行政院國家科學委員會專題研究計畫 期末報告

半導體量子點兆赫波輻射源之研製

計 畫 類 別 ： 個別型
計 畫 編 號 ： NSC 101-2221-E-009-122-
執 行 期 間 ： 101 年 08 月 01 日至 102 年 10 月 31 日
執 行 單 位 ： 國立交通大學電子工程學系及電子研究所

計畫主持人： 林國瑞

計畫參與人員： 碩士班研究生-兼任助理人員：陳明睿
碩士班研究生-兼任助理人員：劉乃誠
碩士班研究生-兼任助理人員：白振鴻
碩士班研究生-兼任助理人員：李厚璁

報 告 附 件 ： 出席國際會議研究心得報告及發表論文

公 開 資 訊 ： 本計畫可公開查詢

中 華 民 國 102 年 12 月 26 日

中文摘要： 本計劃係以半導體量子點之磊晶材料與技術來實現兆赫波輻射源；利用外腔式二極體雷射之可調波長及窄頻的特性，調整兩道連續波雷射的中心波長，使其差頻落在兆赫波段，便可利用非線性光學之光混頻或差頻產生等機制得到窄頻且可調頻率之連續兆赫波輻射。

量子點雷射主動區為十層啁啾式堆疊的設計，藉由改變砷化銦鎵覆蓋層的厚度來調變各層量子點的中心波長，我們選擇三個中心波長並以交錯方式堆疊不同層數。雷射磊晶片經脊狀波導製程並劈裂出不同共振腔長度，而為了抑制元件內部共振腔產生 FP 雷射以利外部共振腔的波長選擇機制，我們將量子點雷射的前後端面分別進行抗反射與高反射鍍膜。

首先我們將啁啾式堆疊量子點雷射置於 Litrrow 外腔式雷射架構中而獲致寬達 150-nm（1143-1293 nm）之單一波長可調之外腔式量子點雷射，其操作電流皆可小於 90 mA。接著我們改採富氏轉換外腔式雷射架構來實現多波長雷射，也就是在 Littman 架構下搭配透鏡與特殊 V-型狹縫設計來選擇多個回授波長，我們獲致雙波長、三波長及四波長之外腔式量子點雷射，相鄰波長位置及間距皆是可調的，這對低密度分波多工系統是很有潛力的應用。最後我們將雙波長雷射入射光導天線，利用光混頻機制試圖產生兆赫波輻射源，我們尚須扣除環境及偵測器本身的熱訊號，才能真正確認此調變訊號是否為雷射差頻所產生的兆赫波輻射。

中文關鍵詞： 量子點雷射、可調波長雷射、外腔式二極體雷射、兆赫波輻射源

英文摘要： This project is aimed to demonstrate terahertz (THz) radiation based on epitaxial material and technology of semiconductor quantum dots (QDs). The narrow-band and frequency-tunable THz radiation are proposed to be implemented by combining multi-wavelength lasing emissions of external-cavity diode lasers and nonlinear optical mechanism of phtomixing or difference frequency generation.

The chirped multilayer QD active region consists of 10 layers of self-assembled InAs QDs which are capped by In0.15Ga0.85As strain reducing layers of varying thickness. Three chirped wavelengths of longer, medium, and shorter wavelength range are grown interlaced with different stacking numbers. The wafer is patterned by wet etching into ridge waveguides and cleaved into laser bars with different cavity

lengths. To suppress internal Fabry-Perot emissions and facilitate external grating selection of lasing wavelength, the front facets are deposited with broadband multilayer anti-reflection coating, while the rear facets are deposited with high-reflection distributed Bragg reflector coating.
First, the chirp-stacked multilayer QD lasers are arranged in Littrow external-cavity configuration. The single-wavelength tuning range of 150 nm, from 1143 nm to 1293 nm, is achieved under low operation current of 90 mA. Then, multi-wavelength lasers are achieved by using the Fourier-Transform external-cavity configuration； equivalently, special V-like slit is incorporated in the modified Littman configuration. We have therefore achieved dual-, triple- and quadruple-wavelength lasing emissions for potential application of coarse wavelength-division multiplexing. Finally, the dual-wavelength external-cavity QD lasers are incident on the photoconductive antenna for photomixing. The modulated THz signals are therefore detected by the Golay cell. We still have to subtract the thermal background from the environment and the detector in order to make sure the modulated signal is indeed the THz radiation.

英文關鍵詞： Quantum Dot Lasers, Tunable Lasers, External Cavity Lasers, Terahertz Emitters

行政院國家科學委員會補助專題研究計畫 □期中進度報告
■期末報告

半導體量子點兆赫波輻射源之研製

計畫類別：■個別型計畫　□整合型計畫
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執行期間：101 年 8 月 1 日至 102 年 10 月 31 日

執行機構及系所：國立交通大學電子工程學系暨電子研究所

計畫主持人：林國瑞
共同主持人：
計畫參與人員：陳明睿、劉乃誠、白振鴻、李厚璁

本計畫除繳交成果報告外，另含下列出國報告，共 _1_ 份：
□移地研究心得報告
■出席國際學術會議心得報告
□國際合作研究計畫國外研究報告

處理方式：除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

中　華　民　國 102 年 10 月 31 日

半導體量子點兆赫波輻射源之研製

Semiconductor Quantum Dot Terahertz Emitters

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執行期間：101 年 8 月 1 日 至 102 年 10 月 31 日

主持人：林國瑞 國立交通大學電子工程學系暨電子研究所 副教授

一、中文摘要

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二、英文摘要

Keywords: Quantum Dot Lasers, Tunable Lasers, External Cavity Lasers, Terahertz Emitters

This project is aimed to demonstrate terahertz (THz) radiation based on epitaxial material and technology of semiconductor quantum dots (QDs). The narrow-band and frequency-tunable THz radiation are proposed to be implemented by combining multi-wavelength lasing emissions of external-cavity diode lasers and nonlinear optical mechanism of phtomixing or difference frequency generation.

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First, the chirp-stacked multilayer QD lasers are arranged in Littrow external-cavity configuration. The single-wavelength tuning range of 150 nm, from 1143 nm to 1293 nm, is achieved under low operation current of 90 mA. Then, multi-wavelength lasers are achieved by using the Fourier-Transform external-cavity configuration; equivalently, special V-like slit is incorporated in the modified Littman configuration. We have therefore achieved dual-, triple- and quadruple-wavelength lasing emissions for potential application of coarse wavelength-division multiplexing. Finally, the dual-wavelength external-cavity QD lasers are incident on the photoconductive antenna for photomixing. The modulated THz signals are therefore detected by the Golay cell. We still have to subtract the thermal background from the environment and the detector in order to make sure the modulated signal is indeed the THz radiation.

三、計畫緣由與目的

兆赫波段（Terahertz or THz）嚴格定義係指頻率落在0.3 ~3 THz或者波長介於100~1000 μm的電磁波（較寬鬆的定義為0.1~10 THz或30~3000 μm），從研發的歷史來看，這個波段由於缺乏有效率而且經濟便利的發射輻射源、偵測器及傳輸相關元件因而鮮受重視[1-3]。近年來，由於材料成長與製作技術的成熟，加上許多潛在的應用獲得初步的展示，因此兆赫波元件的研發正引起廣大的興趣。兆赫波的應用層面相當地廣泛，包括：天文研究（觀測宇宙星雲、星塵與星體等輻射光譜）、地球科學研究（分析大氣組成、探討溫室效應與臭氧層破洞等）、分子辨識及顯像（偵測毒性或爆裂性等危安物品）、生物醫學顯像（偵測癌細胞）、食物品管以及半導體廠之製程監控等[2]。

兆赫波輻射源之發展請詳見本研究群顏順通教授所發表的專文 [2]；若以操作原理來區分，大致可分成兩類：自由載子傳輸震盪與量子躍遷輻射。前者多以電子元件的形式呈現，如甘氏二極體（Gunn）、共振穿隧二極體（RTD）、崩渡二極體（IMPATT）以及短通道之高遷移率場效電晶體（FET）等，主要是將電子的震盪頻率由射頻（RF）或微波（microwave）波段往上增加至兆赫波段；國內目前有綦振瀛教授及張翼教授將異質接面雙載子電晶體（HBT）的電流增益截止頻率及最大震盪頻率（f_T與f_{max}）推至兆赫波段，顏順通教授則在高電子移動率電晶體（HEMT）量測到寬頻分佈的兆赫波輻射。後者（量子躍遷輻射）多以光子元件的形式呈現，其一利用黑體輻射原理（如高壓汞燈），其二利用受激輻射原理（如雷射），其三利用非線性光學效應（混頻、差頻或整流等）；國內目前大多利用第三種效應以昂貴的脈衝雷射系統激發天線結構來獲取寬頻且同調的兆赫波輻射 [4]。直接實現兆赫波雷射的研究相對稀少，此乃因雷射主動區材料必須具有兆赫波段的增益以產生受激輻射，而依材料被激發方式又可分為光致輻射及電致輻射；由於光致輻射的效率差、成本高而且不易商品化，一般看好電致輻射的量子串級雷射（Quantum Cascade Lasers）[5]，此部分的研究重點係將光子的躍遷頻率從紅外光或可見光波段向下降低至兆赫波段。

不管是利用電子元件將電子的震盪頻率增加，或者是利用光子元件將光子的躍遷頻率減少，當頻率進入兆赫波段時，兩者的輻射功率與效率均大幅降低，長久以來沒有突破性的發展而形成所謂的兆赫波間隙（THz Gap），因此本計畫將聚焦於兆赫波段輻射源之研製，期

