行政院國家科學委員會補助專題研究計畫 □ 成 果 報 告
■期中進度報告

利用 C-Section 發展雙頻微波耦合器與濾波器

計畫類別：■ 個別型計畫 □ 整合型計畫
計畫編號：NSC 98－2221－E－182－067－MY2
執行期間： 98 年 8 月 1 日至 100 年 7 月 31 日

計畫主持人：郭仁財
共同主持人：
計畫參與人員：吳卓瑜、詹祺宏、賴絲薇、范峻瑜、唐紹展、陳殿靖、陸裕豪

成果報告類型(依經費核定清單規定繳交)：■精簡報告 □完整報告

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
■出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢
■涉及專利或其他智慧財產權，□一年■二年後可公開查詢

執行單位：長庚大學

中 華 民 國 99 年 5 月 31 日

New Miniaturized Dual-Band Rat-Race Coupler With Microwave *C*-Sections

***Abstract*—Based on microwave *C*-sections, rat-race coupler is designed to have a dual-band characteristic and a miniaturized area. The *C*-section together with two transmission line sections attached to both of its ends is synthesized to realize a phase change of 90° at the first frequency, and 270° at the second passband. The equivalence is established by the transmission line theory, and transcendental equations are derived to determine its structure parameters. Two circuits are realized in this presentation; one is designed at 2.45/5.2 GHz and the other at 2.45/5.8 GHz. The latter circuit occupies only 31% of the area of a conventional hybrid ring at the first band. It is believed that this circuit has the best size reduction for microstrip dual-band rat-race couplers in open literature. The measured results show good agreement with simulation responses.**

***Index Terms* — Microwave *C*-section, dual-band, microstrip line, miniaturization, rat-race coupler.**

I. Introduction

In the RF frond-end of a modern communication system, hybrid couplers are one of the most important devices [1]. They are widely used in several microwave and millimeter wave sub-systems such as balanced amplifiers and mixers. In the past few decades, a series of innovative synthesis and design have been proposed for these couplers [2]-[5]. In [2], simple formulation is devised to design the ring coupler. In [3], a rigorous synthesis procedure is demonstrated for branch-line couplers with equal power division. In [4], a rat-race coupler consisting of cascade structure of alternative high- and low-impedance transmission lines is presented to achieve a large power split ratio over a wide bandwidth. On the basis of design equations in [4], a miniaturized periodic stepped-impedance rat-race coupler with arbitrary power division ratio can be realized [5]. Note that all couplers in [2]-[5] are designed for operation at a single band.

Recent rapid progress in wireless communications has created a need of dual-band operation for RF devices, such as the global systems for mobile communication systems (GSM) at 0.9/1.8 GHz and wireless local area network (WLAN) at 2.4/5.2 GHz. Recently, numerous research topics on dual-band hybrid couplers have been published [6]-[13]. In [6], a planar dual-band branch-line coupler with a compact circuit area is proposed. Each quarter wavelength (λ/4) section is replaced by a short transmission line section with a pair of shunt short-circuited or open stubs attached to its ends. Based on a similar circuit structure, a rat-race coupler with two arbitrary operation frequencies is presented in [7]. An alternative branch-line coupler for dual-band operation is introduced in [8]. The circuit consists of cross branches that offer extra degrees of freedom to achieve the design. In [9], a tapped open stub is used to contrive a dual-band branch-line coupler. The two bands can be arbitrarily designated by adequately tuning the length and characteristic impedance of the stub. In [10], a stepped-impedance line section with two open stubs is proposed to establish a dual-band rat-race coupler. In [11], four identical open stubs are devised for design of a novel dual-band rectangular patch hybrid coupler.

The metamaterial approach [12]-[13] can also be used to implement couplers with the dual-band operation. In [12], arbitrary dual-band components such as branch-line and rat-race couplers are realized by composite right- and left-handed transmission line (CRLH TL) sections. Dual-band devices are also carried out on the basis of the simplified CRLH TL [13]. So far, however, it is still a challenge to design a miniaturized dual-band rat-race coupler. In [14], a novel circuit unit is utilized to design a dual-band branch line and rat-race coupler with arbitrary power division ratios. Each unit consists of a stepped-impedance line section with an open stubs tapped with its both ends. Rigorous design procedure is described and several circuits operating at 2.45/5.2 GHz are realized. To the best of our knowledge, it is the first miniaturized dual-band coupler with arbitrary power divisions at two designated bands in open literature.

