行政院國家科學委員會專題研究計畫 成果報告

半導體量子點寬頻光源
研究成果報告(精簡版)

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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

半導體量子點寬頻光源

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計畫主持人：林國瑞
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計畫參與人員：黃俊仁、湯皓玲、王曉微、葉庭聿、溫岳嘉、陳壽賢、鄭旭傑

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中　華　民　國　98　年　10　月　31　日

半導體量子點寬頻光源

Broad Spectrum Light Sources based on Semiconductor Quantum Dots

計畫編號：NSC97-2221-E-009-158

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主持人：林國瑞 國立交通大學電子工程學系暨電子研究所 助理教授

一、中文摘要

關鍵詞：量子點；超高亮度二極體；寬頻光源；光學同調斷層掃描

本年度計畫延續NSC96所設計的啁啾式推疊量子點雷射結構，首先分析量子點雷射的頻譜特性，我們將寬度3 μm、長度3 mm的邊射型雷射於室溫下以脈衝電流驅動至3 A，並以光譜儀在0.1 nm解析度下分析雷射頻譜，其3 dB連續頻寬高達28 nm。

為評估量子點雷射在光學同調斷層掃描系統的適用性，我們架設了一套光纖式的Mach-Zehnder干涉儀來量測雷射的光學同調長度。我們在十倍臨限電流的操作下，量得之光學同調長度小於100 μm，其寬頻所呈現的低同調性有很大的應用潛力。

由於生醫系統使用上必須將半導體雷射耦合至單模光纖，因此光源要能夠滿足低垂直發散角以及高遠場對稱性的系統需求，而以多層堆疊量子點為主動區的波導層通常很厚（0.3~0.5 μm），因此光源的垂直發散角非常大，使得光束遠場的垂直與水平縱橫比超過6:1，造成隨後光纖耦合的損失以及增加封裝的成本。今年我們在磊晶設計上改用了大光腔結構，也就是將主動區的波導厚度大幅增加至2 μm來降低垂直發散角，我們成功地將垂直發散角由原先的54度降至34度。

同時，我們以載子及多模光子的速率方程式進行量子點雷射的理論模擬。我們考慮了兩個以上的量子點能階；載子在多層量子點堆疊間捕抓與逃脫等動態行為也一併考量；量子點的增益計算則加入了均勻與非均勻頻譜寬化效應。雷射頻譜模擬結果成功地解釋NSC96所觀測到雙基態波長於臨限電流附近同時雷射發光的現象，載子在各層的分佈比率隨電流的變化也可獲得預測。

二、英文摘要

Keywords: Quantum Dots, Superluminescent Diodes, Broadband Light Emitters, Optical Coherence Tomography

The chirped multilayer quantum dot (QD) laser structure proposed in NSC96 is continuously investigated in this year. Edge emitting lasers with ridge width of 3 μm and cavity length of 3 mm are operated under pulsed condition at room temperature. With injected current up to 3 A, the 3 dB spectral width is as high as 28 nm without dip under 0.1-nm resolution of optical spectrum analyzer.

To evaluate the feasibility of QD laser application on the optical coherence tomography, we have setup a fiber-based Mach-Zender interferometer to measure the coherence length of lasing light. Under current injection of ten times the threshold current, the optical coherence length of our multilayer QD laser is lower than 100 μm. The low coherence property of broad spectral emission in QD lasers is therefore manifested.

As semiconductor lasers should be coupled into single-mode fibers in the bio-medical application, the lasing light should meet the system requirement of low vertical beam divergence and symmetric far-field pattern (FFP). However, the rather thick (0.3~0.5 μm) separate-confinement-heterostructure (SCH) of conventional multilayer QD laser structure renders the FFP with larger vertical beam divergence and aspect ratio over 6:1. Therefore we have adapted the large-optical-cavity (LOC) structure in this year to reduce the vertical beam divergence. That is, the SCH layer is tremendously increased up to 2 μm. With great success, we have fabricated the QD lasers with narrow beam divergence as low as 34 degree, compared to the conventional 54 degree.

Meanwhile, we have carried out the theoretical simulation by laser rate equations of carriers and multimode photons. More than two energy levels are allowed for carrier relaxation and recombination in the QDs. The dynamic capture and escape process is also considered. Both homogeneous and inhomogeneous broadening are included in the gain calculation.. The simulated lasing spectrum is consistent with our simultaneous two ground-state lasing emissions observed in NSC96. The injection current evolution of carrier population among multilayer QDs could also be predicted from our calculation.

三、計畫緣由與目的

光通訊市場雖逐漸復甦，然光電元件仍亟需找尋新的應用，由於生醫波段恰與光通訊波段一致，因此具有生醫應用潛力的光電元件研發近年來又蓬勃起來，目前備受關注的研究主題為光學斷層掃瞄（OCT）系統中之寬頻光源研發 [1]。由於OCT的解析度與光源的頻寬成反比，現有系統大多採用超快雷射為光源，然其缺點為價格高、體積大且操作及維護不易，因此對於輕薄短小且低價位的寬頻半導體光源的呼聲越來越大。

寬頻半導體光源的研發大多在磷化銦（InP）或砷化鎵（GaAs）基板上成長量子井並製作超高亮度二極體（SLDs）來實現[2-3]，然因InP基板的成本高且光源波長略嫌偏長，而以GaAs為基板的光源波長卻又嫌偏短。近年來在量子點磊晶新技術的發展之下，我們得以GaAs為基板將光源發光波長推至生醫波段中兼顧解析度與穿透深度的波段（1.1~1.3 μm），同時利用自組式量子點本質上的inhomogeneous broadening特性，甚有機會在GaAs基板上開發出低價位、輕薄短小而且具有高輸出光功率的半導體寬頻光源 [4]。

