到會場旅館 Sheraton Waikiki。Check in 後與林教授同住一房，下午報到，並演練口頭報告。十一日至十二日參加大會，因台灣尚有要務，故於十三日上午即搭機經東京返國，於十四日星期四下午返抵台北。

此次台灣各大學參加會議人數眾多，除教授外，亦有多位研究生，足見後生可畏。敝人認為，台灣研究生較缺國際觀，政府應多鼓勵國內研究生參與國際研討會，培育下一代研發人才，此次多位研究生之參與，正是良好之典範。

二、會議經過

報到

六月十日會場報到後，領到資料袋及論文集光碟片。大會每人發放上有標誌之夏威夷衫一件作為紀念品，惜尺碼略大。會議分十四個口頭發表場地，同時進行。進行四天，一共有 126 個口頭發表場次(Session)；另外前三天中午於午餐時間有壁報論文發表(稱為互動論壇，Interactive Forum，以論文主題而非論文評審成績分配)，共 49 場次：口頭與壁報共計發表論文 1700 餘篇，參加人數預估在兩三千人之譜。與前幾年參加相同會議之經驗相較，場次減少，但論文篇數差不多，可能是場地分配的問題。

參加會議與發表論文

此次敝人與學生共發表四篇論文，主題分別為場型可調式天線設計、時域混合計算格網誤差分析、多層印刷電路板 RFID 天線設計、波束方向可切換之智慧型天線設計等，聽眾反應均甚良好。尤其多層印刷電路板 RFID 天線設計論文發表後，聽衆討論特別熱烈；主因是之前的 RFID 天線文獻均未深入考慮應用於印

刷電路板的情形，而我們的研究顯示一般 RFID 天線用於印刷電路板會發生短路，無法運作；我們在電路板上的狹縫天線設計，則可解決此一問題，效能甚佳。

在所聽的論文發表方面，由於個人對時域數值方法的理論特別有興趣，因此印象較深刻的論文主題大多屬之。以下簡單介紹幾篇：

1. 韓國Piljun Park 等人的3D次網格FDTD技術，可以使粗細網格大小間的比例爲任意奇數，並完成比例爲17的天線分析，相當特別，但缺乏誤差及穩定性的理論分析。
2. 法國J. Gazave等人也提出3D次網格FDTD技術，粗細網格大小間的比例爲任意整數，並完成比例爲12的自由空間傳播計算，同樣也缺少誤差及穩定性的理論分析。
3. 美國OSU的Ryan A, Chilton與Robert Lee研發出具有穩定性與守恆性的3D FDTD次網格架構，應用較抽象的數學觀念討論，決定各次網格內插權重。粗細網格大小間的比例也可以爲任意整數，並以導波管的不連續問題驗證其理論，但未完成誤差之理論分析，僅以實例計算說明其粗細網格交界之反射甚低。兩位作者並且稱合宜的次網格FDTD技術爲許多研究者尋找的「聖杯」，其困難與重要性可見一斑。
4. 英國Costa等人利用Huygence次網格FDTD技術，加上Debye模型，可處理UWB超寬頻訊號通過頻率相關媒質的問題。
5. 法國Pascaud等人針對MIMO天線，發展雙網格FDTD技術，以較細網格計算天線單元之近場，再以之爲等效入射場，用正常大小網格計算其輻射場。
6. 巴西de Sousa等人運用TLM技術，將電磁問題區域分成小塊，以電路元件表示，並與SPICE結合，可分析不少問題。
7. 新竹交大陳富強教授指導學生發展出應用於ADI-FDTD的PML結構，並有理論分析，爲可用於高Courant數之ADI-FDTD方法拓展應用範圍。

三、整體印象及心得

今年再度參與此一 IEEE 天線與傳播學會國際研討會，除了發現生面孔很多之外，熟識友人又有數人獲選爲 IEEE Fellow，足見台諺「戲棚下站久就是你的」之真確。此外，平行場次之多，使聽眾常有分身乏術之嘆。壁報論文可使論文作者與有興趣之觀眾互動增加，不失爲一種良好的發表方式。另外，因過去英文口頭報告訓練不夠，國際會議報告常不能令人滿意。去年遂以十餘小時反覆修改背誦全部講稿，效果甚佳。今年同樣花費甚多時間背誦，自覺表現與去年差不多，均較以往進步；且因 Session 較晚開始，遭主持人要求提前三分鐘結束，而仍能臨時彈性調整內容，順利完成演講，皆是熟背講稿之功。此一心得或許可供國內

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