以半導體材料實現輕巧而有效率的兆赫波輻射源。雖然目前以半導體量子井（QW）結構所研製之量子串級雷射已可操作在77 K 以上，波長也可延伸至約1 THz [5]，然此輻射源的最大缺點為堆疊結構需要以分子束磊晶方式成長數百甚至上千層能隙高低不同的半導體薄層，十分耗費時間和成本，而且容易對磊晶儀器造成損害 [2,5]。在上述的現況下，我們挑選量子點（QD）磊晶材料與技術，希望藉此研製新穎的量子點兆赫波輻射源。

量子點磊晶材料與技術雖然不若量子井來得成熟，但因量子點主動區具有低臨限電流密度、高特徵溫度及高微分增益等潛在優勢，因此被視為兆赫波輻射源的最佳候選材料[6-9]。然而研究量子點產生THz的文獻大部分停留在剛起步的階段：Ref. [6] 指出當量子點intersublevel能量間隔小於縱向光學聲子能量（*e.g.* 14 meV or 3.4 THz），其載子鬆弛受到抑制而使得其生存期大幅延長（由ps延長至ns），這個現象可以突破量子井串級雷射在兆赫波段無法室溫操作的限制；Ref. [7] 則探討載子在量子點的共振穿遂（resonant tunneling）效應，這個效應對於製作量子點串級雷射是很重要的。由於串級雷射不但需要精確控制而且多層堆疊容易損害磊晶機台，加上自組式量子點的非均勻展寬（inhomogeneous broadening）特性使得intersublevl無法被精確決定，因此量子點串級雷射可能只是一個達不到的夢想。

Ref. [8] 提出將量子點放入圓柱狀微共振腔（micro-cylinder），結合GaAs-AlGaAs材料的非線性係數、微共振腔的巨大Q值（quality factor）以及圓柱波導的WGM模場（whispering gallery mode），利用兩個WGM的頻率差異應可發出兆赫波輻射，然目前僅停留在光激發量測與數值模擬的階段，距離室溫操作與通電激發有很大的落差。較有可能性實現量子點兆赫波輻射源的研究應屬Ref. [9]，法國CNRS實驗室在磷化銦基板上成長1.55 μm波段之量子點雷射，他們在單段式電極架構下觀測到自鎖模（self-mode-locking）的現象，經縮短共振腔至120 μm，其自鎖模之脈衝重複率達兆赫波段的346 GHz，由於脈衝光場伴隨電子的震盪與電流的調制，預期可觀測到如同光導天線之兆赫波輻射產生。我們執行NSC98計畫也在砷化鎵基板上首次觀測到1.3 μm波段之自鎖模量子點雷射 [10]，然因鎖模程度不完全，建議還是採用傳統兩段式電極的被動鎖模架構來實現。由於量子點成長條件及堆疊應力控制需要相當的經驗累積，國內僅有少數單位展示1.3 μm波段的雷射，因此尚無鎖模量子點雷射的相關研發，而以量子點製作兆赫波輻射源的研究更是付之闕如。

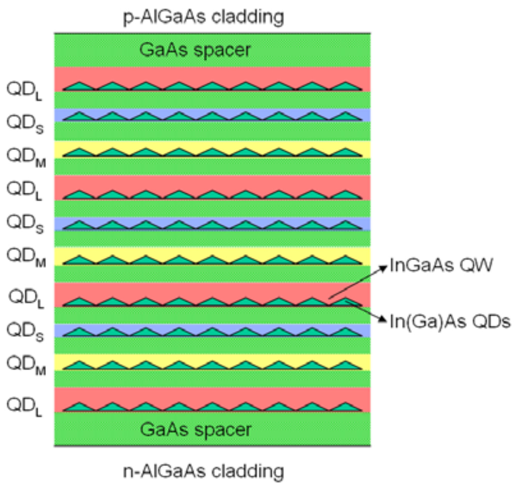
四、研究方法及成果

本計劃係以半導體量子點之磊晶材料與技術來實現兆赫波輻射源（THz emitters），利用外腔式雷射（external-cavity lasers）之波長可調及窄頻的特性，調整兩道連續波（continuous-wave or cw）雷射的中心波長（或頻率），使其差頻落在兆赫波段，便可利用非線性光學之光混頻（photomixing）或差頻產生（Difference Frequency Generation or DFG）等機制放出連續兆赫波輻射；由於雷射的中心波長可調，因此可以得到窄頻且可調頻率之連續兆赫波輻射。

若是要以外腔式雷射實現可調頻率之兆赫波輻射，除了要讓兩道雷射光的差頻落在兆赫波段，雷射本身的線寬（linewidth）也要控制在數十GHz的範圍，這是目前外腔式雷射可以達到的 [11-13]；而如果選擇雷射中心波長為1.3 μm波段，則1~3 THz的差頻相當於兩道雷射光的中心波長相隔5~15 nm，這也是量子點增益介質所能達到的增益頻寬。

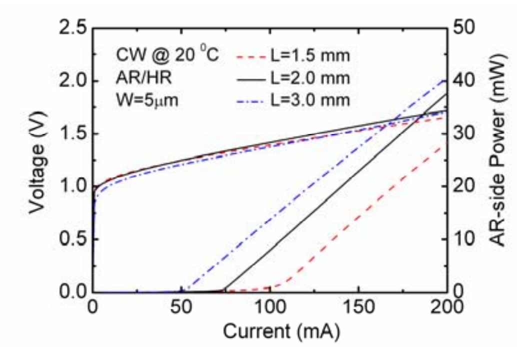
圖一為本計畫所採用之啁啾式堆疊多層量子點雷射結構，我們固定InAs QDs上方

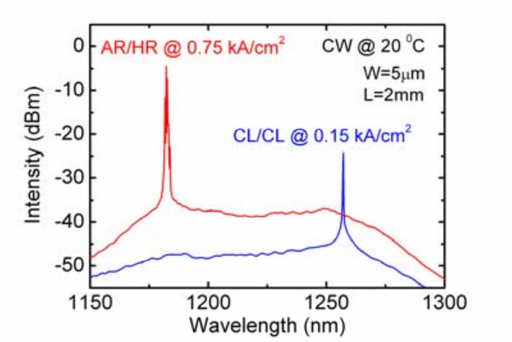
InGaAs QW覆蓋層的成分，藉由改變InGaAs QW覆蓋層的厚度來調變各層量子點的中心波長，中心波長由長而短分別以QD_L、QD_M與QD_S表示，磊晶層數分別為4層、3層與3層並且以交錯方式堆疊。完成生長之磊晶片經標準雷射製程，製作出寬度5 μm之脊狀波導，共振腔則劈裂出1.5 mm、2.0 mm與3.0 mm等三種長度。



圖一 啁啾式堆疊多層量子點雷射結構示意圖

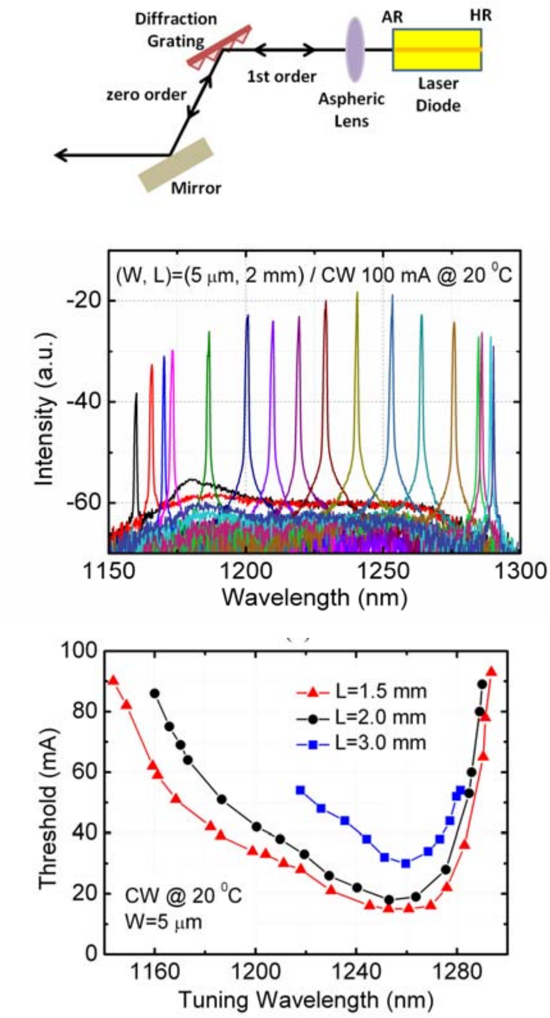
為了抑制元件內部共振腔的Fabry-Perot雷射以利外部共振腔的波長選擇機制，我們將量子點雷射的前後端面分別進行抗反射與高反射鍍膜（AR/HR coating），圖二顯示鍍膜後之*L-I-V*與波長特性，圖二(b)顯示長度2 mm之量子點，鍍膜後臨限電流密度由0.15 kA/cm^{2}上升至0.75 kA/cm^2，發光波長也由基態的1260 nm切換之激態的1180 nm。





