出國報告（出國類別：出席國際研討會發表論文）

出席「2009 國際電機電子工程師學會天線科技研討會」會議報告

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出國時間：98 年 02 月 27 日至 03 月 07 日

摘　要

本次會議為 2009 年國際電機電子工程師學會天線科技研討會，由國際電機電子工程師學會(IEEE－Institute of Electrical and Electronics Engineers)主辦，美國加州大學洛杉磯分校(UCLA－University of California, Los Angeles)協辦。本次會議發表的論文超過 150 篇，參加的各國學者家約 350 人。會議合計分三天進行，在 03 月 02 日至 04 日假美國加州洛杉磯郡聖塔莫妮卡市(Santa Monica, CA) 之 Doubletree Guest Suites 飯店舉辦；會議主題為小型天線及超穎材質，計有八大子題分別進行相關領域探討。

本人此次為國科會航太學門研究計畫 NSC 97-2221-E-606-009 補助出席國際會議，所展示的研究內容及成果為提出一種將矩形微帶天線包埋入複合層板之天線模組，除對於其電磁模式進行探討，亦針對電磁波在異向性複合層板內傳播特性進行分析。會議期間除參與相關子題之會議研討外，亦與領域相關學者進行交流。

目　次

一、目的

本人此次出國爲國科會航太學門研究計畫 NSC 97-2221-E-606-009 補助出席國際會議，所展示的研究內容及成果爲提出一種將矩形微帶天線包埋入複合層板之天線模組，除對於其電磁模式進行探討，亦針對電磁波在異向性複合層板內傳播特性進行分析。會議期間不僅參與相關子題之會議研討外，除進一步了解目前國際上對於小型天線研究現況與未來發展方向，亦與領域相關學者進行交流。希望藉由實際交流，進而建立合作契機，藉以增進研究績效。

二、過程

本次會議爲 2009 年國際電機電子工程師學會天線科技研討會 (2009 IEEE International Workshop on Antenna Technology)，國際電機電子工程師學會天線科技研討會係由國際電機電子工程師學會 (IEEE－Institute of Electrical and Electronics Engineers)主辦，爲國際間小型天線研究學者的年度盛事，近年來持續在新加坡、英國及日本等地先後舉辦。本年度國際電機電子工程師學會天線科技研討會係由美國加州大學洛杉磯分校 (UCLA－University of California, Los Angeles)協助主辦，在 03 月 02 日至 04 日假美國加州洛杉磯郡聖塔莫妮卡市 (Santa Monica, CA) 之 Doubletree Guest Suites 飯店舉辦。本次會議合計分三天進行，會議主題爲小型天線及超穎材質，會議發表的論文超過 150 篇，參加的各國學者家約 350 人，計有八大子題分別進行相關領域探討。

大會在 03 月 02 日早上 08 時 30 分開幕，隨即由大會主席－美國加州大學洛杉磯分校電機系教授 Y. E. Wang 介紹第一子題 **Advancement in Portable Device Antennas** 的專題講座講員 B. K. Lau 教授；前述講員爲來自瑞典的學者，講座主題爲 “Unleashing Multiple Antenna Systems in Compact Terminal Devices”，主要在探討多重天線系統在終端之應用及其電磁相互耦合現象。在講座講員的精闢解說之後，本子題隨後進行了 Y. Rahmat-Samii 等人的論文發表，其發表論文主題與大會子題相符，除探討如同 PIFA 等不同外形之小型天線研究外，亦針對目前熱烈討論之第四代通訊系統 WiMAX 提出看法，使個人對於無線傳輸系統有了更進一步了解。第一子題結束後，緊接著進行第二子題 **mmWave, THz and Nano Antennas** 的研討；該子題發表論文主要在探討高頻毫米波電磁傳播應用所需天線相關研究，雖然個人對於此一領域所知較少，但仍由與會學者熱烈討論中得知進一步研究概念，從演講內容之中實在獲益良多。