由於量子點的成長條件及堆疊應力控制需要相當的經驗累積，國內僅少數單位展示1.3 μm波段的雷射結果，目前雖有工研院開始長波段量子點寬頻光源的研發，但仍未對元件的物理特性有所著墨，也因此對於元件的設計與製程尚未最佳化。國外的研究機構近年所開始關注以量子點為主動區之超高亮度二極體，某些在頻譜的頻寬上取得優勢 [5]，某些則在光源的強度上取得領先 [6]，仍未同時獲致寬頻、高功率且對稱發散角的光源要求；另德國Innolume公司於2006年6月新聞發布量子點雷射在高操作電流下具有寬廣的雷射發光頻譜[7]，由於雷射本身高效率及高功率的特性，這將使得此款特殊結構設計的半導體量子點雷射更具競爭優勢。

以量子點為主動區的寬頻半導體雷射目前僅有非常少量的文獻發表 [8]，國內外也尚未有系統的研究，也因此還未能最佳化雷射元件的結構設計及磊晶和製程等參數，本計劃將以新提之啁啾式堆疊多層量子點雷射為研究

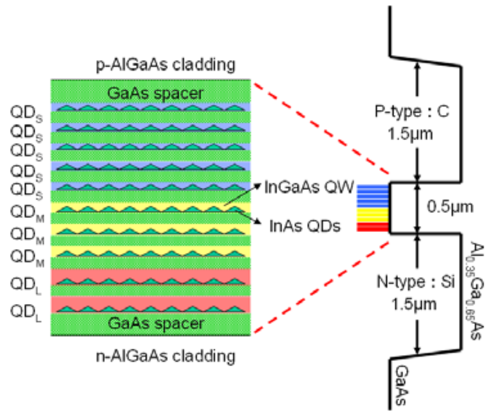
起點，透過完整的量測與分析來釐清多層量子點內載子的分佈特性及材料增益，為元件最佳化提供具體可改善的方向，並從中累積研發能量以實現可具體應用的寬頻光源及掃頻式可調光源為研究的目標。

四、研究方法及成果

自組式成長（self-assembled growth）量子點的大小、形狀及成分組成呈現相當寬廣的分佈，加上量子點本身的密度亦受到成長條件的限制而相當有限（1E10~1E11 cm^{-2}），因此以量子點作為半導體雷射的增益介質（gain medium），其材料增益偏離理論的預測而呈現相當低的飽和增益（saturation gain），解決方式為多層堆疊來提升元件操作所需的光模增益（optical modal gain）。一般來說，傳統量子點雷射的多層堆疊均採用相同的磊晶成長條件，我們稱之為均勻堆疊量子點（uniformly stacked QDs），以符合雷射窄頻的發光特性（narrow-band lasing emission）。

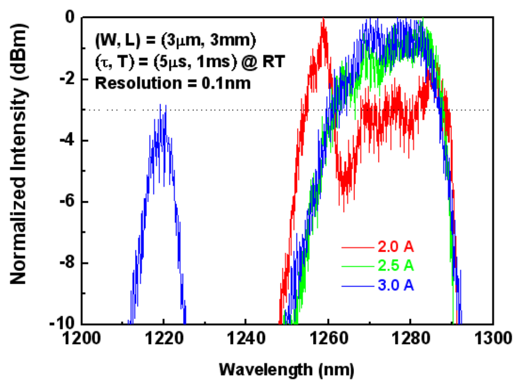
量子點主動區的飽和增益雖然相當有限，然其增益頻譜（gain spectrum）卻相當的寬廣，為充分運用其寬廣的頻譜，L. H. Li et al. [4] 改變覆蓋於InAs QDs 上方之InGaAs QW的In 成分來連續調變各層量子點的中心發光波長，獲致發光頻寬高達121 nm 的超高亮度二極體，我們將此調變方式稱之為連續啁啾式堆疊（continuously chirpy stack）量子點。

以上述調變方式製程為半導體雷射，一者In effusion cell 的溫度控制恐因連續改變造成重複性不佳，再者若量子點的磊晶品質改變導致飽和增益太低，都可能造成無法雷射發光。我們在 NSC96 提出一種數位啁啾式堆疊（digitally chirpy-stacked）量子點的磊晶結構（見圖一），主動層中有十層量子點，其中包含三種不同的 InAs 量子點結構，依波長的差異標示成 QD_L(波長較長)、QD_M(波長中等)和 QD_S(波長較短)，其發光波長藉由改變覆蓋在 InAs 量子點上的 $In_{0.15}Ga_{0.85}As$ 厚度來調整，三種量子點對應的 $In_{0.15}Ga_{0.85}As$ 厚度分別為 4nm、3nm 和 1nm，而三種波長的量子點所占的層數依序為 2 層、3 層和 5 層，目的是改變不同發光波長的飽和增益，希望可以藉此觀察到三種量子點的基態在不同的共振腔損耗下依序發光。



圖一：啁啾式堆疊量子點磊晶結構及能帶示意

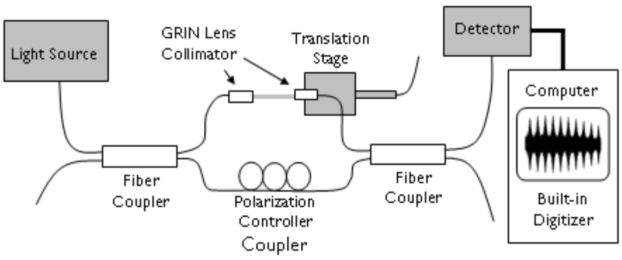
本年度計畫延續 NSC96 所設計的啁啾式推疊量子點雷射結構，首先分析量子點雷射的頻譜特性，我們將寬度 3 μm、長度 3 mm 的邊射型雷射於室溫下以脈衝電流驅動至 3 A，並以光譜儀在 0.1 nm 解析度下分析雷射頻譜，其發光頻寬橫跨 80 nm，3dB 連續頻寬亦高達 28 nm（見圖二）。