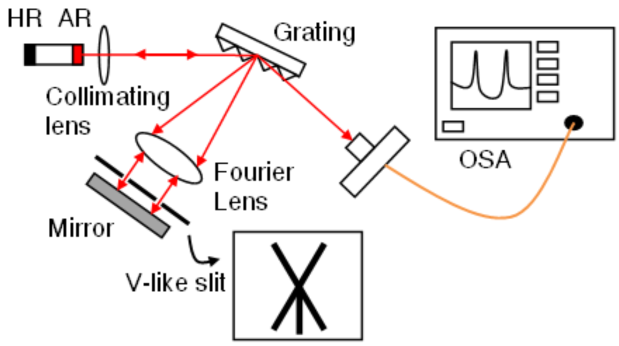
圖二 AR/HR 雷射之(a) *L-I-V* 與(b)波長特性

首先，我們利用外部光柵選擇回授波長，以圖三(a)之 Littrow 外腔式雷射架構來實現單波長可調雷射，圖三(b)展示可調範圍寬達 150 nm（1143-1293 nm）之外腔式量子點雷射；在工作電流不超過 90 mA 的條件下，我們得到可調波長對臨限電流關係如圖三(c)。

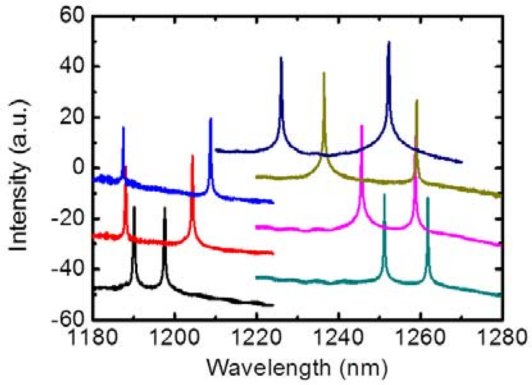


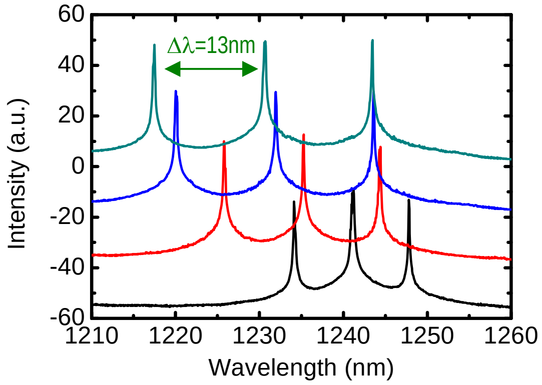
圖三 (a) Littrow架構 (b)150-nm可調雷射波長 (c)可調波長與臨限電流關係圖

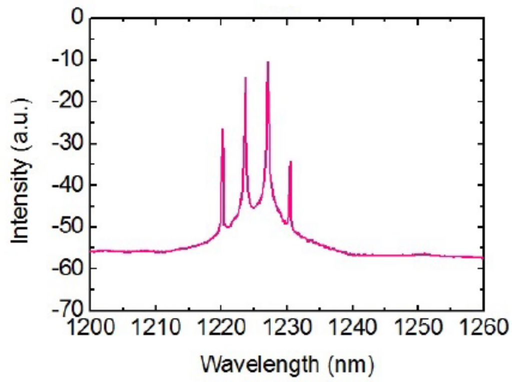
接者，我們改採圖四之富氏轉換外腔式雷射架構來實現多波長雷射，也就是在 Littman 架構下搭配透鏡與特殊 V-型狹縫設計來選擇多個回授波長，我們獲致了圖五(a)之雙波長、圖五(b)之三波長及圖五(c)之四波長外腔式量子點雷射，相鄰波長位置及間距皆是可調的，這對低密度分波多工系統（Coarse Wavelength Division Multiplexing or CWDM）是很有潛力的應用。



圖四　富氏轉換外腔式雷射架構

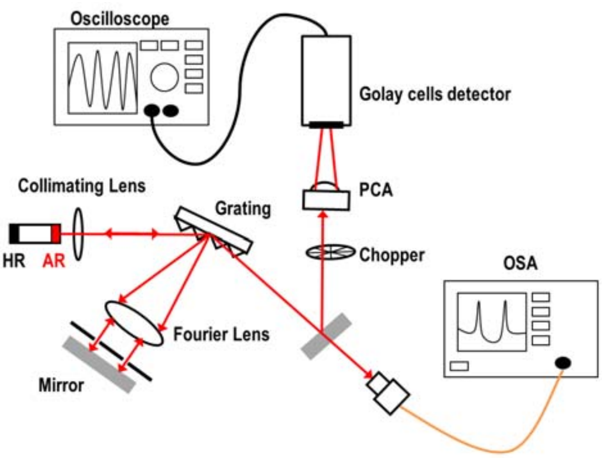




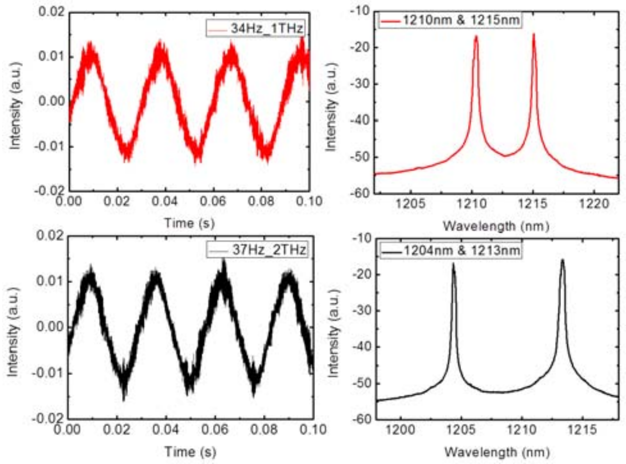


圖五 (a)雙波長(b)三波長及(c)四波長之外腔式量子點雷射

最後，我們架設如圖六之實驗架構來進行雙波長雷射之差頻以實現兆赫波輻射，利用光導天線（PhotoConductive Antenna or PCA）對兩道窄頻的雷射光作差頻產生，我們在高勒池偵測器（Golay Cell）觀測到圖七之調變訊號，我們尚須扣除環境及偵測器本身的熱訊號，才能真正確認此調變訊號是否為雷射差頻產生的兆赫波輻射。



圖六　兆赫波輻射源之實驗架構



圖七 高勒池所偵測到之調變訊號

五、結論與建議

於本年度計畫中，首先我們將啁啾式堆疊量子點雷射置於Litrrow外腔式雷射架構中而獲致寬達150-nm（1143-1293 nm）之單一波長可調之外腔式量子點雷射，其操作電流皆可小於90 mA。接著我們改採富氏轉換外腔式雷射架構來實現多波長雷射，也就是在Littman架構下搭配透鏡與特殊V-型狹縫設計來選擇多個回授波長，我們獲致雙波長、三波長及四波長之外腔式量子點雷射。最後我們將雙波長雷射入射光導天線，利用差頻機制試圖產生兆赫波輻射源，我們尚須扣除環境及偵測器本身的熱訊號，才能真正確認此調變訊號是否為雷射差頻產生的兆赫波輻射。

六、參考文獻

[1] B. Ferguson and X. C. Zhang, "Materials for terahertz science and technology," Nat. Mater., vol. 1, pp. 26-33, 2002.

[2] 鐘佩鋼、顏順通。兆赫波源之發展與原理簡介。物理雙月刊 31(2): 109-116。2009。

[3] Y. Kawano, "Terahertz Sensing, Imaging and Application," 2010 CMOS Emerging Technologies Workshop, Whistler, BC, Canada, 19-21 May, 2010. Available from: http://www.cmoset.com/uploads/Yukio_Kawano_2010.pdf

[4] 洪勝富、齊正中。短脈衝雷射激發兆赫輻射技術及其應用。物理雙月刊 23(2): 322-328。2001。

[5] B. S. Williams, "Terahertz quantum-cascade lasers," Nat. Photonics, vol. 1, pp. 517-525, 2007.

[6] E. A. Zibik, T. Grange, B. A. Carpenter, N. E. Porter, R. Ferreira, G. Bastard, D. Stehr, S. Winnerl, M. Helm, H. Y. Liu, M. S. Skolnick and L. R.Wilson, "Long lifetimes of quantum-dot intersublevel transitions in the terahertz range," Nat. Mater., vol. 8, pp. 803-807, 2009.

[7] H. C. Liu, B. Aslan, J. A. Gupta, Z. R. Wasilewski, G. C. Aers, A. J. SpringThorpe and M. Buchanan, "Quantum dots for terahertz generation," J. Phys., vol. 20, pp. 384211, 2008.

[8] A. Taormina, A. Andronico, F. Ghiglieno, S. Ducci, I. Favero and G. Leo, "Microsoft Room Temperature Integrated Terahertz Emitters Based on Three-Wave Mixing in Semiconductor Microcylinders," Recent Optical and Photonic Technologies, Ki Young Kim (Ed.), ISBN: 978-953-7619-71-8, InTech, 2010. Available from: http://www.intechopen.com/articles/show/title/microsoft-room-temperature-integrated-terahertz-emitters-based-on-three-wave-mixing-in-semiconductor

[9] K. Merghem, A. Akrout, A. Martinez, G. Aubin, A. Ramdane, F. Lelarge, and G.-H. Duan, "Pulse generation at 346 GHz using a passively mode locked quantum-dash-based laser at 1.55 μm," Appl. Phys. Lett., vol. 94, pp. 021107, 2009.

[10] G. Lin, H. C. Cheng, K. F. Lin, R. Xuan, and C. P. Lee, "Incomplete mode-locking in one-section QD lasers with ultra-long cavity," European Conference on Lasers and Electro-Optics and the XIth European Quantum Electronics Conference 2009 (CLEO Europe - EQEC 2009).

[11] F. Havermeyer, L. Ho and C. Moser "Compact single mode tunable laser using a digital micromirror device," Opt. Express, vol. 19, no. 15, pp. 14642–14652, 2011.