In this paper, a miniaturized dual-band rat-race coupler is implemented with the microwave *C*-sections. Each λ/4 section of a conventional rat-race coupler is replaced by the proposed elementary two-port which consists of two line sections with a *C*-section in between. Design equations are formulated by establishing the equivalence between the two-port and the λ/4 section at two frequencies. To facilitate the circuit design, some design graphs are provided.

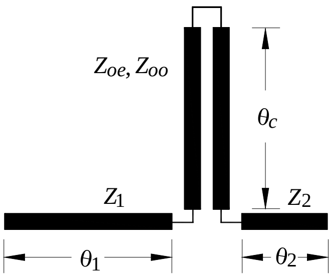


Fig. 1. The proposed elementary two-port with a *C*-section.

The presentation is organized as follows. In Sec. II, the dual-band characteristic of the proposed *C*-section is investigated and some design equations are formulated. Two circuits operating at 2.45/5.2 GHz and 2.45/5.8 GHz are fabricated and measured to validate the analysis. Sec. III demonstrates the simulation and measured results of these two experimental circuits, and Sec. IV draws the conclusion.

II. ELEMENTARY TWO-PORT FOR DUAL-BAND OPERATION

Figure 1 shows the proposed elementary two-port network for the dual-band operation. The two-port is built with two transmission line segments of lengths θ_1 and θ_2 and characteristic impedances Z_1 and Z_2 with a microwave *C*-section of length θ_c in between. Since the phase-shift of the *C*-section is nonlinear with respect to frequency [15], it is suitable for realizing the dual-band function.

Let the two designated operation frequencies be f_1 and $f_2 = nf_1$. In our approach, the six λ/4 sections of the traditional coupler are replaced by the proposed two-port. For simplicity, let $Z_1 = Z_2 = \sqrt{Z_{oe}Z_{oo}}$, where Z_{oe} and Z_{oo} are the even and odd mode characteristic impedances of the coupled-line. By enforcing the *ABCD* matrix of the two-port to be equal to those of a uniform transmission line section of 90° and 270° at f_1 and f_2, respectively, the following four equations can be readily obtained:

$$P(\theta_c)\cos\theta + 2Z_1\sin\theta = 0 \qquad \text{(1a)}$$

$$P(\theta_c)\sin\theta - 2Z_1\cos\theta = Q(\theta_c)\times Z_T/Z_1 \qquad \text{(1b)}$$

$$P(n\theta_c)\cos n\theta + 2Z_1\sin n\theta = 0 \qquad \text{(1c)}$$

$$P(n\theta_c)\sin n\theta - 2Z_1\cos n\theta = -\,Q(n\theta_c)\times Z_T/Z_1 \qquad \text{(1d)}$$

where

$$P(\theta_c) = Z_{oo}\tan\theta_c - Z_{oe}\cot\theta_c \qquad \text{(2a)}$$

$$Q(\theta_c) = -(Z_{oo}\tan\theta_c + Z_{oe}\cot\theta_c) \qquad \text{(2b)}$$

In (1) and (2), $\theta = \theta_1 + \theta_2$, Z_o is the reference impedance, and $Z_T = \sqrt{2}Z_o$ is the characteristic impedance of the six λ/4 sections of a conventional hybrid ring. After some algebraic manipulations, the following equations can be obtained for determination of Z_{oe} and Z_{oo}:

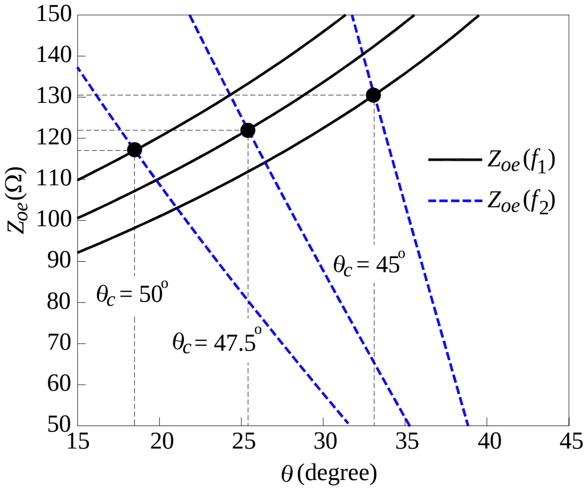
$$Z_T \times Z_{oe}(f_1) = Z_1^2\sec\theta\tan\theta_c + Z_1\tan\theta\tan\theta_c \qquad \text{(3a)}$$

$$Z_T \times Z_{oo}(f_1) = Z_1^2\sec\theta\cot\theta_c - Z_1\tan\theta\cot\theta_c \qquad \text{(3b)}$$

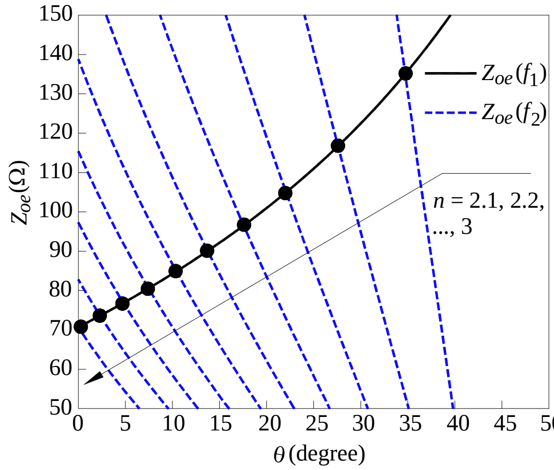
$$Z_T \times Z_{oe}(f_2) = Z_T\ \ Z_1\tan n\theta\tan n\theta_c - Z_1^2\sec n\theta\tan n\theta_c \qquad \text{(3c)}$$

$$Z_T \times Z_{oo}(f_2) = -Z_T\, Z_1\tan n\theta\cot n\theta_c - Z_1^2\sec n\theta\cot n\theta_c \qquad \text{(3d)}$$

One can validate that $Z_{oe}(f_1)Z_{oo}(f_1) = Z_{oe}(f_2)Z_{oo}(f_2) = Z_1^2$ when $Z_1 = Z_T$. Here, the dispersion of microstrip characteristic impedance is neglected. Once n, θ_c and θ are given, by enforcing $Z_{oe}(f_1) = Z_{oe}(f_2)$ or $Z_{oo}(f_1) = Z_{oo}(f_2)$, the structure parameters of the dual-band element can be solved as follows. Figure 2(a) plots the changes of $Z_{oe}(f_1)$ and $Z_{oe}(f_2)$ with respect to the variation of θ for θ_c = 50°, 47.5° and 45° for n = 2.12. This specific n value is used when f_1 = 2.45 GHz and f_2 = 5.2 GHz. As shown in Fig. 2(a), when θ_c is decreased from 50° to 45°, the Z_{oe} solution, i.e. the intersected points, is increased. When θ_c = 45°, the solution reads Z_{oe} = 130 Ω and $Z_{oo} = 2Z_o^2/Z_{oe}$ = 38.45 Ω. Implemented by coupled microstrips, the gap size over substrate thickness ratio S/h will be 0.08 for a substrate with ε_r = 10.2. When the substrate thickness h = 1 mm, such gap sizes will be critical for microstrip realization by the standard fabrication process since it is close to being beyond the resolution limit. One may increase θ_c to release the tight gap size as indicated in Fig. 2(a). Figure 2(b) draws the $Z_{oe}(f_1)$ and $Z_{oe}(f_2)$ solutions against the variation of θ for n = 2.1, 2.2, …, 3 for θ_c = 45°. When n is increased, the Z_{oe} solution decreases. Note that when θ = 0 and n = 3, the solution Z_{oe} = 70.7 Ω. It validates the fact that when the two-port is used to imitate a λ/4 section at f_1 and 3λ/4 at $f_2 = 3f_1$, the C-section becomes a folded section with $Z_{oe} = Z_{oo}$.

