UNIVERSITI PUTRA MALAYSIA

ENHANCED DESIGN OF FIBER GRATING FABRY-PEROT LASER FOR DENSE WAVELENGTH DIVISION MULTIPLEXING SYSTEMS

HISHAM K. HISHAM AL MUSAWI

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DOCTOR OF PHILOSOPHY
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By

HISHAM K. HISHAM AL MUSAWI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

July 2012

DEDICATION

To my parents,

To my Beloved wife and my children

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman: **Assoc. Prof. Ahmad Fauzi Abas, PhD**

Faculty: **Engineering**

Semiconductor laser diodes (SLDs) have been widely used in wavelength-division-multiplexing (WDM) systems due to small size, low power consumption, fast response, and its ability to perform direct modulation at moderate bit rates. A major obstacle preventing closer channel spacing is the drift of emission wavelength with ambient temperature variation. Therefore, with the development of dense WDM (DWDM) systems, lasers with narrow linewidth, high side mode suppressed ratio (SMSR), low chirp, low cost, and stable dynamic single-mode operation are indispensable.

In recent years, fiber grating Fabry-Perot (FGFP) laser is proposed as an alternative light source for WDM systems, which can generate light with highly stable wavelengths. This is because; the emission wavelength of such laser depends only on the Bragg wavelength of fiber grating (FG), thus, independent of chip temperature and injection current. However, FGFP laser output experiences phase fluctuations due to the quantum nature of the light. In addition, ambient temperature variation causes fluctuation in the gain spectrum, threshold current, and other cavity parameters. Furthermore, external optical feedback (OFB) level (i.e. the light reflected back from grating fiber) significantly

affects the performance of FGFP laser, which may fluctuate the FGFP light intensity and varies the dynamical and spectral behaviors of the laser. These will produce unwanted effect such as mode hopping and/or the coherence collapse.

In this thesis, the performance of the FGFP laser is enhanced by optimizing parameters in its original model. The effect of ambient temperature variation, OFB, injection current, cavity volume, nonlinear gain compression factor, spontaneous emission factor, linewidth enhancement factor, antireflection (AR) coating reflectivity, external cavity length, amplitude coupling coefficient, and fiber Bragg grating (FBG) parameters on the performance characteristics of the FGFP laser, namely dynamic response (transient response, turn-on time delay, relaxation oscillation frequency), modulation responses (intensity modulation, frequency modulation) and noise characteristics (relative intensity noise, phase noise, linewidth characteristics) has been demonstrated. In this study, we modeled FGFP laser based on the three-mirror laser cavity model. The reflection from the external mirror is combined with the reflection of the laser end front facet, ending up with a complex-valued effective reflection coefficient, which is equivalent to two-mirror cavity. The expressions that describe the laser characteristics have been modified by considering the effect of temperature, external OFB and other external cavity parameters.

This thesis is presented based on the alternative format which has been approved by University Putra Malaysia's Senate, which is the manuscript-based format. The major difference between this alternative format and the conventional ones is that, this format uses published papers in place of the regular chapters on the results and discussion.

The first paper, which deals with the turn-on time delay characteristics of the semiconductor diode lasers, is a comment paper, contains new results of the effect of the

carrier recombination rate coefficients on the laser turn-on time delay which is published in Optics and Laser Technology. This journal in indexed by ISI Thomson Scientific with 2010 impact factor of 1.616. The results in this paper corrected the misconception to the behavior of the carrier recombination rate coefficients on the laser turn-on time delay, which has been published by Zhang et al, Opt. & Laser Technol. 39 (2007) 997–1001. This paper is based on a numerical closed-form equation for turn-on time delay in terms of all carrier recombination rate coefficients. The comparison between our results and those that has been published was based on the practical and physical concepts for the operation principle of semiconductor lasers. It has been shown that the main effect of increasing any of the carrier recombination rate coefficients is to increase the turn-on time delay (not to decrease, as in original report), which is due to increase of the carrier-recombination rate. This fact has been supported further by investigating the effect of carrier recombination rate coefficients on the laser threshold current.

The second paper contains a comprehensive analysis on FGFP laser peak intensity modulation and relaxation oscillation frequency (ROF) characteristics, which is published in Optical Review, the Japan Society of Applied Physics. This journal in indexed by ISI Thomson Scientific with 2010 impact factor of 0.55. The frequency of the relaxation oscillation plays an important role in determining laser response. The study is performed by modifying the general expression of ROF equation, which is often expressed in terms of the carrier and photon lifetimes. It is demonstrated that by optimizing design parameters, ROF increased significantly to produce high flat frequency operation.