[12] M. Breede, C. Kasseck, C. Brenner, N. C. Gerhardt, M. Hofmann, and R. Hofling, "Micromirror device controlled tunable diode laser," Electron. Lett., vol. 43, no. 8, pp. 456–457, 2007.

[13] M. Breede, S. Hoffmann, J. Zimmermann, J. Struckmeier, M. Hofmann, T. Kleine-Ostmann, P. Knobloch, M. Koch, J. P. Meyn, M. Matus, S. W. Koch, and J. V. Moloney, "Fourier-transform external cavity lasers," Opt. Comm., vol. 207, pp. 261–271, 2002.

附件四

國科會補助專題研究計畫項下出席國際學術會議心得報告

日期： 102 年 5 月 8 日

計畫編號	NSC 101-2221-E-009 -122		
計畫名稱	半導體量子點兆赫波輻射源之研製		
出國人員姓名	林國瑞	服務機構及職稱	交通大學電子工程系所/副教授
會議時間	102 年 4 月 15 日至 102 年 4 月 18 日	會議地點	Prague, Czech Republic
會議名稱	(中文) 光學與光電子學國際會議 (英文) 2013 SPIE Optics + Optoelectronics		
發表論文題目	(中文) 可調式多波長量子點外腔室雷射 (英文) tunable multiwavelength quantum dot external-cavity lasers		

一、參加會議經過

2013 SPIE Optics + Optoelectronics 於 4 月 15~18 日在捷克的首都 Prague 城市舉辦，會議大致可分為兩個部分：技術會議跟特別活動，其中技術會議共有 16 種不同議題的 session，主題涵蓋了合成材料、非線性光學應用、光子計量應用、量子光學應用、光感測器、微結構與特殊光纖、全像術、VUV+EUV+X-ray 光學相關理論及應用、雷射加速、生醫應用、超高能雷射和整合光學的物理與模擬…等光學光電子學相關研究議題；而特別活動包含了 3 場重點演說、歡迎晚會、ICO 頒獎典禮及 3 個研討會（Workshop），發表論文（口頭和壁報）超過 600 篇，參展廠商逾 30 家，與會人員估計近千人。

在第一天安排的 3 場重點演說中，第二場演說邀請到了近年來非常有名的研究機構-比利時微電子中心（IMEC）的 Roel Baets 教授，演講題目為『Silicon Photonics: a Generic Technology Platform for Innovation in Many Markets』；內容從一開始簡單介紹 IC 的發展，隨著技術的進步，將 IC 與雷射整合在單一晶片進而形成了 Silicon Photonics 的相關研究，為何要將雷射的發光概念與 IC 作整合，換句話問，為何是 Silicon Photonics？由於 Si 有很高的折射係數，更重要的是，藉由現存且非常成熟的 CMOS 製程技術，同時可以符合低成本高產出的商業化需求，接著講者展示了各種形狀波導與其成果，每一種展示的研究成果都非常令人印象深刻，最讓我佩服的是自動化量測的影片展示，和我們用人工所量測的速度、效率實是難以望其項背！最後講者對這次主題給了如下的結論：Silicon Photonics 是一個正以非常快速度成長的主流產業，利用現有的 CMOS 技術可以應用在如遠端通訊、資料通訊、中間連結和感測應用；另一方面，對於這項新興的科技需要一套標準的製程程序來達到標準化，最後才能進到代工端達成真正的商業化應用。

我們所發表的論文『tunable multiwavelength quantum dot external-cavity lasers』時間安排在 4/16 的下午 5:10~5:30，聽眾約有十多人。我們的研究內容強調如何利用 chirped QD 有著較寬的

發光頻譜，設計不同的外腔式結構以得到多波長雷射的調變，而我們達到的成果是相關領域的研究中最低的注入電流密度，但聽眾似乎多投入於光纖與非線性光學的研究，因此詢問的二個問題與研究的重點較無相關。第一個問題是有關於多波長雷射的情況下，如何控制這些雷射波長的訊號強度，雖然這與目前我們研究的方向較為無關，但在研究的過程我們已經有想過並討論控制訊號的可能性，藉由理解外腔室雷射的原理，控制反饋光的反饋強弱程度，確實可以達成控制訊號的目的，相同的概念台大的林清富教授也有發表於 IEEE Photonics Technology Letters；而第二個問題是談到在這些多波長之間調變的速度能到多快，很可惜的目前我們量測的系統並不是自動化控制，這些不同波長雷射的變換都是完全手動，所以我們只能回覆提問者在未來透過結合微機電系統（MEMS）的整合控制後，我們才有辦法做到較為快速的變換。

二、與會心得

2012 年參加 SPIE 在聖地牙哥舉辦的 Optics+Photonics 國際會議，盛況空前令我留下深刻印象，而 2013 年 Optics+Optoelectronics 又在旅遊城市布拉格舉辦，因此吸引我投稿這個會議。投稿時未能找到完全符合的分類，原以為會被拒絕，收到接受通知令人有意外的驚喜。這個會議的論文接受率應該不到五成，或許是議題涵蓋高能量、加速器及非線性光學等較不熱門的領域，因此未列入交大電機學院的重要國際會議。

此次會議的規模比我想像的小，參與人數估計七~八百人，地點選在遠離舊城區的飯店內舉辦，雖然周邊的交通還算便利，搭乘地鐵、公車或電車都可以到達，但會場的空間不大，參與的廠商也嫌少，此外主辦單位的通知及提醒資訊不夠詳盡，接待晚宴還遠離會場 45 分鐘車程。晚宴中與交大光電許根玉教授聊起，才知道此會議每兩年在布拉格周邊飯店輪流舉辦，多為歐洲地區特別是捷克的教研及碩博生參與，當然不若 SPIE optics+Photonics 年會性質的國際會議來得規模盛大與經驗豐富。

這次會議我帶了一位碩二研究生出席，由於他有交換學生的經驗，我大膽地讓他作英文口頭報告，雖然這不是他第一次英文簡報，不過在各國頂尖研究人員的場合，還是有不小的壓力，緊張更是難免；一開始上台有點不太順暢，開始報告後愈來愈流暢，報告時間的掌控剛好，該提到的研究重點也都有講出來，對他本人應該是一個難忘的培訓與經驗。此外我們也聆聽多場受邀演講以及相近研究的發表，雖然大部分研究有點陌生，但對於啟發新的想法或進入新的研究領域還是很有助益。

三、考察參觀活動(無是項活動者略)

略。

四、建議

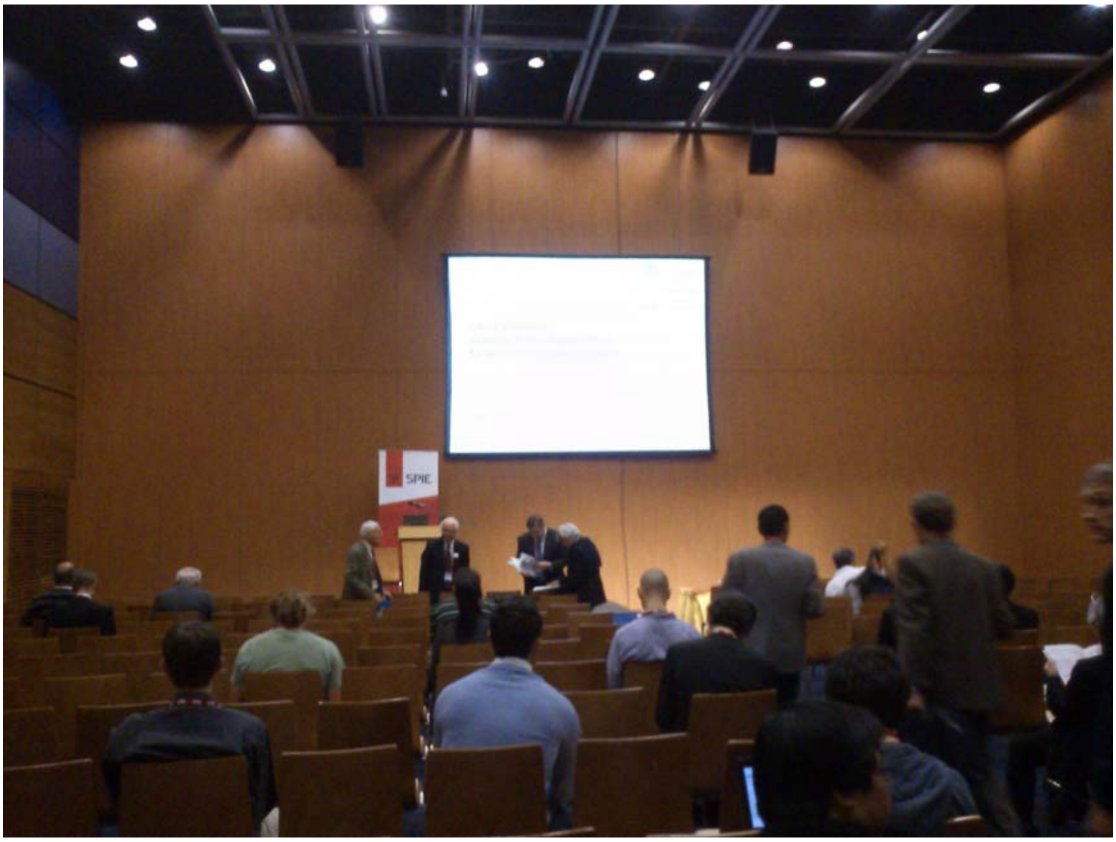
無。

五、攜回資料名稱及內容

Proceedings and CD for SPIE Optics + Optoelectronics 2013

六、其他

附上會場照片、口頭報告照片、指導碩士生與 session chairman 合照及廠商展場照片。

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Tunable multi-wavelength quantum dot external-cavity lasers

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ABSTRACT

The chirped multilayer quantum-dot (QD) gain media are arranged in Fourier-transform external-cavity laser (FT-ECL) configuration. Novel slit designs select 2, 3, and 4 different wavelengths that are diffracted from the grating for optical feedback. Therefore, the dual-, triple- and quadruple-wavelength ECLs are demonstrated in this study. The resulted multi-wavelength lasing emissions are achieved under injected current of 100 mA (or 1.33 kA/cm^2) with signal to amplified spontaneous emission (ASE) ratio over 20 dB. Around peak-gain wavelength of 12xx-nm range, the adjacent wavelength separation is over 50 nm for dual-wavelength lasing, up to 13 nm for triple-wavelength lasing, and about 4-5 nm for quadruple-wavelength lasing emissions. To further extend the wavelength separation for dual-wavelength lasing emissions, another modified scheme with two separate external mirrors are adopted and the achieved maximum value is about 126 nm in wavelength separation or over 25 THz in frequency difference. The terahertz (THz) generation by photomixing of dual-wavelength ECLs is also discussed in this study.