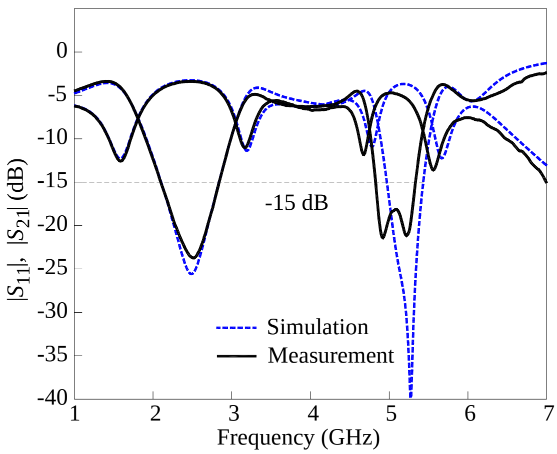


(a)

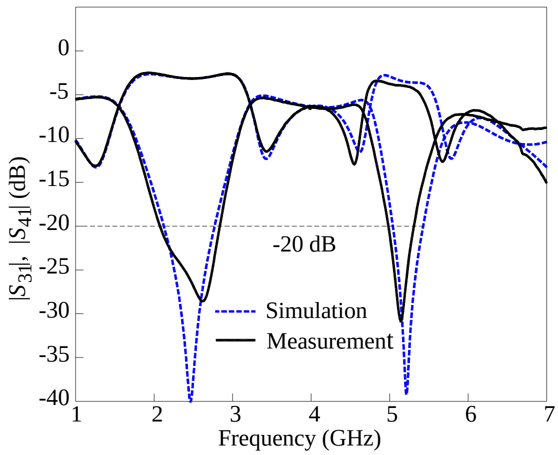


(b)

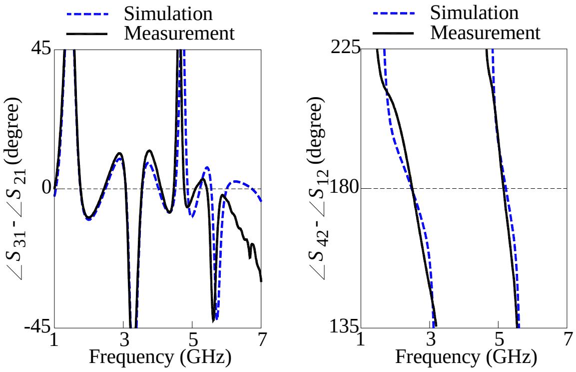
Fig. 2. $Z_{oe}(f_1)$ and $Z_{oe}(f_2)$ against the variation of θ, where Z_1 = 70.7 Ω. (a) n = 2.12. (b) θ_c = 45°.



(a)



(b)



(c) (d)

Fig. 3. Simulated and measured responses of the fabricated rat-race coupler at 2.45/5.2 GHz. (a) $|S_{11}|$ and $|S_{21}|$. (b) $|S_{31}|$ and $|S_{41}|$. (c) $\angle S_{31} - \angle S_{21}$. (d) $\angle S_{42} - \angle S_{12}$. n = 2.12, θ_c = 48°, θ = 23.85°, Z_1 = 70.7 Ω, Z_{oe} = 120.65 Ω and Z_{oo} = 41.45 Ω.

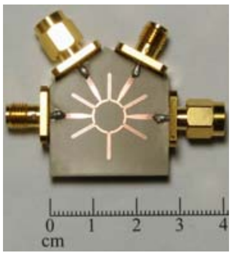


Fig. 4. Photograph of the dual-band rat-race.

III. Simulation and Measurement

Two rat-race couplers designed at 2.45/5.2 GHz and 2.45/5.8 GHz are fabricated and measured for demonstration Figures 3 and 4 show the simulated and measured results. The circuit has a substrate of ε_r = 10.2 and h = 1.27 mm. Simulation data are obtained by the electromagnetic software package IE3D [16]. Figure 3(a) plots $|S_{11}|$ and $|S_{21}|$ responses. It can be observed that all measured $|S_{11}|$ at both the designated frequencies are better than 18 dB. If a 15-dB return loss is referred, measured data indicate that the circuit has bandwidths of 30% and 9% at f_1 and f_2, respectively. Figure 3(b) shows the $|S_{31}|$ and $|S_{41}|$ curves. The measured isolations $|S_{41}|$ at f_1 and f_2 are better than 25 dB. For a 20-dB reference, the measured isolations possess bandwidths of 27% and 8% at f_1 and f_2, respectively. Also, detailed data show that the total power loss of the circuit $P_L = 1 - |S_{11}|^2 - |S_{21}|^2 - |S_{31}|^2 - |S_{41}|^2$ at f_1 and f_2 are 4% and 8.2%, respectively.