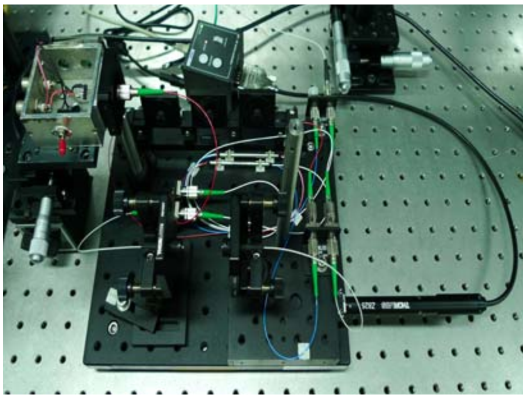


圖二：高頻譜解析下之高電流驅動雷射頻譜

為評估量子點雷射在光學同調斷層掃描系統的適用性，我們架設了一套光纖式馬赫•任德（Mach-Zehnder）干涉儀（見圖三）來測量雷射的同調長度（coherence length）；透過

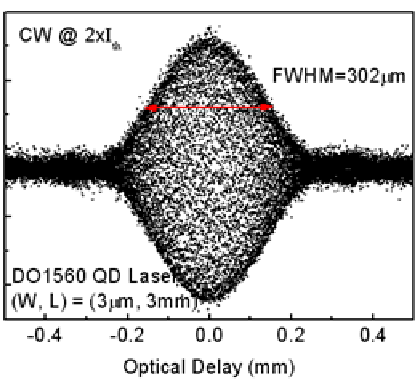
奈米級致動器（actuator）來驅動平移台以造成光程差的改變，並以高速示波器（high-speed digitizer）擷取干涉後的光訊號，我們可獲取如圖四的光學自相關函數。

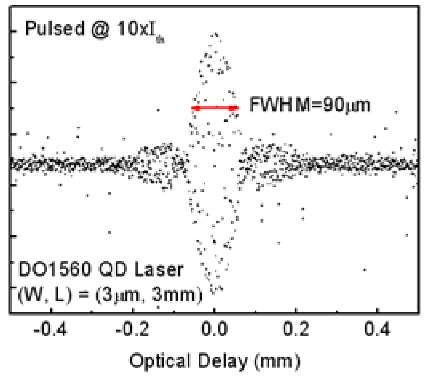




圖三：光纖式 Mach-Zehnder 干涉儀實驗架設

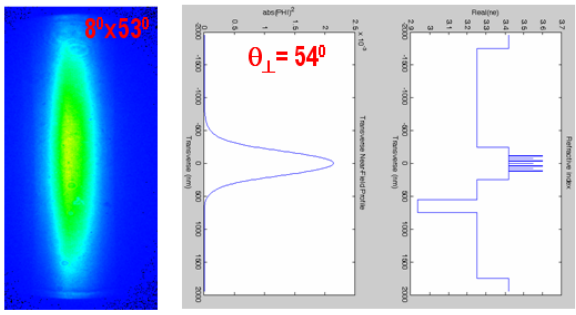
圖四顯示兩倍及十倍臨限電流下的光學自相關函數，其中兩倍臨限電流以直流（CW）操作，而十倍臨限電流則是以脈衝（Pulsed）操作，如此可降低量子點雷射元件過熱及鏡面損壞等問題。我們在十倍臨限電流的操作下，量測所得之光同調長度為 90 μm，相較於一般 FP 雷射的幾個釐米，以及 DFB 雷射的數十至數百釐米，其寬頻所呈現的低同調性有很大的應用潛力。



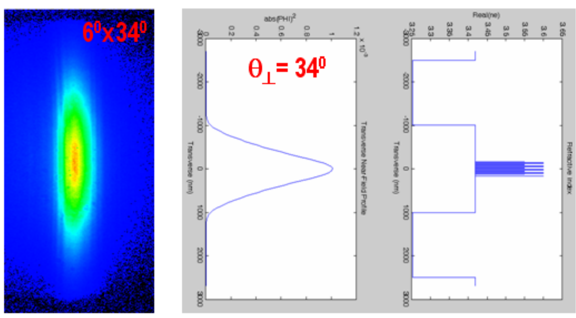


圖四：自相關函數與光程差關係圖

由於生醫系統使用上必須將半導體雷射耦合至單模光纖，因此光源要能夠滿足低垂直發散角以及高遠場對稱性的系統需求，而以多層堆疊量子點為主動區的波導通常很厚（0.3~0.5 μm），因此光源的垂直發散角非常大（見圖五），這使得光束遠場的垂直與水平縱橫比超過 6:1，造成隨後光纖耦合的損失以及增加封裝的成本。今年我們在磊晶結構上改用大光腔（Large Optical Cavity）設計，也就是將主動區的波導層厚度大幅增加（~2 μm）來降低垂直發散角，我們成功地將垂直發散角由原先的 54 度(見圖五)降至 34 度(見圖六)。