Keywords: tunable lasers, external-cavity lasers, quantum-dot lasers, semiconductor lasers

1. INTRODUCTION

External-cavity lasers (ECLs) incorporated with semiconductor gain media are promising for novel light sources. The widely tunable and multi-wavelength feature of ECLs has great potentials for coarse wavelength-division multiplexing (CWDM) in fiber-optic communications. Moreover, photomixng of multi-wavelength ECLs [1] has made possible the compact, cost-effective, and tunable THz generation in many applications such as spectroscopy, medical imaging, and security. To achieve simultaneously multi-wavelength lasing with semiconductor lasers, the common approaches are utilizing single laser with physically separated gain media for each wavelength [2] or multiple lasers in the external cavity [3]. However, these approaches require elaborate fabrication and packaging procedures which lead to larger dimension of the external cavity system.

The largest wavelength separation of dual-wavelength operation with quantum-well (QW) gain medium has been achieved by Huang *et al*. in grating-coupled external cavity [4]. Nevertheless, ECLs with QW gain medium require very high injection current density (typically more than 10kA/cm^2) to populate carriers to higher energy state for broadband tuning. Consequently, QD gain medium is a better choice since it can fulfill both low injection current density and broad spectral-tuning requirements [5-8]. Furthermore, low injection current density is also beneficial for cost and power consumption issues.

In this work, chirped multilayer QD structure of 1.3μm wavelength range [9] is incorporated in two modified schemes of Littman ECL configuration. In the first configuration, dual-, triple-, and quadruple-wavelength lasing emissions as well as their continuous tuning are demonstrated at record low injection current density of 1.33 kA/cm^2. Then in the second configuration, the maximum wavelength separation of 126 nm is achieved for dual-wavelength ECL by independent control of the optical feedback. Finally, we discuss the laser characteristics of dual-wavelength ECLs as well as their terahertz (THz) generation by photomixing.

2. EXPERIMENTAL DETAILS

The QD laser structure is grown by molecular beam epitaxy on Si-doped GaAs substrate. The active region consists of 10 layers of self-assembled InAs QDs which are capped by $In_{0.15}Ga_{0.85}As$ layers of varying thickness and spaced by GaAs of 33 nm. Three chirped wavelengths of longer, medium, and shorter wavelength range, with stacking numbers of 4, 3 and 3 layers, are designed with InGaAs layer thickness of 4, 3 and 1.5 nm, respectively. The detailed layer structure can be found in [9]. The wafer is processed into ridge waveguides of 5-μm width. As-cleaved laser bars are then

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passivated with broadband anti-reflection coating (R < 1%) in the front facets as well as high-reflection distributed Bragg reflector coating (R > 99%) in the rear facets.

Figure 1 shows the light-current-voltage (*L-I-V*) characteristics of solitary AR/HR coated QD laser with 1.5 mm in cavity length. The lasing wavelength of as-cleaved QD lasers is 1260 nm; however, it moves to shorter wavelength 1180 nm after AR/HR coating due to the increased mirror loss. In addition, the threshold current dramatically increases from 20mA to 100mA.

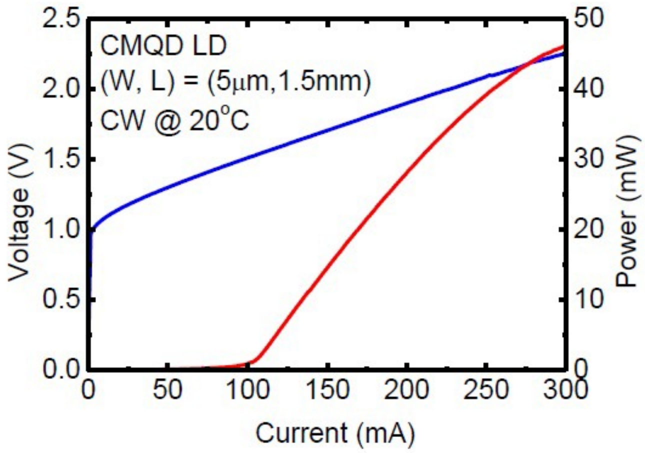

Figure 1. *L-I-V* characteristics of solitary AR/HR coated QD laser with 5-μm width and 1.5-mm length.

The AR/HR coated QD lasers are investigated in the Fourier-transform external-cavity laser (FT-ECL) configuration, i.e. the first modified scheme of Littman configuration by insertion of Fourier lens and slit in the first-order diffracted path [3]. Figure 2 shows the experimental setup. A collimating lens is utilized to collect the divergent light from the front mirror facet. The optical feedback is provided by first-order diffraction light which is diffracted from an external grating and then collected by a lens focused onto an external mirror. To select the multi-wavelength lasing emissions, a V-like slit is designed and put between Fourier lens and external mirror. The external grating is with groove density of 1200 lines/mm and blazed at wavelength of 1.0 μm. To tune the center wavelength or change the wavelength separation, one can move the V-like slit vertically or horizontally. The zeroth-order diffracted light is coupled via a multimode optical fiber into an optical spectrum analyzer.

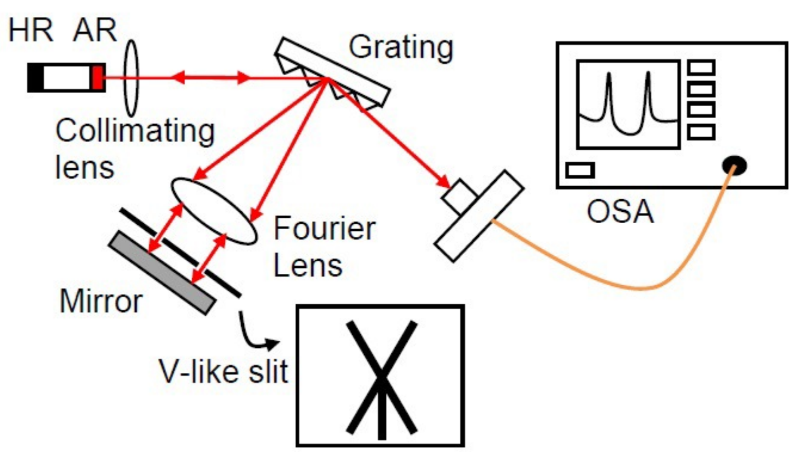

Figure 2. Experimental setup of tunable FT-ECL configuration.

Concerned to two-color ECLs, several concept schemes are proposed in the literature [10]. In above modification scheme, increasing the adjacent wavelength separation means increased spatial separation of selected wavelengths, which is limited by the slit design. However, the two separate wavelengths may be too far away to make nonzero incidence to the end mirror, and results in poor optical feedback. Therefore, the second modification scheme of Littman configuration, termed double-Littman ECL, is adopted and shown in Figure 3. Only two separate end mirrors are utilized for independent control of optical feedback. Since neither Fourier lens nor slit aperture is introduced, it is hard to get small wavelength separation due to the large physical dimension of end mirrors. The maximum wavelength separation achieved in this work is demonstrated by this scheme.

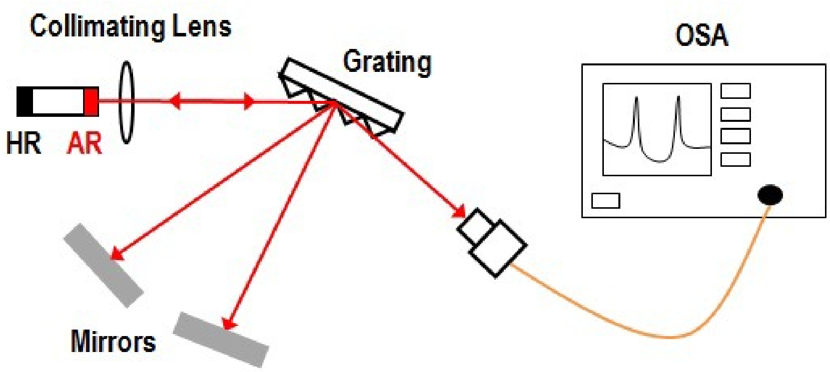

Figure 3. Experimental setup of double-Littman ECL configuration.