大會第一天 03 月 02 日下午首先登場是 Poster Session 1 的論文海報現場展示及發表解說，本人此次論文發表主題爲「Design and Analysis of Rectangular Microstrip Patches Embedded in Electromagnetically Anisotropic Composite Laminates」，其海報展示編號爲 PS115。個人論文研究之主要內容係爲提出一種將微帶天線包埋入複合層板之創新天線模組，除對於其電磁模式進行探討外，亦針對電磁波在異向性複合層板內傳播特性進行分析。由於複合層板係由不同角度之各疊層堆疊而成，使得整體複合層板成爲電磁異向性。本研究係利用赫茲向量位能 (Hertzian vector potentials)推導出頻域之電磁波方程式，進而得到天線之阻導矩陣 (immittance matrix)。再藉由巴塞維定理 (Parseval’s theorem)及伽遼金法 (Galerkin’s method)對於不同角度疊層以及複合層板在頻域之阻導函數 (immittance function)進行運算，可以得到在給定操作頻率下之天線設計，藉以對於電磁波在異向性複合層板內傳播特性進行分析，並計算出微帶天線輻射所造成之電磁場型。前述複合層板對於不同疊層角度、異向比與堆疊方式造成之電磁特性大相殊異，而疊層角度與堆疊方式同樣會造成複合層板機械特性不同。複合層板相對於電磁特性與機械特性之基本方程式極爲相似，亦即複合層板在頻域之電磁特性與複合層板在空間域之機械特性二者之間確有其相似性存在。

此一發表論文係利用赫茲向量位能、阻導矩陣、伽遼金法及巴塞維定理，在頻域提出一種微帶天線包埋在複合層板內之電磁分析模式。在配合表面電流密度單一模態展開下，本研究提出一組簡易之矩形微帶天線設計規則，可以輕易得到包埋在複合層板內之矩形微帶天線設計，並且進一步可以計算出包埋於複合層板內微帶天線輻射所造成之遠場場型。分析結果顯示，具有不同堆疊方式使得複合層板之特性和單軸性基板之特性大爲不同，而此一分析結果目前僅能由本研究提出之電磁模式分析而得。本研究藉由分析結果進一步驗證，前述包埋於複合層板內之微帶天線模組在航太通訊應用上確有其實用價值。

這一天大會在 Poster Session 1 之後隨即進行第三子題 **Application of Metamaterial** 的研討，該子題由美國賓州州立大學 (Pennsylvania State University) 的 Raj Mittra 教授擔任專題講座講員，主要在介紹使用 EBG 等介質層增加微帶天線在電磁波傳播之指向性功效；而其他如 A. Alu 等人發表之論文係在介紹一些介電係數極小之超穎材質作爲印刷天線使用介質之相關研究。

大會第二天 03 月 03 日主要在進行第四子題 **MIMO and Beamforming Antennas**、第五子題 **Measurement Issues of Small Antennas** 及第六子題 **Wearable, Implantable and Ingestible Antenna** 的相關研究論文發表；今天大會邀請專題講座講員爲美國楊百瀚大學

(Brigham Young University)的 Karl F. Warnick 教授及美國猶他州大學 (University of Utah)的 Cynthia M. Furse 教授擔任，分別在介紹新一代的陣列化天線設計及其特性，還有天線在生化醫療科技所需訊號傳送方面之相關研究。此外亦有 J. R. De Luis 等人之論文發表，其中 Y. Rahmat-Samii 提出之微小膠囊型天線概念著實令人驚豔；其利用微製程技術將天線及發射元件整合在不到 3 cm 膠囊內，在吞服後可以取代內視鏡將人體腸道內部情況藉由 RF 訊號以 1.4 GHz 頻率傳送至接收端，此技術一旦成熟將可降低健康檢查內視鏡穿過消化道的痛苦，電影或卡通所描述之「迷你縮小軍」在人體內悠遊檢查之夢想也可望逐步實現。同樣在這一天下午研討子題開始之前進行 Poster Session 2 的論文海報現場展示及發表解說，期間個人亦在聆聽論文發表空檔前往參觀並與在場學者交換意見。

大會最後一天 03 月 04 日主要在進行第七子題 **UWB Antennas** 及第八子題 **Performance Enhancement of Small Antennas** 的相關研究發表，並同步在會場進行 Poster Session 3 的論文海報現場展示及發表解說。這一天大會邀請的專題講座講員爲來自新加坡的 Zhi Ning Chen 教授以及美國亞歷桑那大學 (University of Arizona)的 Richard W. Ziolkowski 教授，二人分別就超寬頻天線之應用、超穎材質應用在小型天線及其性能提升等方面提供相關看法，對於個人將來若有興趣在此一方面進行研究有不少助益。這一天亦有 Ning Guan 等世界各國學者陸續發表對於小型天線在各應用領域及諸如增加頻寬等性能提升等方面之精闢見解，對於個人天線專業亦有所增強。個人亦同樣在聆聽論文發表空檔前往參觀論文海報現場展示區，並與在場學者交換意見，大會最後在 03 月 04 日下午 5 點結束所有論文發表並舉行閉幕儀式，並預定明年在葡萄牙里斯本 (Lisbon, Portugal)持續舉辦 2010 年國際電機電子工程師學會天線科技研討會(2010 IEEE International Workshop on Antenna Technology)。個人在研討會結束後，即返回住宿飯店略事休息，旋於隔天 03 月 05 日整理行囊並束裝返台。