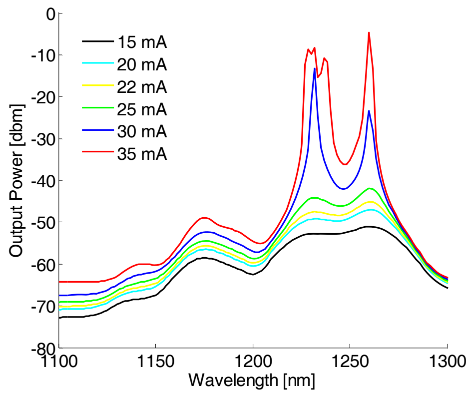


圖五：傳統多層堆疊量子點及二維遠場量測

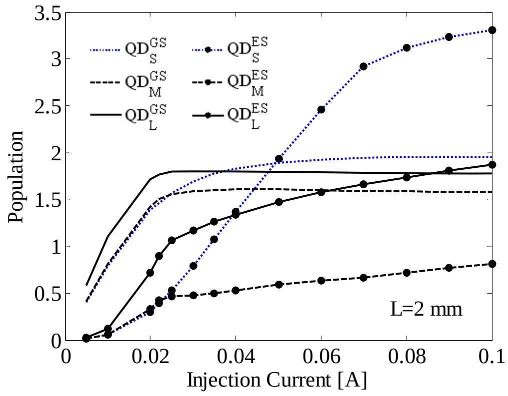


圖六：LOC 多層堆疊量子點及二維遠場量測

同時，我們以載子及多模光子的速率方程式進行量子點雷射的理論模擬。我們考慮了兩個以上的量子點能階；載子在多層量子點堆疊間捕抓與逃脫等動態行為也一併考量；材料增益計算則加入量子點的均勻與非均勻頻譜寬化效應。雷射頻譜模擬結果（見圖七）成功解釋 NSC96 所觀測到雙基態波長於臨限電流附近同時雷射發光的現象，載子在各層的分佈比率隨電流的變化也可獲得預測（見圖八）。



圖七：模擬之雷射頻譜



圖八：模擬雷射元件之載子分佈比率

五、結論與建議

本年度計畫中，在理論計算上，我們模擬了量子點雷射的發光頻譜，成功地分析解釋 NSC96 所觀測到臨限電流附近有兩基態波長同時發光的新奇特性，我們並可以預測載子在各層的分佈比率隨電流的變化。在實驗與量測上，我們架設了一套光干涉儀，量測了高注入電流下之量子點雷射的同調長度。同時，我們改變了磊晶結構，製程與量測結果成功地降低量子點雷射的垂直發散角至 34 度。

今後我們將繼續進行量子點雷射結構的設計與製作，希望垂直發散角可以降低至25度以內。而為了將雷射頻寬繼續推展，我們要對雷射元件進行鏡面鍍膜與共晶鍵合封裝，以利室溫下直流操作，最後希望透過廠商將雷射光耦合至單模光纖，並將此元件交付生醫研究的單位進行影像掃描的測試。本計劃研究成果，已於本年度發表國內外會議論文共5篇，並已投稿相關期刊論文。

六、參考文獻

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出席國際學術會議心得報告

計畫編號	NSC 97-2221-E-009-158 (97R401)
計畫名稱	半導體量子點寬頻光源
出國人員姓名 服務機關及職稱	鄭旭傑 / 交通大學電子工程系所 / 博士候選人
會議時間地點	14-19 June 2009 @ Munich, Germany
會議名稱	CLEO Europe - EQEC 2009
發表論文題目	Incomplete mode-locking in one-section QD lasers with ultra-long cavity

一、參加會議經過

Conference on Lasers and Electro-Optics(CLEO) 在世界各地皆有不同的分支，包括亞洲、歐洲、北美、世界等會議，主要議題在雷射與其他電光耦合系統的原理、製作與應用，European Quantum Electronics Conference(EQEC)則偏重在量子光學、非線性光學與其他物理的探討，歐洲的 CLEO-Europe 與 EQEC 每兩年舉辦一次，齊聚來自世界各地的學者與研究人員彼此切磋研討，今年於 6 月 14~19 日在德國南部大城慕尼黑(Munich)舉辦，慕尼黑同時也是集歷史文化與現代科技工業於一身的城市。

此次會議除了 CLEO 與 EQEC 共同召開之外，尚有一些其他相關領域附屬的 session，共計有 28 個議程，涵蓋範圍包括雷射、光纖、通訊、奈米、生醫、光學感測、非線性光學、量子光學、兆赫波、光學材料、meta-material、雷射冷卻與捕捉、…等光學相關領域，內容涵蓋相當廣泛，供同樣是光學相關領域卻侷限於某一分支的人員更加拓展了視野，一共 5 天半的議期，包含了 100 場的 invited talk，發表論文（oral & poster）數目超過 1000 篇，參展廠商逾 150 個攤位，與會人員更高達數千人，主要仍以歐洲地區的人士為主，台灣僅約 20 餘人參加，而來自日本的與會人士在亞洲地區中則相對多很多。會議場地相當大，從數百個座位到可容納上千人的演講廳共 20 多個，依主題劃分了數個區域，分佈不同主題的演講與壁報論文，每日每場共有 6 個小時約 20 場的 oral，排得相當密集，而由於壁報論文數量多，每篇壁報只展示一天，poster session 則為每天 13:30~14:30 的休息時間，另外主辦單位也準備數個大電漿螢幕供與會者隨時查閱壁報與口頭發表者的報告，在 WLAN Lounge 區域則提供全天無線上網。