3. RESULTS AND DISSICUSIONS

3.1 Multi-wavelength FT-ECLs

Figure 4 shows the dual-wavelength tuning spectra under injection current of 100 mA at heatsink temperature of 20 ^{0}C. The signal to ASE ratio is in the range of 20 to 40 dB. The wavelength separation over 86 nm or frequency difference of 17 THz (not shown) can be achieved in FT-ECL configuration and it is limited by our design of slit separation. To further increase the wavelength separation may render the nonzero incidence of two selected wavelengths. Therefore, single end mirror should be replaced with two end mirrors or the second modification scheme of double-Littman ECL should be adopted.

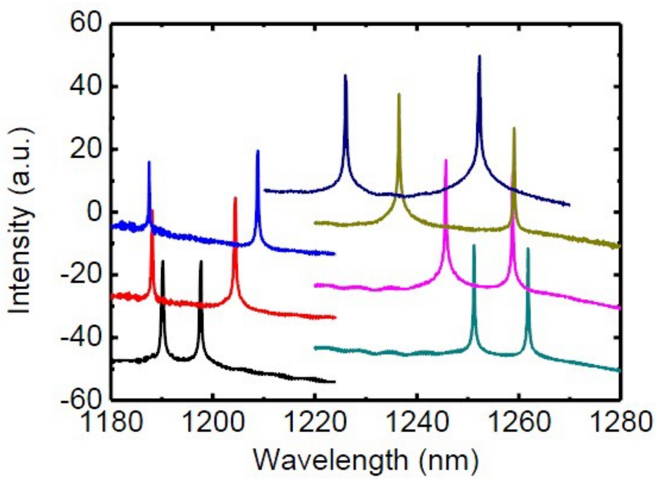

Figure 4. The dual-wavelength lasing spectrum in FT-ECL configuration.

Figure 5 shows the triple- and quadruple-wavelength lasing emissions. Continuously triple-wavelength tuning is obtained by utilizing the lower part of V-like slit as shown in Figure 2. The slit design can operate as a switch from two wavelengths to three wavelengths. The maximum adjacent wavelength separation is 13 nm and the signal to ASE ratio is also larger than 20 dB. With different slit design, the quadruple-wavelength lasing emissions is demonstrated and shown in Figure 5(b). The adjacent wavelength separation is about 4 nm; however, the intensities of four wavelengths vary in a large range. This phenomenon results from uneven optical feedbacks between these four wavelengths.

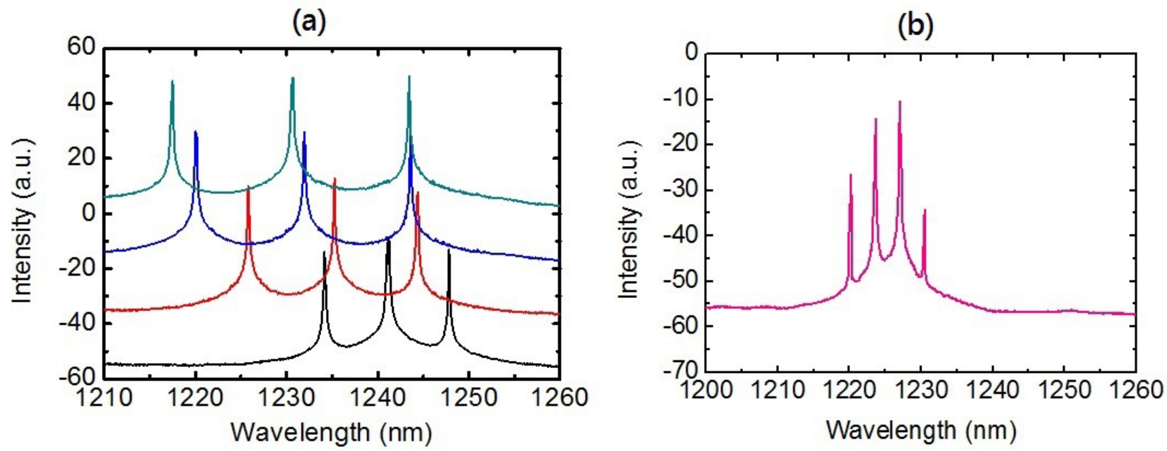

Figure 5. The spectrum of (a) triple-wavelength lasing emission (b) quadruple-wavelength lasing emission in FT-ECL configuration.

3.2 Double-Littman ECLs

Since the wavelength separation in FT-ECL configuration is limited by the slit, the double-Littman ECL configuration is adopted to achieve dual-wavelength lasing emission. Figure 6 shows the dual-wavelength lasing spectrum measured in double-Littman ECL configuration. The maximum wavelength separation or frequency difference is about 126 nm or over 25 THz. This result is in reasonable agreement with our maximum tuning range of 132 nm (from 1148 nm to 1281 nm) in conventional Littman configuration. The signal to ASE ratio is over 20 dB even at maximum wavelength separation as shown in Figure 6.

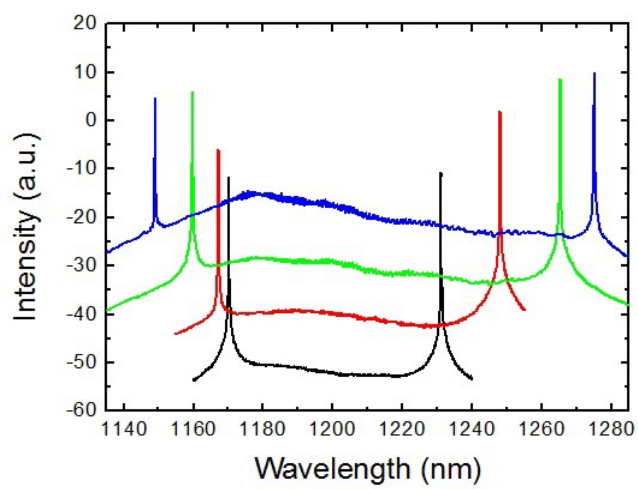

Figure 6. The dual-wavelength lasing spectrum in double-Littman ECL configuration.

The optical intensity distribution between the two wavelengths is an interesting issue in dual-wavelength lasing emissions. Matus *et al.* have theoretically analyzed the dynamics of various two-color ECL configurations by studying their time dependence of optical intensity distribution [11]. Here we present the static *L-I-V* characteristics of dual-wavelength lasing emissions in double-Littman ECL configuration. We first generate dual-wavelength lasing emissions of equal intensities with wavelength separation of 46 nm (1169nm and 1215nm) and then collect the total optical power of zeroth-order diffracted light. As shown in Figure 7, the current dependence of optical power seems to exhibit certain oscillating periodicity which needs further investigation.

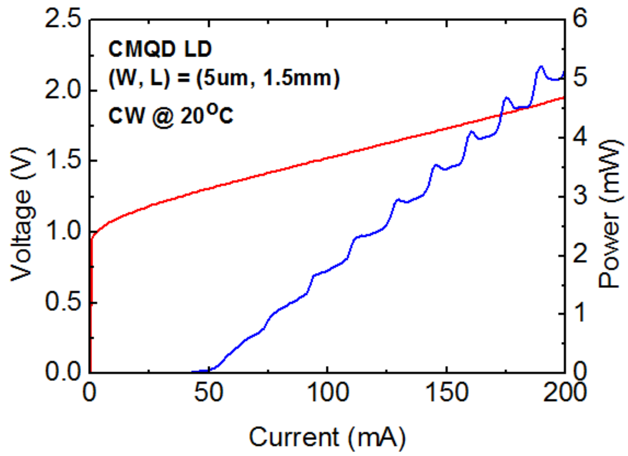

Figure 7. The *L-I-V* characteristics of dual-wavelength in double-Littman ECL configuration.

3.3 THz generation

Multi-wavelength ECLs are promising for THz generation by photomixing of multi-wavelength lasing emissions. Matus *et al.* have identified and characterized five two-color lasing regimes of coherent, semicoherent, multimode, chaotic, and multimode chaotic operation by numerical simulation of several two-color ECL configurations [11]. They have concluded that the two-color coherent laser regime should be the most attractive one for THz signal generation [11] and later demonstrated experimentally in FT-ECL configuration [14]. Moreover, direct THz emission out of dual-wavelength ECLs is investigated by Wang *et al.* [13] and Hoffmann *et al.* [14]. Figure 8 shows our photomixing setup for THz generation. The dual-wavelength lasing emissions is monitored by OSA and focused onto a biased photoconductive antenna (PCA). An aspheric focusing Si lens is mounted on the back side to collect wide-angel emission THz wave radiating from the PCA. The focused THz wave is then detected by the bolometer. Since the bolometer cannot discriminate the emitted THz signal from any other far infrared radiation (e.g. heat radiation) from the laser diode [12], we are going to confirm it by Fourier Transform Infrared Spectrometer (FTIR) of Bruker IFS 66v/S.

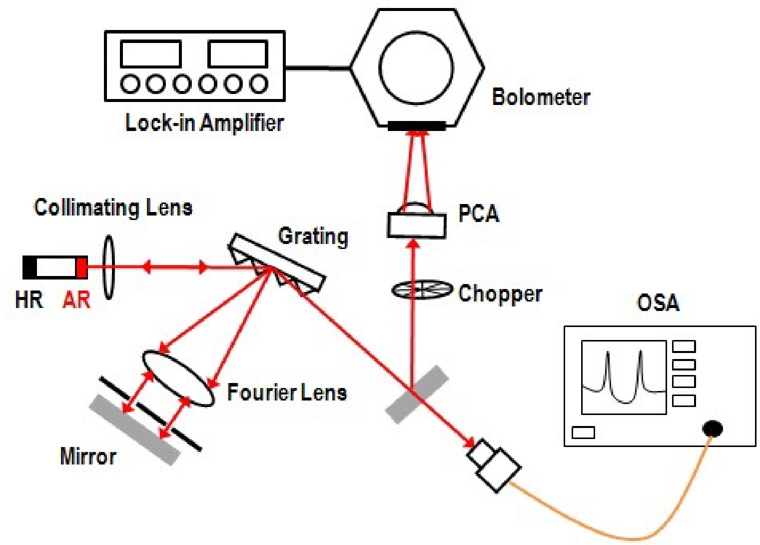

Figure 8. The photomixing setup for generating THz radiation with FT-ECL.