圖 1　2009 年 03 月 02 日報到並在大會場地 Doubletree Guest Suites 飯店前留影

圖 2　2009 年 03 月 02 日報到註冊情形

圖 3　2009 年 03 月 02 日論文發表準備情形

圖 4　2009 年 03 月 02 日與會學者至本人海報區討論情形（一)

圖 5　2009 年 03 月 02 日與會學者至本人海報區討論情形（二)

圖 6　2009 年 03 月 03 日本人參觀海報展示區留影

圖 7　2009 年 03 月 03 日與會學者熱列討論情形

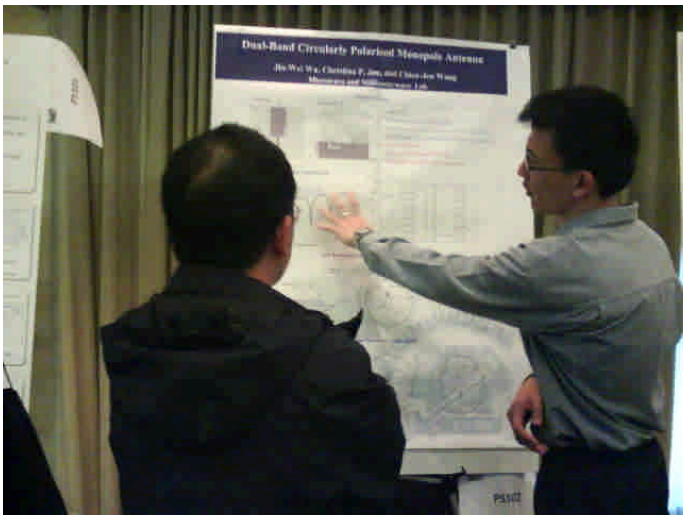


圖 8　2009 年 03 月 04 日本人參觀海報展示區並與發表學者討論情形

三、心得

本研討會之目的主要爲探討小型天線及超穎材質等相關議題，然而天線及電磁波傳播所屬範圍非常廣泛，不是一己之力可以獨立思索；所以參與本次會議可以接觸到各種不同領域之問題，並與各國專家學者討論問題之解析方法及經驗，不僅使個人在參與當中增廣見聞，對於問題的分析亦更加嚴謹。此次與會從事相關研究人士均將其最新研究成果公開，並且各有其獨到見解；故參與此次會議可獲得目前最新的知識，使個人深覺獲益良多。經由本次的論文發表，使個人對未來研究更具信心；日後研究仍將一秉積極態度，期望能對相關領域研究的提升有所助益。在經歷國際學術會議洗禮後，個人專業能力得以成長；相信日後除了在微帶天線設計方面可以精進外，希望也可以整合個人原有飛行載具外形設計之航空專長，發

展無人飛行載具(UAV, Unmanned Aerial Vehicle)偵蒐訊號無線傳輸模組，進而達成無人飛行載具系統整合目標。

此外，本次參與研討會亦親身體會到美國在科技方面的實力與進步，不論研究人才及研究經費都是令人稱羨；不過在這一波經濟不景氣的影響下，此次來到美國較之以往抵美的感受有著大大的不同。此次來到美國，不論走在美國街道或是駕車在公路上行駛，可以明顯感受到這一波不景氣已重重挫傷美國的經濟實力，一些交通繁忙以及往來貨物運送現象已不若以往，尤其是以洛杉磯國際機場給予感受最爲強烈。洛杉磯機場內整修待建的 25 年高齡國際航廈 Tom Bradley International Terminal，加上國際空港內貨櫃及貨機寥寥可數，整體航空貨運似已停擺，個人身爲航空界一員亦不禁聊添一絲感傷。