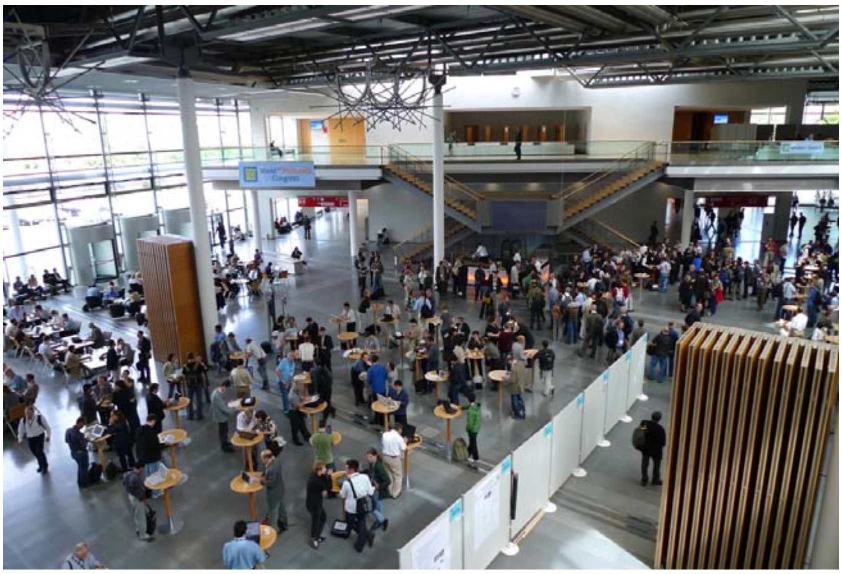
我此次的發表為 poster 形式，隸屬於 Semiconductor Lasers Session，被安排在第二天，由於報名人數太多，從第一天到第四天每天都開放報到，陸續有人到來及離去，故雖有上千人報名，但每日的與會人士不盡相同，僅約數百人。會議安排上，部分可容納千人之眾的演講廳由於位置偏僻，演講者報告時台下卻僅有 10 數人，而有些只能容納百人的演講廳則呈現爆滿的現象，我想這點是主辦單位在場地安排上必須調整的一點，而部分主題的 poster 缺席情況則甚為嚴重，主辦單位未提供張貼所需的工具，部分 poster 的區域安排也不甚理想。

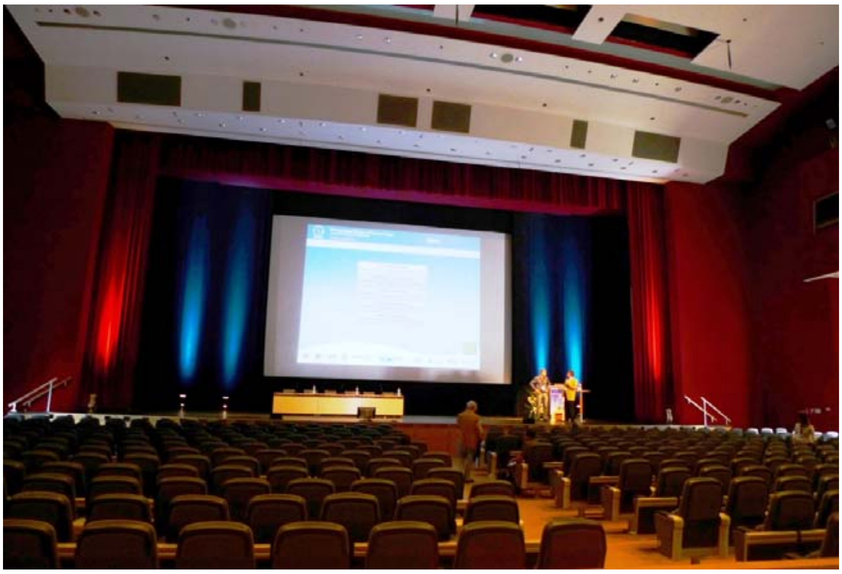
二、與會心得

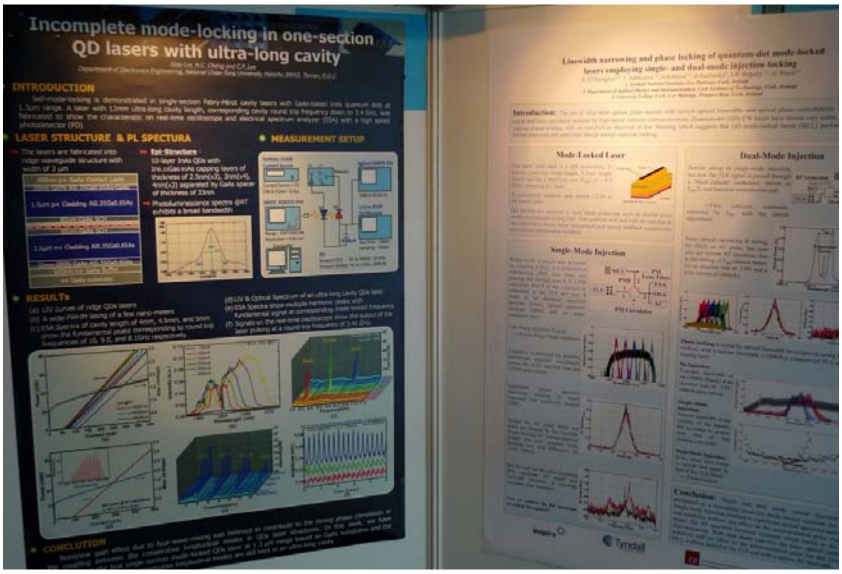
第一次出國參加國際性大型的學術研討會，會議整體而言是非常的龐大，場地設施非常的先進，而研究的內容亦相當的廣大，而且已超出我所專精的領域太多，我所能給的評價是報告的量非常多，而質雖然參差不一，但亦具有一定的水準。對於會議的規劃，則與國內相差甚多，議程排得相當密集，而休息時間相當長，poster session 緊接著午餐時間之後，但由於不像國內會議會幫忙準備餐點，會場餐廳的應變能力又似乎不足，對於我們這些外國來的與會者而言，實甚為不便，poster session 在午餐之後，亦多淪為午休時間，反倒是早上與下午 coffee break 的時間流覽 poster 的人則較多，而在 poster 的部分，大部分國外的學者似乎都不拘泥於海報的形式，而大會的規定也是給予每人多少空間，供投稿者張貼，而非一定要海報的形式，因此可以看到許多外國學者使用 A4 投影片的格式張貼，更利於現場的報告與攜帶。此外，對於 oral 的部分有點諷刺的是，大部分的時間在 WLAN Lounge 的區域，總是擠滿了人，在此處使用無線網路，大型會議廳裡的聽講者反倒不多，我想這與大會的規劃無關，而是參與者熱中程度的關係。