The third paper investigated the FGFP laser modulation response characteristics, which is published in Optics and Laser Technology. This journal in indexed by ISI Thomson

Scientific with 2010 impact factor of 1.616. In this paper, a unified and comprehensive study on the small-signal intensity modulation (IM) and frequency modulation (FM) characteristics of FGFP laser have been numerically conducted. This study has been presented by developing the general expressions of the intensity and frequency modulations response using the single-mode laser rate equation. It was shown that with laser dimension optimization, IM and FM responses with low peak amplitude, high flat frequency operation and high temperature stability can be obtained.

The most important feature of a semiconductor laser used in optical communication systems is the ability to operate with low relative intensity noise. In the fourth paper, we present a comprehensive analysis on the FGFP laser relative intensity noise (RIN) characteristics, which is published in IEEE Journal Quantum Electronics. This journal is indexed by ISI Thomson Scientific with 2010 impact factor of 2.48. In this paper, the analysis has been performed numerically by developing a set of nonlinear single-mode laser rate equations. It is shown that by laser optimization, the relative intensity noise level of FGFP laser can be reduced significantly.

Finally, the phase noise characteristics of a semiconductor laser are of interest in evaluating the performance of a coherent optical communication system. Because of the quantum nature of the lasing process, the laser output exhibits phase as well as intensity fluctuations. The fifth paper discussed the phase noise characteristics of FGFP laser, which is published in the Journal of Modern Optics. This journal in indexed by ISI Thomson Scientific with 2010 impact factor of 0.988. In this paper, the analysis was performed numerically by modifying the general expression of the laser phase noise equation. Through a comprehensive analysis, the results clearly show that by laser optimization, the FGFP laser phase noise performances significantly improved.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

DIPERTINGKATKAN REKABENTUK BAGI GENTIAN PARUTAN FABRY-PEROT LASER UNTUK SISTEM PEMULTIPLEKSAN PEMBAHAGIAN PANJANG GELOMBANG PADAT

Oleh

HISHAM K. HISHAM AL MUSAWI

Julai 2012

Pengerusi: **Prof. Madya Ahmad Fauzi Abas, PhD**

Fakulti: **Kejuruteraan**

Semikonduktor diod laser (SLDs) telah digunakan secara meluas dalam sistem pemultipleksan pembahagian-panjang-gelombang (WDM) kerana saiz yang kecil, penggunaan tenaga yang rendah, tindak balas yang cepat, dan keupayaan untuk melaksanakan modulasi langsung pada kadar bit yang sederhana. Satu kekangan utama yang menghadkan saiz saluran yang lebih kecil adalah hanyutan pancaran panjang gelombang yang berkadar dengan perubahan suhu persekitaran. Oleh itu, dengan pembangunan sistem WDM padat (DWDM), laser dengan lebar-garis yang sempit, nisbah pempadatan mod sisi yang tinggi (SMSR), decit dan kos yang rendah serta operasi dinamik mod-tunggal yang stabil adalah diperlukan.

Dalam tahun-tahun kebelakangan ini, laser gentian parutan Fabry-Perot (FGFP) dicadangkan sebagai sumber cahaya alternatif untuk sistem WDM, yang mana ia boleh menjana cahaya dengan panjang gelombang yang amat stabil. Ini adalah kerana panjang gelombang pancaran laser tersebut hanya bergantung pada panjang gelombang gentian parutan Bragg (FG), oleh itu ia bebas daripada suhu cip dan arus suntikan. Walau bagaimanapun, keluaran laser FGFP mengalami turun naik fasa kerana sifat kuantum

cahaya. Tambahan pula, perubahan suhu persekitaran menyebabkan ketidakstabilan gandaan spektrum, kadar arus dan parameter rongga yang lain. Seterusnya, tahap suapan semula optik luaran (OFB), iaitu cahaya dipantulkan kembali dari gentian parutan sangat mempengaruhi prestasi laser FGFP yang boleh mengubah turun naik cahaya FGFP dan mempelbagai tingkah laku dinamik dan spektrum laser. Ini akan menghasilkan kesan yang tidak diingini seperti melompat mod dan/atau keruntuhan koheren.