4. SUMMARY

Tunable multi-wavelength light emitters based on InAs/InGaAs/GaAs QDs are demonstrated in this study. The chirped multilayer QD gain media are arranged in FT-ECL configuration, i.e. the first modified scheme with Fourier lens and slit introduced in the first-order diffracted path. Novel slit designs with 2, 3, and 4 slit apertures select different wavelengths that are diffracted from the grating for optical feedback. Therefore, the dual-, triple- and quadruple-wavelength ECLs are implemented for promising applications, such as wavelength-division multiplexing (WDM) in fiber-optic communications and THz light sources generation by difference-frequency generation (DFG) mechanism.

The resulted multi-wavelength lasing emissions are achieved under injected current of 100 mA (or 1.33 kA/cm2). Around peak-gain wavelength of 12xx-nm range, the adjacent wavelength separation is over 50 nm for dual-wavelength lasing, up to 13 nm for triple-wavelength lasing, and about 4-5 nm for quadruple-wavelength lasing emissions. The maximum wavelength separation is limited by our slit design while the minimum wavelength separation is determined by the slit width. Moreover, the signal to ASE ratio is over 20 dB. Application of coarse-WDM or even dense-WDM can be benefited from further optimization.

To further extend the wavelength separation for dual-wavelength lasing emissions, the second modified scheme of double-Litman ECL configuration with two separate external mirrors are adopted and the maximum achieved value is about 126 nm in wavelength separation or over 25 THz in frequency difference. The terahertz (THz) generation by photomixing of dual-wavelength ECLs is also discussed in this study.

ACKNOWLEDGMENT

The authors are indebted to K. F. Lin of Industrial Technology Research Institute (ITRI) for device fabrication. The growth of QD laser structure is credited to Innolume GmbH in Dortmund, Germany. This work was supported by the Ministry of Education under the Aiming for the Top University and Elite Research Center Development Plan as well as the National Science Council Project under the contract number NSC 101-2221-E-009-122 and NSC 101-3113-P-009-004.

REFERENCES

[1] Gu, P., Chang, F., Tani, M., Sakai, K., and Pan, C. L., "Generation of Coherent cw-Terahertz Radiation Using a Tunable Dual-Wavelength External Cavity Laser Diode," Jpn. J. Appl. Phys. 38(11A), 1246-1248 (1999).

[2] Poguntke, K. R., Soole, J. B. D., Scherer, A., LeBlance, H. P., Caneau, C., Baht, R., and Koza, M. A., "Simultaneous multiple wavelength operation of a multistripe array grating integrated cavity laser," Appl. Phys. Lett. 62(17), 2024-2026 (1993).

[3] Breede, M., Hoffmann, S., Zimmermann, J., Struckmeier, J., Hofmann, M., Kleine-Ostmann, T., Knobloch, P., Koch, M., Meyn, J. P., Matus, M., Koch, S. W., and Moloney, J. V., "Fourier-transform external cavity lasers," Opt. Commun. 207(1-6), 261-267 (2002).

[4] Huang, C. C., Cheng, C. H., Su, Y. S., and Lin, C.F., "174-nm mode spacing in dual-wavelength semiconductor laser using nonidentical InGaAsP quantum wells, " IEEE Photon. Technol. Lett. 16(2), 371-373 (2004).

[5] Tabuchi, H. and Ishikawa, H., “External grating tunable MQWlaser with wide tuning range of 240 nm,”Electron. Lett. 26(11), 742-743 (1990).

[6] Seltzer, C. P., Bagley, M., Elton, D. J., Perrin, S., and Cooper, D. M., "160 nm continuous tuning of an MQW laser in an external cavity across the entire 1.3μm communication window," Electron. Lett. 27(1), 95-96 (1991).

[7] Varangis, P. M., Li, H., Liu, G. T., Newell, T. C., Stintz, A., Fuchs, B., Malloy, K. J., and Lester, L. F., "Low-threshold quantum dot lasers with 201 nm tuning range," Electron. Lett. 36(18), 1544-1545 (2000).

[8] Biebersdorf, A., Lingk, C., De Giorgi, M., Feldmann, J., Sacher, J., Arzberger, M., Ulbrich, C., Böhm, G., Amann, M.-C., and Abstreiter, G., "Tunable single and dual mode operation of an external cavity quantum-dot injection laser," J. Phys. D Appl. Phys. 36(16), 1928–1930 (2003)

[9] Lin, G., Su, P. Y., and Cheng, H. C., "Low threshold current and widely tunable external cavity lasers with chirped multilayer InAs/InGaAs/GaAs quantum-dot structure," Opt. Express 20(4), 3941-3947 (2012).

[10] Friedrich, C.-S., Brenner, C., Hoffmann, S., Schmitz, A., Mayorga, I.C., Klehr, A., Erbert, G., and Hofmann, M.R., "New Two-Color Laser Concepts for THz Generation," IEEE J. Quantum Electron. 14(2), 270-276 (2008).

[11] Matus, M., Kolesik, M., Moloney, J. V., Hofmann, M., and Koch, S. W., "Dynamics of two-color laser systems with spectrally filtered feedback," J. Opt. Soc. Am. B 21(10), 1758-1771 (2004).

[12] Hoffmann, S. and Hofmann, M., "Generation of terahertz radiation with two color semiconductor lasers," Laser Photon. Rev. 1(1), 44-56 (2007).

[13] Wang, C. L. and Pan, C. L., "Tunable multiterahertz beat signal generation from a two-wavelength laser-diode array," Opt. Lett. 20(11), 1292-1294 (1995).

[14] Hoffmann, S., Hofmann, M., Kira, M., and Koch, S. W., "Two-colour diode lasers for generation of THz radiation," Semicond. Sci. Technol. 20(7), 205-210 (2005).

Session 6 . . . . Tue 13:30 to 15:20

Applications/Devices I

Session Chair: **Mario Bertolotti,** Univ. degli Studi di Roma La Sapienza (Italy)

Attosecond electron synchrotron on a nanoscale *(Invited Paper)*, J. Mikhailova, Max-Planck-Institut für Quantenoptik (Germany) . . . . [8772-22]

Non-maxwellian electron distribution in time-dependent simulation of low-Z elements iluminated by a high intensity X-ray laser, Alberto G. Garcia, Pedro Velarde, Univ. Politécnica de Madrid (Spain); François de Gaufridy, Univ. Politécnica de Madrid (Spain) and Czech Academy of Sciences (Czech Republic); Manuel Cotelo, David Portillo, Alfonso Barbas, Augustín I. González, Univ. Politécnica de Madrid (Spain); Philippe Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France) . . . . [8772-23]

Experimental study of a crystalline-resonator based optoelectronic oscillator, Patrice Salzenstein, Aurélien Coillet, Rémi Henriet, Laurent Larger, Yanne K. Chembo, Ctr. National de la Recherche Scientifique (France) . . . . [8772-24]

Nonlinear self-reflection of intense ultra-wideband femtosecond pulses in optical fiber, Leonid Konev, Yuri A. Shpolyanskiy, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation) . . [8772-25]

A high efficiency wavelength conversion scheme based on four wave mixing in semiconductor optical amplifiers utilizing EDFA broadband sources at 240Gbs bit rate, Osayd M. T. Kharraz, David I. Forsyth, Univ. Teknologi Malaysia (Malaysia). . . . . [8772-26]

Session 7 . . . . Tue 15:50 to 18:10

Applications/Devices II

Silicon nitride waveguide with flattened chromatic dispersion, Jose Manuel Chavez Boggio, Daniel Bodenmüller, Tino Fremberg, Leibniz-Institut für Astrophysik Potsdam (Germany); René Eisermann, Leibniz-Institut für Innovative Mikroelektronik (Germany); Roger Haynes, Martin M. Roth, Leibniz-Institut für Astrophysik Potsdam (Germany). . . . . [8772-27]

Bulk dipole contribution to second harmonic generation in diamond lattices, Hendradi Hardhienata, David Stifter, Kurt Hingerl, Johannes Kepler Univ. Linz (Austria) . . . . [8772-43]

Numerical model for DGD estimation in optical transmission system, Ján Litvik, Daniel Benedikovic, Univ. of Zilina (Slovakia); Marc Wuilpart, Univ. de Mons (Belgium); Milan Dado, Michal Kuba, Univ. of Zilina (Slovakia). . . . . [8772-28]

Double-frequency Brillouin fiber lasers, Andrei A. Fotiadi, Faculté Polytechnique de Mons (Belgium) and Ioffe Physico-Technical Institute (Russian Federation) and Ulyanovsk State Univ. (Russian Federation) . . . . [8772-29]

Tunable multiwavelength quantum dot external-cavity lasers, Gray Lin, Chen-Hung Pai, National Chiao Tung Univ. (Taiwan) . . . . [8772-30]

The analytical model of ground-state lasing in broadband semiconductor quantum dot lasers, Vladimir V. Korenev, Artem V. Savelyev, Alexey E. Zhukov, Alexander I. Omelchenko, Saint Petersburg Academic Univ. (Russian Federation); Mikhail V. Maximov, Ioffe Physico-Technical Institute (Russian Federation) . . . . [8772-31]