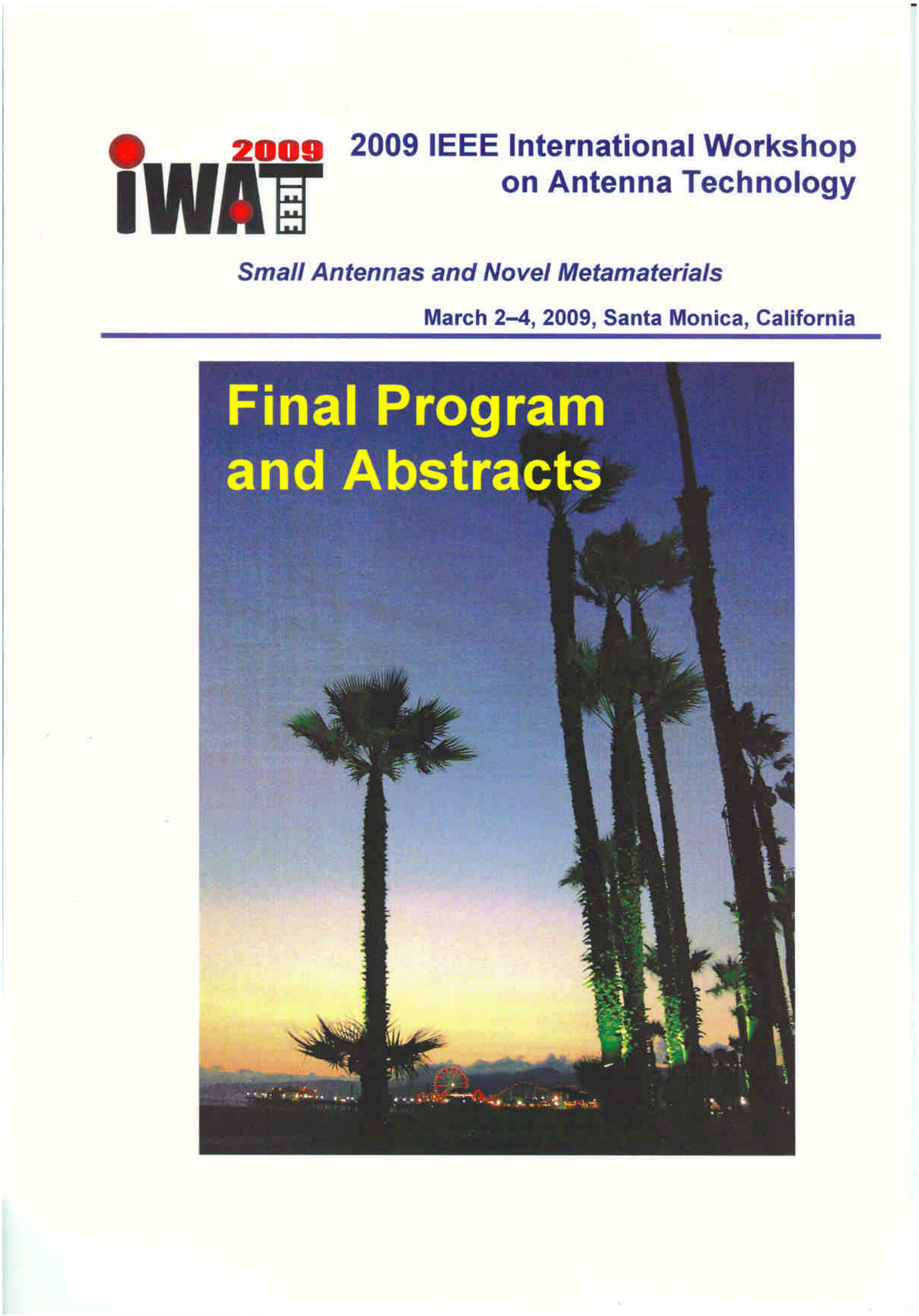
四、建議事項

在參與此次會議後，發現先進各國對於參與此類學術活動相當熱烈，在在顯示參與各種國際會議或是相關學術交流活動，可以提升科技相關研究及產業發展。因此，個人覺得國際交流是促進科技發展及學術成長的最佳途徑，國科會或相關機構應該提供足夠的經費推動國際學術活動，並且多鼓勵國內學者或研究人員踴躍參與國際會議。