Figure 3(c) and 3(d) plots the responses of relative phase $\angle S_{31} - \angle S_{21}$ and $\angle S_{42} - \angle S_{12}$, respectively. One can observe that these responses have relatively smooth variations over the first band as compared with those over the second. It reflects the fact that the circuit has a bandwidth at f_1 larger than that at f_2. Good agreement between the simulation and measured responses for the experiment circuits can be observed. Figure 4 shows the photograph of the experimental circuit.

Figure 5(a) and 5(b) plots the magnitude responses of S_{11}, S_{21}, S_{31} and S_{41} of the second experimental dual-band rat-race. At both f_1 and f_2, the measured $|S_{11}|$ results are better than 20 dB. The measurement indicates that the circuit has bandwidths of 37% and 8% at f_1 and f_2, respectively, for a 15-dB return loss. These bandwidths are closely related to the relative phases $\angle S_{31} - \angle S_{21}$ and $\angle S_{42} - \angle S_{12}$ shown in Fig. 5(c) and 5(d), respectively. The experimental $|S_{41}|$ data show that the isolations are better than 35 dB, and the total power losses P_L are 3.2% and 7.3% at f_1 and f_2, respectively.

Figure 6 shows the photograph of the experimental circuit. In this design, all the *C*-sections can be placed inside the ring circumference. This is because this circuit has a larger n value than the previous one so that the θ_c solution shown in Fig. 2 can be shorter. It occupies only 31% of the area of a conventional rat-race coupler. It is believed that this circuit has the best size reduction comparing with the microstrip dual-band rat-race couplers in open literature.

IV. Conclusion

The function of a microwave *C*-section is exploited for dual-band and circuit miniaturization operation. For design of a dual-band rat-race coupler, the *C*-section together with two short microstrip sections at its ends is used to replace each of the six λ/4 sections of a traditional coupler at the two design frequencies. This approach can save more than 69% of the circuit area. The proposed two-port is viable for development of other dual-band microwave passive devices.