整體而言，工作時間短而密集，休息時間長而悠閒，這似乎與歐洲的生活步調有關，工作務實而重視休閒，但對於舉辦會議來說，然有效率，但卻不一定合時宜，又或許只是我們習慣亞洲地區的步調，因而感到許多不便。

雖然是第一次出國，但德國人的英文能力普遍而言都算不錯，因而在語言溝通上不致有太大的問題，慕尼黑的交通也非常方便，雖然住宿點在火車站附近，離研討會地點有 10 數公里遠，但就像台北捷運一樣，慕尼黑的市內交通規劃得更為密集與完善，每天來回只消一個小時，飲食部分也很方便，唯獨消費與台灣比起來貴了很多，約在 3～4 倍左右，晚宴地點在飯店中準備了 900 個座位，近千人同時暢飲啤酒與大啖德國道地美食。會議結束後，也另外花了兩天到慕尼黑近郊的景點走走，可以令人深深感受到德國雖然是個工業大國，但對於環境保護與歷史文化保存工作的重視，大城裡與鄉間，人類與自然相處得很融洽，並未因科技的發展而改變太多，平日裡努力工作，而假日則盡情享受悠閒，在研究上更是有其獨到之處，深深值得我們去學習。






Incomplete mode-locking in one-section
QD lasers with ultra-long cavity
INTRODUCTION
LASER STRUCTURE & PL SPECTURA
MEASUREMENT SETUP
RESULTS
CONCLUSION
Linewidth narrowing and phase locking of quantum-dot mode-locked
lasers employing single- and dual-mode injection locking
Introduction
Mode-Locked Laser
Dual-Mode Injection
Single-Mode Injection
Conclusion
Tyndall

Incomplete mode-locking in one-section QD lasers with ultra-long cavity

***Gray Lin*[1]*, Hsu-Chieh Cheng*[1]*, Kun-FengLin*[2]*, Rong Xuan*[2]*, and Chien-PengLee*[1]**

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Semiconductor light emitters based on quantum dot (QD) have recently been used in the fabrication of mode-locked lasers owing to their broad gain spectrum as well as fast carrier dynamics [1-3]. For GaAs-based InAs QD lasers at 1.3 μm range, mode-locking behaviours of two-section devices with cavity length between 800 and 8000 μm, corresponding to round-trip frequency between 5 and 50 GHz, were investigated to show transform-limited pulses with low uncorrelated timing jitter [2]. While for InP-based InAs QD lasers at 1.5 μm range, self-mode-locking in one-section configuration without saturable absorption was reported to show repetition rate as high as 45 and 134 GHz, corresponding to cavity length of 950 and 340 μm, respectively [1,3].

Since long-wavelength Fabry-Perot (FP) lasers show a broader spectrum compared with short-wavelength FP lasers, optical pulse generation operated under continuous wave (CW) was demonstrated at 100 GHz using a one-section InGaAsP quantum-well (QW) FP lasers at 1.5 μm range [4]. Nonlinear gain effect due to four-wave-mixing was believed to contribute the strong phase correlation or coupling between consecutive longitudinal modes in QDs and long-wavelength QW structures [3,4]. In this work, we demonstrate, to the best of our knowledge, the first one-section mode-locked QD lasers at 1.3 μm range based on GaAs substrates.

The laser structures incorporated 10-layer InAs QDs grown by molecular beam epitaxy and were processed into ridge waveguides with stripe width of 3 μm. As-cleaved lasers were operated under CW and fiber-coupled to a high-speed photodetector followed by a electrical spectrum analyzer (ESA). QD lasers with cavity lengths of 4, 4.5, 5, 10.8, 12.0 and 16.8 mm were mode-locked at corresponding round trip frequencies of 10, 9.0, 8.1, 3.8, 3.4, and 2.4 GHz, respectively.