五、攜回資料名稱及內容

1. 2009 IEEE International Workshop on Antenna Technology 議事手冊 × 1

— Final Program and Abstract



2009 IEEE International Workshop on Antenna Technology

Small Antennas and Novel Metamaterials

March 2–4, 2009, Santa Monica, California

Final Program and Abstracts

2. 2009 IEEE International Workshop on Antenna Technology 會議論文集光碟 × 1

附錄：「包埋於電磁異向性複合層板之矩形微帶天線設計及分析」論文內容（如後附）

－ Design and Analysis of Rectangular Microstrip Patches Embedded in Electromagnetically Anisotropic Composite Laminates

Design and Analysis of Rectangular Microstrip Patches Embedded in Electromagnetically Anisotropic Composite Laminates

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ABSTRACT: This paper proposes an innovative antenna module where the microstrip antennas are embedded in composite laminates. The electromagnetic fields of the anisotropic medium by using Hertzian potentials will be derived to form the bases to develop the electromagnetic model of anisotropic composite laminates and the dimensions of radiators at desired operating frequency are solved by the spectral domain immittance functions with Parseval's theorem and Galerkin's method. Analyses show that ply angle, anisotropy ratio and stacking sequence are critical to performance and the composite laminates embedded with microstrip antennas will be a good candidate in aerospace communication applications.

INTRODUCTION

This paper presents an innovative idea of smart antenna module where the microstrip antennas are embedded into composite laminate structure. The concept of smart antenna module is inspired by the smart structures with built-in sensor/actuator [1]. The fabrication technique of embedding piezoelectric material in glass fiber and carbon/graphite laminated layers is successfully developed and a design concept of smart layer module by using flexible printed circuit is recently developed [2].

Most of the previous work on microstrip antennas has been largely confined to antennas on isotropic substrates. Many of the materials used in microstrip structures have been treated as isotropic; they, for example, sapphire, alumina, and even fiber-reinforced laminated composites, are anisotropic [3-4]. Recent interests have been in analyzing microstrip antennas on uniaxial substrates [5-9]. However, the studies were limited to the case of the optical axis normal to the microstrip patch. In practice, a microstrip antenna whose optical axis of its substrate may not coincide with any of the principal axes, the permittivity matrix of an anisotropic composite laminate is a full matrix with distinct dielectric constants and the solution technique will be necessary to analyze the performance of a microstrip antenna embedded in anisotropic composite laminates.

ELECTROMAGNETIC MODEL

The composite laminates consist of multiple laminae, or plies, oriented in desired directions and bonded together, and each fiber-reinforced lamina has dielectric constant ε_1 along the fiber orientation of ply and ε_2 along the other two axes normal to the ply. The geometry of a microstrip antenna on lamina is shown as Fig. 1, with the optical axis along the fiber orientation, and its permittivity matrix in principal axes is

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_2 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_1 \end{bmatrix}. \tag{1}$$

The permittivity matrix will no longer be diagonal and leading to coupling terms as the fiber orientation, θ_j, changes. The electromagnetic wave propagation can be solved by the electric and magnetic Hertzian potentials

$$\boldsymbol{\Pi}_{\boldsymbol{e}_j} = \Pi_{e_j}\hat{a}_\xi = \Pi_{e_j}(\cos\theta_j\ \hat{a}_z + \sin\theta_j\ \hat{a}_x)\,, \tag{2}$$

and

$$\boldsymbol{\Pi}_{\boldsymbol{h}_j} = \Pi_{h_j}\hat{a}_\xi = \Pi_{h_j}(\cos\theta_j\ \hat{a}_z + \sin\theta_j\ \hat{a}_x)\,, \tag{3}$$

where *j* is subscript of the *j*-th ply, and $\hat{a}_\xi$ are the unit vectors along the optical axis ξ (e.g. the optical axis ξ is the principal 1-axis for this anisotropic fiber-reinforced lamina in Fig. 1). For a microstrip antenna embedded into a composite laminate of *N* plies as shown in Fig. 2, the associated electric and magnetic fields of each lamina in terms of Hertzian potentials are

$$\boldsymbol{E}_j = \omega^2\mu_0\varepsilon_0\boldsymbol{\Pi}_{\boldsymbol{e}_j} + \frac{\varepsilon_0}{\varepsilon_2}\nabla\left(\nabla\cdot\boldsymbol{\Pi}_{\boldsymbol{e}_j}\right) - j\omega\mu_0\nabla\times\boldsymbol{\Pi}_{\boldsymbol{h}_j}\,, \tag{4}$$