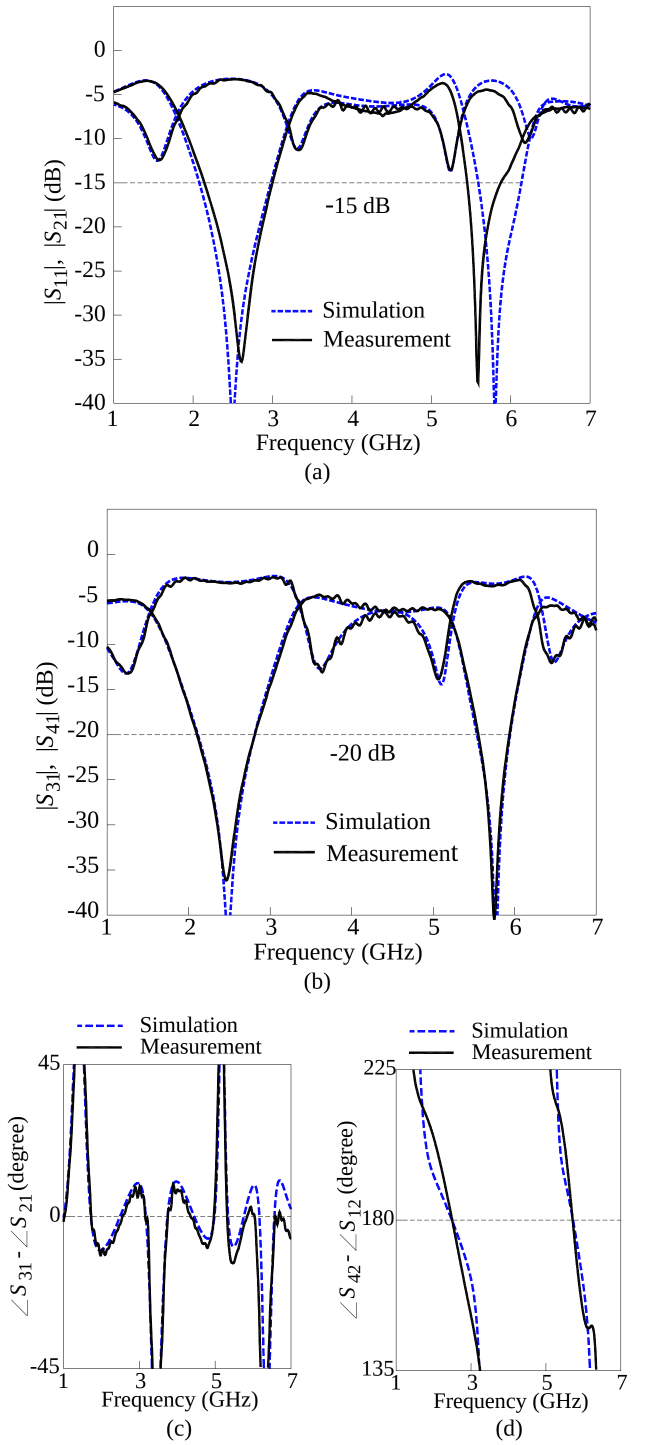


Fig. 5. Simulated and measured responses of the fabricated dual-band rat-race coupler at 2.45/5.8 GHz. (a) $|S_{11}|$ and $|S_{21}|$. (b) $|S_{31}|$ and $|S_{41}|$. (c) $\angle S_{31} - \angle S_{21}$. (d) $\angle S_{42} - \angle S_{12}$. $n = 2.37$, $\theta_c = 36.5°$, $\theta = 43.22°$, $Z_1 = 70.7\ \Omega$, $Z_{oe} = 121\ \Omega$ and $Z_{oo} = 41.33\ \Omega$.

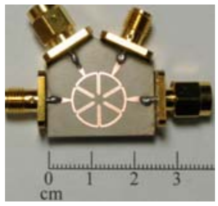


Fig. 6. Photograph of the fabricated 2.45/5.8 GHz rat-race coupler.

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出席國際學術會議報告

99 年 6 月 2 日

報告人姓名	郭仁財	服務機構及職稱	長庚大學電子系教授
時間 會議地點	99 年 5 月 23 日 至 5 月 28 日 美國加州安納罕市（洛杉磯）	本會核定補助文號	NSC 98-2221-E-182-067-MY2
會議名稱	（中文）2010 國際微波工程與學術會議 （英文）2010 International Microwave Symposium		
發表論文題目	（中文）具有準橢圓函數響應及可調整頻寬之新型雙模雙頻帶通濾波器 （英文）New dual-mode dual-band bandpass filter with quasi-elliptic function passbands and controllable bandwidths （中文）微波平面濾波器電路之最新發展 (受邀專題演講) （英文）Planar Microwave Filters (Invited Workshop Speaker)		

報告內容應包括下列各項：

一、參加會議經過

今年的國際微波工程與學術會議於 5 月 23 日至 5 月 28 日在美國加州的安納罕（Anaheim）的會議中心舉行，安納罕市位於洛杉磯東南方，下機後的 Shuttle 約開 40 分鐘，可抵達。會議中心隔壁街（走路 15 分鐘）就是名聞遐邇的迪斯奈樂園（Disneyland）。

整個會議的議程包括 5/23（日）、5/24（一）以及 5/28 （五）的 workshops （專題講演）與 short courses，5/25（二） ~5/27（四）則有學術與技術論文研討。

筆者這一次參加本研討會的主要任務有二，一是在 5/23 的 “The State of Art of Microwave Filter Synthesis, Optimization and Realization”「微波濾波器合成、最佳化與實現的最新發展」專題講演（全天）中，發表近年來研究的成果。由於筆者在星期天就必須上台演講，所以必須於前一天（5/22）就到達旅館，5/23 當天早上 8 點向主持人（Dr. Ming Yu）報到。整個 IMS 在星期天（5/23）共有 14 個專題講演同時進行，筆者受邀的專題演講從早上 8：00 一直到下午 5：00，共有 9 位講者，以英語報告，每一位約時 45 分鐘。受邀作專題講演除了是榮譽之外，也可以豁免專題講演的註冊,每一個專題講演每位參加者的現場註冊費為美金 280 元(約合台幣 9000 元) (註：IEEE MTT-S 也賺太多了)。