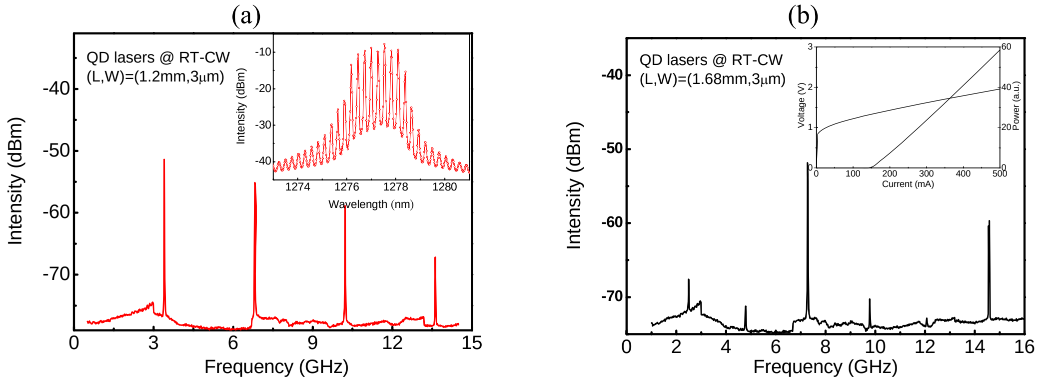

Fig. 1 (a) Electrical power spectrum and optical spectrum (inset) of the mode-locked QD laser with cavity length of 1.2 cm. (b) Electrical power spectrum and L-I-V characteristics (inset) of mode-locked lasers with cavity length of 1.68 cm.

Fig. 1 shows the power spectrum from ESA for two QD lasers with ultra-long cavity lengths of 12.0 and 16.8 mm. Multiple harmonics appeared in the measurable range of 0-16 GHz with fundamental signal at corresponding mode-locked frequency. No self-pulsation was observed accompanying the mode locking. The larger linewidth of 3~5 MHz implies the presence of larger phase modulation; however, coupling of multi-longitudinal modes is manifested. The direct temporal measurement in a 4-GHz-oscilloscope revealed the incomplete mode-locking with optical pulses superimposed on a DC offset. Further autocorrelation measurement will determine the pulse shape and its pulse width. Moreover, that the signal intensity at 3rd harmonics in Fig. 1(b) is higher than that at fundamental and 2nd harmonics is not observed before. Significant group-velocity dispersion as well as inevitable device uniformity in longer cavity length may be the underlying causes for further study.

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[4] *Institute of Laser-Physical Research of Russian Federal Nuclear Center, Sarov, Russia*
Rod amplifiers (RA) and disk amplifiers (DA) with apertures of ∅ (20-140)mm and (200×200)mm and (300×300)mm are presented accordingly. Platinum-free Nd-glass with different concentration of neodymium ions is used.

CA.P.37 TUE
High efficiency diode-side-pumped Nd3+:YLiF4 laser at 1053nm
•*N. Wetter, E. Colombo de Sousa, F. Camargo, I. Ranieri,* and *S. Baldochi*; *Centro de Lasers e Aplicações - Instituto de Pesquisas Energéticas e Nucleares, São Paulo, Brazil*
Using a novel double pass resonator configuration, 6.9W of output power and 33% optical efficiency were obtained in fundamental mode and 45% in multimode operation with a very compact cavity.

CA.P.38 TUE
Cr^{4+}:YAG Passive Q-switching of Directly Pumped Nd Lasers
•*N. Pavel, T. Dascalu, V. Lupei,* and *N. Vasile*; *National Institute for Lasers, Plasma and Radiation Physics, Laboratory of Solid-State Quantum Electronics, Bucharest, Romania*
The pump at 0.88 μm, directly into the $^4F_{3/2}$ emitting level, was used to demonstrate Nd:YAG and Nd-vanadates lasers passively Q-switched by Cr^{4+}:YAG with improved performances in comparison with the classical pump at 0.81 μm.

CA.P.39 TUE
Spectroscopic Bases for Performance Enhancement and Power Scaling of Nd: Gadolinium Scandium Gallium Garnet Lasers
•*L. Voicu*[1], *L. Aurelia*[1], *P. Nicolaie*[1], and *I. Akio*[2]; [1]*National Institute for Lasers, Plasma and Radiation Physics, Lab. ECS, Bucharest, Romania*; [2]. *World-Lab. Co. Ltd, Nagoya, Japan*
Extended spectroscopic investigation of Nd:GSGG crystals and ceramics suggest and the laser emission in CW and pulsed regimes confirms the improvement of performances and power scaling by direct pumping into the emitting level.

CA.P.40 TUE
Radially polarized mode-locked Nd:YAG oscillator
•*F. Enderli* and *T. Feurer*; *Institute of Applied Physics, University of Bern, Bern, Switzerland*
We demonstrate mode-locked operation of a Nd:YAG laser emitting radially polarized 400 ps long pulses by exploiting the thermally induced birefringence of the active medium and a special cavity design.

CA.P.41 TUE
Cone-refringent solid-state bulk laser
•*A. Abdolvand*[1], *K. Wilcox*[1], *T. Kalkandjiev*[2], and *E. Rafailov*[1]; [1]*University of Dundee, Dundee, United Kingdom*; [2]*Conerefringent Optics SL, Barcelona, Spain*
We present the first diode pumped cone-refringent Nd:KGW laser producing excellent beam quality from a simple two mirror cavity configuration independent of the cavity length.

CA.P.42 TUE
Research on Coherent Beam Combination for Radial Slab Solid-State Laser
•*Z. Tian*; *Information Optoelectronics research institute, Harbin Institute Of Technology at Weihai, Weihai, China, People's Republic of (PRC)*
Experimental results on radial slab solid-state laser are presented. The laser consists of eight radial Nd:glass slabs bumped by four flash lamps.

CA.P.43 TUE
High efficiency 17W single frequency ring laser with feedback mirror
•*P. Shardlow* and *M. Damzen*; *Photonics, The Blackett Laboratory, Imperial College London, London, United Kingdom*
Single longitudinal mode TEM_{00} operation at 17W is demonstrated in $Nd : YVO_4$ bounce geometry ring laser. Unidirectionality is imposed through retro-reflection of one cavity direction output. Efficiency is improved through additional amplifier pass by the output.