$$\boldsymbol{H}_j = j\omega\varepsilon_0\nabla\times\boldsymbol{\Pi}_{\boldsymbol{e}_j} + \nabla\times\nabla\times\boldsymbol{\Pi}_{\boldsymbol{h}_j}\,. \tag{5}$$

where ω is the operating frequency in radian, ε_0 is the permittivity of free-space, and μ_0 is the permeability of free-space. The electric and magnetic fields can be found from the above equations in space domain. However, the derivation of electric and magnetic fields and Hertzian potentials in space domain will be more complicated by ways of Green's function representations and differential-integral expression for anisotropic substrates [10]. It should be noted that the relationship between the tangential components of the electric fields and the unknown current sources could be expressed in terms of a simple impedance matrix expression in spectral domain. Equations (4) and (5) can be derived by solving the homogeneous wave equations in terms of Fourier transform of electric and magnetic Hertzian potentials, and the tangential electric fields on the top surface can be represented as

$$\begin{Bmatrix}\tilde{E}_x\\ \tilde{E}_z\end{Bmatrix}_{N-ply} = \begin{bmatrix}\tilde{Z}_{xx} & \tilde{Z}_{xz}\\ \tilde{Z}_{zx} & \tilde{Z}_{zz}\end{bmatrix}_{N-ply}\cdot\begin{Bmatrix}\tilde{J}_x\\ \tilde{J}_z\end{Bmatrix}_{N-ply}\,, \tag{6}$$

where $\tilde{J}_z$ and $\tilde{J}_x$ are the Fourier transforms of the current densities on microstrip antenna, and $\tilde{Z}_{ij,N-ply}$ are the so-called immittance functions in spectral domain [6-7].

DESIGN OF RECTANGULAR MICROSTRIP PATCH

The immittance functions in spectral domain can be derived from Hertzian potentials and boundary conditions at the interfaces. The unknown spectral current components, $\tilde{J}_z$ and $\tilde{J}_x$, can be expanded in terms of linear combinations of known basis functions [5-6],

$$\tilde{J}_z(k_z,k_x) = \sum_{n=1}^{N} d_n\tilde{J}_{zn}(k_z,k_x)\,, \tag{7}$$

$$\tilde{J}_x(k_z,k_x) = \sum_{m=1}^{M} c_m\tilde{J}_{xm}(k_z,k_x)\,. \tag{8}$$

$\tilde{J}_{xm}$ and $\tilde{J}_{zn}$ are the Fourier transforms of J_{xm} and J_{zn} which are nonzero only on the antenna, and the numbers of modes are *M* and *N*, respectively. As the immittance functions being derived from Hertzian potentials in spectral domain, $\tilde{J}_z$ and $\tilde{J}_x$ can be expanded in terms of the linear combinations of known basis functions to solve the problem that microstrip antennas embedded in composite laminates. By substituting (7) and (8) into (6) and applying Galerkin's method and Parserval's theorem, the corresponding homogeneous matrix form is given as

$$\begin{bmatrix}K_{pm}^{xx} & K_{pn}^{xz}\\ K_{qm}^{zx} & K_{qn}^{zz}\end{bmatrix}_{N-ply}\cdot\begin{Bmatrix}c_m\\ d_n\end{Bmatrix}_{N-ply} = 0\,, \tag{9}$$

where the typical matrix element is given by

$$K_{qm}^{zx} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{J}_{zq}\tilde{Z}_{zx}\tilde{J}_{xm}dk_z dk_x,\ q = 1,2,...,N\,. \tag{10}$$

The nontrivial solution will determine the suitable dimension of rectangular microstrip patch embedded in the anisotropic laminate at a given operating frequency. Consider rectangular microstrip antenna of dimensions $L\times W$, the basis functions in space domain are selected as [8]

$$J_{zn} = \sin\left[p\pi(z+L/2)/L\right]\cdot\cos\left[q\pi(x+W/2)/W\right], \tag{11}$$

$$J_{xm} = \sin\left[r\pi(x+W/2)/W\right]\cdot\cos\left[s\pi(z+L/2)/L\right], \tag{12}$$

where *p*, *q*, *r,* and *s* are the integers of the mode numbers and the origin of coordinates is located on the centroid of the rectangular patch.