筆者的另一個主要任務是發表長篇口頭報告的學術論文，在 5/26（三）上午由碩士班學生林祖偉同學報告，筆者在台下全程參與，過程順利。該生申請國科會以及傑出人才基金會，獲得全額補助。出國前，已協助其 ppt 檔案修改過數次，另該生去年 12 月時曾參加過新加坡的 APMC，英語部分也足以應付。

二、與會心得

根據大會數據，今年共有 250 篇論文通過審查，其中口頭報告 123 篇，122 篇

壁報討論論文。（根據前年資料：共有 762 篇投稿，279 篇口頭報告，（接受率 36.6%），132 篇壁報討論論文，合計接受率為 54.9%。）數據相比，顯然篇數少多了。據說是經濟狀況尚未完全復甦。

筆者在專題講演結束後，隨即（6：00 – 9：00）參加 MTT-8 「微波被動元件」支會的會議，討論（1）本支會推出明年 workshop 主題，（2）IEEE 標準中，微波濾波器之相關專有名詞標準化的訂定，以及（3）選定本支會明年召集人。

參加此會議，與 Dr. Wang 有一席聊：因為我發現今年 IMS 中「平面電路」的論文應該少了 40%，為什麼？他是「平面電路」TPC 的召集人，他說有很多論文對於理論敘述不清，很像在做勞作，同時也有一位 TPC 委員堅持論文品質，所以 IMS 中「平面電路」的接受率不到 30%。整體 IMS 所有論文的接受率為 50% 左右，所以「平面電路」領域的論文接受率僅有其他領域的 60% 不到，可見挑戰性很高。

由於 Dr. Wang 與筆者同時擔任 TMTT 的 Associate Editor，他有點不安的問：「你負責的 TMTT 期刊接受率是多少？」「40% 左右，你呢？」「大概不到 30%。」顯見我不是最嚴格的，「我知道有人也接近 30%，但也有人在 55%，每一個 AE 不一樣」；很慶幸的事，Editor-in-Chief （Dr. Dylan Williams） 充分尊重我們所有 AE 對論文接受或拒絕的最後決定，從不過問。

在 5/24（一）中午，受邀參加 Editor's Lunch，與 IEEE TMTT、IEEE MWCL的 Editor-in-chief（EIC）及 Associate Editors（AE）共聚一堂。筆者目前仍是 TMTT 的 AE 之一，除了社交目的之外，也宣布一些重要的交接等。從今年 6/1 開始，TMTT 的 EIC 由 Dr. George Ponchak 接任，他的作風與這一屆的 EIC 不同，全部投稿均改由 Manuscript Center 處理，藉由網路處理相關事務，所有作者也不會知道處理審查的 AE 是哪一位，而且最後「接受」與「拒絕」論文的決定，完全由他做決定，AE 僅能「建議」。對 EIC 而言，其實整個機制是很大的負擔，因為一年將近千篇的投稿長篇論文，遍佈 IC 設計、數值分析、理論、實作、量測方法、太空、半導體 … 等各種微波理論、工程與技術各領域，想要做好確實不容易。

在 5/25（二）的晚上，則有 Reviewer's reception，請所有在 2009 年協助TMTT 與 MWCL 審查期刊稿件至少一篇的人用餐，並藉機會交換心得，原預期會有超過數百人，但估計實際參加約莫百人而已。

坐飛機到美國參與這種國際大型且優良的研討會，雖然獲益良多，感覺品質很好，但確實很辛苦，光是適應時差就很不容易，不用說回國後需要更多時間休息；尤其近幾年來年紀漸漸增加，對於這種行程更是倍覺勞累。

三、考察參觀活動（無是項活動者省略）

四、建議

五、攜回資料名稱及內容

攜回資料有專題講演講義一冊，以及研討會論文集 USB 一只。

六、其他