CA.P.44 TUE
Mode-Selective Toroidal Mirrors for Unstable Resonator Planar Waveguide and Thin Slab Solid-State Lasers
K.L. Wlodarczyk, I.J. Thomson, •*H.J. Baker,* and *D.R. Hall*; *Heriot-Watt University, Edinburgh, United Kingdom*
Toroidal resonator mirrors with in-built mode selectivity have been produced by laser machining techniques, enabling new hybrid unstable resonator configurations for Nd: and Yb:YAG planar lasers, e.g. a 300micron wide mirror with 230x30 mm radii.

13:30 – 14:30
CB.P: CB Poster Session

CB.P.1 TUE
Fast physical random bit generator based on chaotic semiconductor lasers: Application to quantum cryptography
•*A. Uchida*[1], *T. Honjo*[2], *K. Amano*[3], *K. Hirano*[3], *H. Someya*[3], *H. Okumura*[1], *S. Yoshimori*[3], *K. Yoshimura*[4], *P. Davis*[4], and *Y. Tokura*[2]; [1]*Saitama University, Saitama, Japan*; [2]*NTT Basic Research Laboratories, Kanagawa, Japan*; [3]*Takushoku University, Tokyo, Japan*; [4]*NTT Communication Science Laboratories, Kyoto, Japan*
We report on the application of a fast physical random bit generator based on chaotic semiconductor lasers to generation of random pulse sequences at 1.0 Gbps in the differential-phase-shift quantum-key-distribution (DPS-QKD) system.

CB.P.2 TUE
Vertical Modulator Array for Fast Intra-Cavity Wavelength Control
•*M. Bülters*; *Zentrum für Halbleitertechnik und Optoelektronik, Duisburg, Germany*
We present a new concept for wavelength switching and multi wavelength operation of an external-cavity laser diode using an intra-cavity array of vertical electro absorption modulators (EAMs).

CB.P.3 TUE
Optimization of self-mixing modulation in VCSELs for sensing applications
•*D. Larsson, K. Yvind,* and *J. Hvam*; *Department of Photonics Engineering, Technical University of Denmark, Kgs Lyngby, Denmark*
We have numerically investigated the visibility of self-mixing interference in VCSELs for use in sensing applications. By optimizing the epitaxial structure of a standard VCSEL we can improve the performance by 100 percent.

CB.P.4 TUE
1.3 μm VCSEL Transmission Performance over 20 km at 12.5 Gb/s
•*A. Gatto*[1], *A. Boletti*[1], *P. Boffi*[1], *C. Neumeyr*[2], *M. Ortsiefer*[2], *E. Roenneberg*[2], and *M. Martinelli*[1]; [1]*Politecnico di Milano, Dipartimento di Elettronica e Informazione, Milano, Italy*; [2]*VERTILAS GmbH, Garching, Germany*
We demonstrate 1335nm VCSEL propagation performances at 12.5 Gb/s. Error-free measurements are presented over 20-km SSMF uncompensated fiber at different temperatures (20°C-70°C) in order to verify its uncooled capabilities for short and medium distances.

CB.P.5 TUE
Mechanical properties of a movable micro-mirror membrane for electro-statically tunable optical filters and vertical-cavity surface-emitting lasers
•*C. Gierl*[1], *G.D. Cole*[2], *B. Koegel*[1], *S. Jatta*[1], *K. Zogal*[1], *H. Davani*[1], and *P. Meissner*[1]; [1]*FG Optische Nachrichtentechnik, Technische Universität Darmstadt, Darmstadt, Germany*; [2]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Wien, Austria*
A wavelength tunable vertical-cavity surface-emitting laser with movable mirror membrane is presented. In agreement the measured and simulated mechanical frequency response show a fundamental resonance near 200 kHz, which enables high-speed tuning under electro-static actuation.

CB.P.6 TUE
Band-structure and gain-cavity tuning of 2.4-μm GaSb buried tunnel junction VCSELs
•*I. Marko*[1], *B. Ikyo*[1], *S. Sweeney*[1], *A. Adams*[1], *A. Bachmann*[2], *K. Kashani-Shirazi*[2], and *M.-C. Amann*[2]; [1]*Advanced Technology Institute, University of Surrey, Guildford, United Kingdom*; [2]*Walter Schottky Institut, Technische Universität München, Garching, Germany*
The band-structure and gain-cavity alignment of 2.4μm GaSb-based BTJ-VCSELs is manipulated using high pressure. Experiments demonstrate that changing the gain-cavity alignment by ~10meV can provide temperature independent operation by compensating for losses in the devices.

CB.P.7 TUE
Incomplete mode-locking in one-section QD lasers with ultra-long cavity
•*G. Lin*[1], *H.-C. Cheng*[1], *K.-F. Lin*[2], *R. Xuan*[2], and *C.-P. Lee*[1]; [1]*National Chiao-Tung University, Hsinchu, China, Republic of (ROC)*; [2]*Industrial Technology Research Institute, Hsinchu, China, Republic of (ROC)*
The first self-mode-locked QD lasers at 1300-nm range based on GaAs substrates were fabricated in one-section configuration. Incomplete mode-locking with repetition frequency of 2.4 GHz was achieved with ultra-long cavity length of 1.68 cm.

CB.P.8 TUE
Linewidth narrowing and phase locking of quantum-dot mode-locked lasers emloying single- and dual-mode injection locking
•*T. Habruseva*[1,2], *S. O'Donoghue*[1], *N. Rebrova*[1,2], *D. Rachinskii*[3], *S. Hegarty*[1,2], and *G. Huyet*[1,2]; [1]*Tyndall National Institute, Cork, Republic of Ireland*; [2]*Cork Institute*