The dimension of a rectangular microstrip patch can be determined if the basis functions of surface current densities are selected. As a check on the convergence of the basis functions, a patch embedded in the composite laminate with different anisotropy ratios is evaluated and the anisotropy ratio is defined as

$$\eta_2/\eta_1 = \sqrt{\varepsilon_2/\varepsilon_1} = \sqrt{\varepsilon_{r2}/\varepsilon_{r1}}\,, \tag{13}$$

where ε_{r1} is the relative permittivity along the optical axis, and ε_{r2} is the relative permittivity in the directions perpendicular to the optical axis. Consider one basis function expansion ($M = N = 1$), the design rule will be obtained only by substituting the one-mode expansion into (9) and setting the determinant to be zero; that is,

$$\left[\tilde{Z}_{xx}(0,\pi/W)+\tilde{Z}_{xx}(0,-\pi/W)\right]\cdot\left[\tilde{Z}_{zz}(\pi/L,0)+\tilde{Z}_{zz}(-\pi/L,0)\right]=0\ . \tag{14}$$

The far field radiation pattern of microstrip patches can be calculated and transformed into polar coordinates by using the inverse Fourier transform and the rectangular-spherical transformation.

ANALYSIS OF ELECTROMAGNETIC WAVE PROPAGATION

The design of microstrip antennas embedded in composite laminates are determined by using the vector Hertzian potentials, Galerkin's method, Parseval's theorem in spectral domain. However, the effects of the overlay and the sequence of stacking play an important role in the electromagnetic properties of microstrip antennas embedded in composite laminates. Tab. 1 shows some design examples of rectangular microstrip patch embedded in 6-ply composite laminate of distinct stacking sequence (the thickness of each ply is 5 mm): symmetric balanced, symmetric cross-ply, antisymmetric angle-ply, and asymmetric balanced laminates and the corresponding length and width ratios with respect to those of microstrip patch on isotropic substrates are also illustrated (the subscript *iso* denotes the design on isotropic substrate). The dimensions of microstrip patches will no longer be square in composite laminates; however, microstrip antenna embedded in laminae of ply angles $\pm 45^\circ$ will remain in square in spite of the anisotropy ratio. Microstrip patches will not be square when embedded in composite laminates, even if in symmetric stacking.

Fig. 3(a) is the far field patterns of microstrip patches embedded in 6-ply [45/-45/45/45/-45/45] laminates. The patterns have more radiation intensity in specific directions, i.e., they have good directivity in specific direction due to the effect of ply angles $\pm 45^\circ$ laminae. Fig. 3(b) shows another patch design in substrates of different stacking sequences. The far field pattern of asymmetric [30/45/60/-30/-45/-60] laminate as $\eta_2/\eta_1 = 0.50$ in Fig. 3(b) has more apparent ripples on its boundary and it is higher than that on isotropic substrate. Despite its asymmetry, this pattern performs well than that on isotropic substrate in all direction. Analytic results also show that without suitable design, the microstrip antennas embedded in composite laminate will have poor far field patterns.

CONCLUSIONS

An innovative electromagnetic model of anisotropic composite laminates embedded with antennas has been established, and this model provides a simple and efficient way to design and evaluate microstrip antennas in composite laminates. The performance of microstrip antennas embedded in composite laminates is much different from those on isotropic, uniaxial or fiber-reinforced laminae, and the changes in ply angles, anisotropy ratios and stacking sequence result in different electromagnetic characteristics. The difference between the mechanical properties in symmetric and asymmetric laminates will not be "transferable" to their electromagnetic properties. Without the electromagnetic model developed in this paper, such analyses would be much more difficult up to the present. Furthermore, (6) and (9) give the similar matrix forms as those of composite mechanics [11]. The similarities are listed in Tab. 2 and it is interesting that electromagnetic wave propagation in spectral domain gives the similar matrix forms as mechanical wave in space domain.