Cascaded carbon monoxide laser frequency conversion mid IR range in a single $ZnGeP_2$ crystal, Igor O. Kinyaevskiy, P.N. Lebedev Physical Institute (Russian Federation) . . . . [8772-32]

Wednesday 17 April

Session 8 . . . . Wed 9:00 to 10:10

Materials I

Session Chair: **Joseph W. Haus,** Univ. of Dayton (United States)

DNA: a nonlinear material for green photonics *(Invited Paper)*, Valentin I. Vlad, National Institute for Lasers, Plasma and Radiation Physics (Romania). . . [8772-33]

Enhanced optical transmission through the periodically patterned nanoprobe and its effect on DNA translocation, Seong Soo Choi, Myoung Jin Park, Sun Moon Univ. (Korea, Republic of); Namkyoo Park, Seoul National Univ. (Korea, Republic of); Kun Ho Kim, Gyeongsang National Univ. (Korea, Republic of); Luke P. Lee, Seung Min Park, Univ. of California, Berkeley (United States) . . . . . . [8772-34]

Application of layered graphene for solid state laser mode-locking in the near-infrared, Uwe Griebner, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Elena Ugolotti, Univ. degli Studi di Pavia (Italy); Andreas Schmidt, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Jun Wan Kim, Dong-Il Yeom, Fabian Rotermund, Ajou Univ. (Korea, Republic of); Sukang Bae, Byung Hee Hong, Seoul National Univ. (Korea, Republic of); Xavier Mateos Ferre, Francesc Díaz, Univ. Rovira i Virgili (Spain); Antonio Agnesi, Univ. degli Studi di Pavia (Italy); Valentin P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany) [8772-35]

Session 9 . . . . Wed 10:30 to 12:30

Materials II

Session Chair: **Mario Bertolotti,** Univ. degli Studi di Roma La Sapienza (Italy)

Reflection and propagation of laser pulse with a few cycles in medium with time-dependent dielectric permittivity, Vyacheslav A. Trofimov, Ivan V. Mishanov, Lomonosov Moscow State Univ. (Russian Federation). . . . . . [8772-36]

Spatial localization of microwave pulse energy in a layered linear medium containing metamaterial in some layers, Vyacheslav A. Trofimov, Evgeniy V. Trykin, Lomonosov Moscow State Univ. (Russian Federation); Sergey I. Taparov, Sergey V. Nedukh, Usikov Institute of Radiophysics and Electronics (Ukraine) . . . . [8772-37]

Numerical investigation of the Gaussian pulses propagating in optical fibers with refractive indices stochastically changed due to environmental conditions, Libor Ladányi, Róbert Menkyna, Jarmila Müllerová, Univ. of Zilina (Slovakia) . . . . [8772-38]

Two-photon polymerization of diacrylate mesogens for producing polymer with patterned orientation structures, Wenjun Zheng, Wei-Zhe Huang, National Sun Yat-Sen Univ. (Taiwan). . . . . [8772-39]

Laser beam bending cylindrical gradient curved lens under atmospheric conditions, Remzi Yildirim, Gazi Univ. (Turkey) . . . . [8772-40]

The role of MgO and CuO on the optical properties of lithium potassium borate, Yasser Alajerami, Univ. Teknologi Malaysia (Malaysia) and Alazhar Univ. (Palestinian Territory, Occupied); Suhairul Hashim, Wan Muhamad S. Wan Hassan, Ahmad Termizi Ramli, Univ. Teknologi Malaysia (Malaysia) . . . . [8772-41]

Poster Session. . . . . Wed 17:40 to 19:15

Conference attendees are invited to attend the Poster Session on Wednesday afternoon. Come view the posters, enjoy light refreshments, ask questions, and network with colleagues in your field. Authors of poster papers will be present to answer questions concerning their papers. Attendees are required to wear their conference registration badges to the poster sessions. Poster authors: view poster presentation guidelines and set-up instructions on page 6, and at http://spie.org/x30951.xml.

Determination of the uncertainty for phase noise delivered by an optoelectronic based system, Patrice Salzenstein, Ekaterina Pavlyuchenko, Ctr. National de la Recherche Scientifique (France) . . . . [8772-42]

Semiclassical model of lasing in nanowires, Vladimir G Bordo, Univ of Southern Denmark (Denmark). . . . . [8772-44]

Polarization properties of vector solitons generated by modulation instability in circularly birefringent fibers, Evgeny A. Kuzin, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Ariel Flores Rosas, Univ. de Guanajuato (Mexico); Balder-Arturo Villagomez-Bernabe, Josue-Israel Peralta-Hernandez, Nikolai A. Korneev, Baldemar Ibarra-Escamilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Manuel Durán-Sánchez, Univ. Tecnológica de Puebla (Mexico); Andres Gonzalez-Garcia, Instituto Tecnologico Superior de Guanajuato, (Mexico); Olivier J. Pottiez, Ctr. de Investigaciones en Óptica, A.C. (Mexico). . . . . [8772-45]

Two-photon excited fluorescence with thermal light, Andreas Jechow, Univ. Potsdam (Germany) and Griffith Univ. (Australia); Henning Kurzke, Michael Seefeldt, Axel Heuer, Ralf Menzel, Univ. Potsdam (Germany) . . . . [8772-46]

Compact blue light source by single-pass second harmonic generation of DBR tapered laser radiation, Junhee Park, Tai-Young Kang, Han-Young Lee, Korea Electronics Technology Institute (Korea, Republic of) . . . . [8772-47]

Frequency doubling of 1560nm laser with single-pass, double-pass and cascaded PPMgO:LN crystals and frequency locking to Rb D2 line, Junmin Wang, Shanlong Guo, Yashuai Han, Baodong Yang, Jun He, Shanxi Univ. (China) . . . . [8772-48]

Highly nonlinear tellurite fiber with engineered chromatic dispersion for broadband optical parametric amplification, Edmund P. Samuel, Tong H. Tuan, Koji Asano, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan). . . . . [8772-49]

Second order optical nonlinear processes as tools to probe anomalies inside high confinement microcavities, Marc Collette, Normand Beaudoin, Serge Gauvin, Univ. de Moncton (Canada) . . . . [8772-50]

All-optical switching using a power tunable junction formed by interacting nematicons, Johannes Rebling, Aix-Marseille Univ. (France); Yana V. Izdebskaya, Anton S. Desyatnikov, The Australian National Univ. (Australia); Gaetano Assanto, Univ. degli Studi di Roma Tre (Italy); Yuri S. Kivshar, The Australian National Univ. (Australia). . . . . [8772-51]

Experimental investigation of high power picosecond 1.06 m pulse propagation in Bragg fibers, Michal Jelínek, Václav Kube?ek, Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Vlastimil Mat?jec, Ivan Ka?ik, Ond?ej Podrazk?, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic) . . . . [8772-52]

SPIE European Conference on Optics and Optoelectronics
(SPIE EOO 2013)
April 15 - 18, 2013, Prague, Czech Republic

Prague, March 6, 2013

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Issue date of the passport: 05/02/2010
Expiry date of the passport: 05/02/2020
Duration of the stay in the Czech Republic: April 14 – 18, 2013
Accommodation: EuroAgentur Hotel Downtown, April 14 – 18, 2013

Dear Prof. Lin,

As you have been informed, the „**SPIE European Conference on Optics and Optoelectronics**“ will be held April 15 – 18, 2013 in Prague, Czech Republic.

Knowing of your interest and achievements in this field, we would like to invite you cordially to attend the conference and to present there your contribution titled

Tunable multiwavelength quantum dot external-cavity lasers.

We hope that you will find participation at the conference useful for your professional specialization. Nevertheless, we have to inform you that this invitation cannot grant any financial support of your stay at this event.

Looking forward to meeting you in Prague,
Kind regards

Helena Loneková
SPIE EOO 2013 Registration Office

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國科會補助計畫衍生研發成果推廣資料表

日期:2013/12/26

<table>
<tr><td rowspan="3">國科會補助計畫</td><td>計畫名稱: 半導體量子點兆赫波輻射源之研製</td></tr>
<tr><td>計畫主持人: 林國瑞</td></tr>
<tr><td>計畫編號: 101-2221-E-009-122- 學門領域: 固態電子</td></tr>
<tr><td colspan="2">無研發成果推廣資料</td></tr>
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101 年度專題研究計畫研究成果彙整表

計畫主持人：林國瑞			計畫編號：101-2221-E-009-122-				
計畫名稱：半導體量子點兆赫波輻射源之研製							
成果項目			量化			單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
			實際已達成數（被接受或已發表）	預期總達成數(含實際已達成數)	本計畫實際貢獻百分比		
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	1	1	100%		
		研討會論文	1	1	100%		台灣電子材料與元件協會 - IEDMS 2012 最佳論文獎（2012/11/29）
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
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	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
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		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
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		博士後研究員	0	0	100%		
		專任助理	0	0	100%		

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	友嘉科技委託案：高功率半導體雷射封裝熱阻量測（2013/1/1~2013/12/31） 台灣電子材料與元件協會：IEDMS 2012 最佳論文獎（2012/11/29）

	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

   ■達成目標

   □未達成目標（請說明，以 100 字為限）

   □實驗失敗

   □因故實驗中斷

   □其他原因

   說明：

2. 研究成果在學術期刊發表或申請專利等情形：

   論文：■已發表 □未發表之文稿 □撰寫中 □無

   專利：□已獲得 □申請中 ■無

   技轉：□已技轉 □洽談中 ■無

   其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）