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Tab. 1 Length and width ratios of rectangular microstrip patches in composite laminates

Stacking sequence	η_2/η_1	L/L_{iso}	W/W_{iso}
symmetric balanced [45/-45/45/45/-45/45]	0.75	1.219	1.219
	0.50	1.075	1.075
symmetric cross-ply [90/90/0/0/90/90]	0.75	1.141	1.114
	0.50	1.090	1.053
antisymmetric angle-ply [45/-45/-45/45/45/-45]	0.75	1.125	1.125
	0.50	1.063	1.063
asymmetric balanced [30/45/60/-30/-45/-60]	0.75	1.251	1.106
	0.50	1.100	1.092

Tab. 2 Analogy of mechanical and electromagnetic quantities in composite laminates

Mechanical System		Electromagnetic System	
Stress of lamina	σ_i	Electric field of lamina	$\tilde{E}_i$
Strain of lamina	ε_j	Current density of lamina	$\tilde{J}_i$
Transformed lamina stiffness matrix	$\overline{Q}_{ii}$	Immittance function of lamina	$\tilde{Z}_{ii}$
Force per unit length	N_i	Electric field of laminate	$\tilde{E}_{i,N-ply}$
Strain on middle surface	ε_i^0	Current density of laminate	$\tilde{J}_{i,N-ply}$
Laminate extensional stiffness	A_{ij}	Immittance function of laminate	$\tilde{Z}_{ii,N-ply}$
Governing equations for lamina: $\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix}=\begin{bmatrix}\overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16}\\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26}\\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66}\end{bmatrix}\cdot\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{Bmatrix}$ for laminate: $\begin{Bmatrix}N_x\\ N_y\\ N_{xy}\end{Bmatrix}=\begin{bmatrix}A_{11} & A_{12} & A_{16}\\ A_{12} & A_{22} & A_{26}\\ A_{16} & A_{26} & A_{66}\end{bmatrix}\cdot\begin{Bmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \gamma_{xy}^0\end{Bmatrix}$		Governing equations for lamina: $\begin{Bmatrix}\tilde{E}_x\\ \tilde{E}_z\end{Bmatrix}=\begin{bmatrix}\tilde{Z}_{xx} & \tilde{Z}_{xz}\\ \tilde{Z}_{zx} & \tilde{Z}_{zz}\end{bmatrix}\cdot\begin{Bmatrix}\tilde{J}_x\\ \tilde{J}_z\end{Bmatrix}$ for laminate: $\begin{Bmatrix}\tilde{E}_x\\ \tilde{E}_z\end{Bmatrix}_{N-ply}=\begin{bmatrix}\tilde{Z}_{xx} & \tilde{Z}_{xz}\\ \tilde{Z}_{zx} & \tilde{Z}_{zz}\end{bmatrix}_{N-ply}\cdot\begin{Bmatrix}\tilde{J}_x\\ \tilde{J}_z\end{Bmatrix}_{N-ply}$	

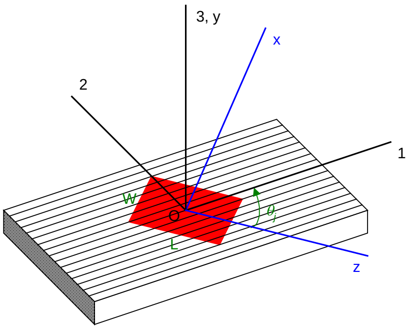


Fig. 1 Microstrip patch on lamina

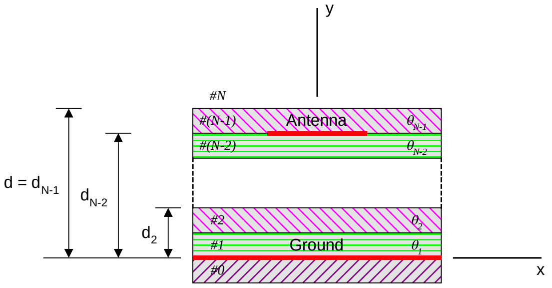
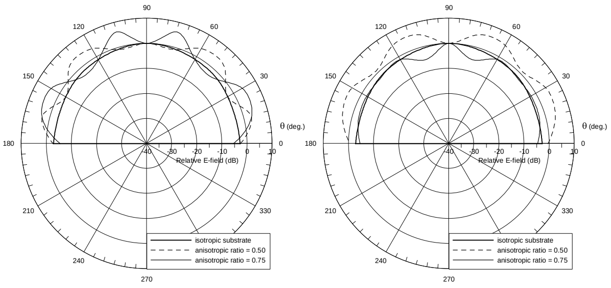


Fig. 2 Microstrip patch in composite laminate



(a) 6-ply [45/-45/45/45/-45/45] **(b) 6-ply [30/45/60/-30/-45/-60]**

Fig. 3 Far field at 2.40 GHz of microstrip patch embedded in composite laminate