Dalam tesis ini, prestasi laser FGFP dipertingkatkan dengan mengoptimumkan parameter dalam model asalnya. Kesan-kesan berikut telah ditunjukkan; perubahan suhu persekitaran, OFB, suntikan arus, isipadu rongga, faktor mampatan gandaan tidak linear, faktor pelepasan spontan, faktor peningkatan lebar-garis, tindak balas salutan antipantulan (AR), panjang rongga luaran, pekali gandingan amplitud dan parameter gentian parutan Bragg (FBG) pada ciri-ciri prestasi laser FGFP, iaitu tindak balas dinamik (tindak balas transient, tangguhan masa hidup, kekerapan kelonggaran ayunan), tindak balas modulasi (modulasi keamatan modulasi frekuensi) dan ciri-ciri kebisingan (kekuatan kebisingan relatif, fasa kebisingan, ciri-ciri lebar-garis). Dalam kajian ini, kami memodelkan laser FGFP berdasarkan model laser rongga tiga cermin. Pantulan dari cermin luaran digabungkan dengan pantulan hujung facet laser, yang berkesudahan dengan nilai kompleks pekali pantulan berkesan, yang bersamaan dengan rongga dua cermin. Rumus yang menghuraikan ciri-ciri model laser telah diubahsuai dengan mengambil kira kesan suhu, OFB luaran dan lain-lain parameter rongga luar untuk analisa prestasi model secara komprehensif.

Tesis ini disampaikan berdasarkan format alternatif yang telah diluluskan oleh Senat Universiti Putra Malaysia, iaitu berasaskan format manuskrip. Perbezaan utama antara

format alternatif ini dari yang konvensional ia mengemukakan kompilasi kertas kerja yang telah diterbitkan, mengantikan bab-bab keputusan dan perbincangan.

Kertas kerja pertama adalah berkaitan dengan ciri-ciri tangguhan masa penghidupan pada laser diod semikonduktor, merupakan kertas kerja ulasan yang mengandungi keputusan baru dalam kesan pekali kadar penggabungan pembawa semula pada tqangguhan masa penghidupan laser yang disiarkan dalam Laser dan Optik Teknologi. Jurnal ini diindeks oleh ISI Thomson Saintifik dengan *Impact Factor* pada 2010 sebanyak 1.616. Keputusan dalam kertas ini membetulkan salah tanggapan kepada kelakuan pekali kadar penggabungan pembawa semula pada laser seterusnya pada hela masa yang telah diterbitkan oleh Zhang et al, Opt. & Laser Technol. 39 (2007) 997-1001. Kertas kerja ini adalah berdasarkan persamaan bentuk tertutup berangka untuk tangguhan masa penghidupan untuk semua pekali kadar penggabungan semula pembawa. Perbandingan keputusan adalah berdasarkan konsep praktikal dan fizikal bagi prinsip operasi laser semikonduktor. Ia menunjukkan kesan utama peningkatan mana-mana pekali kadar penggabungan semula pembawa adalah dengan meningkatkan kelewatan pusingan pada masa yang ditetapkan (tidak mengurangkan, seperti dalam laporan asal), yang adalah disebabkan untuk meningkatkan kadar pembawa rekombinasi. Fakta ini telah disokong lagi dengan menyiasat kesan pekali kadar penggabungan semula pembawa di kadar arus laser.

Kertas kerja kedua mengandungi analisis komprehensif mengenai ciri-ciri modulasi keamatan puncak dan kelonggaran frekuensi ayunan bagi laser FGFP. Kertas kerja ini diterbitkan dalam Kajian Optik, Persatuan Fizik Gunaan Jepun yang diindeks oleh ISI Thomson Saintifik dengan Impact Factor 2010 adalah 0.55. Kekerapan ayunan longgar memainkan peranan yang penting dalam menentukan tindak balas laser. Kajian ini

dilakukan dengan mengubahsuai persamaan umum ROF yang diungkapkan dari segi pembawa dan jangka hayat foton. Ia menunjukkan bahawa dengan mengoptimumkan reka bentuk parameter, ROF meningkat dengan ketara untuk menghasilkan operasi frekuensi tinggi yang rata.

Kertas ketiga menyiasat tindak balas ciri-ciri pemodulatan laser FGFP yang diterbitkan dalam Laser dan Optik Teknologi. Jurnal ini diindeks oleh ISI Thomson Saintifik dengan *Impact Factor* 2010 sebanyak 1.616. Dalam kertas kerja ini, satu kajian yang seragam dan menyeluruh telah dijalankan secara berangka ke atas ciri-ciri isyarat kecil modulasi keamatan (IM) dan modulasi frekuensi (FM) laser FGFP. Kajian ini telah dibentangkan dengan membangunkan ungkapan umum tindak balas modulasi keamatan dan frekuensi menggunakan persamaan kadar laser satu mod. Ia menunjukkan bahawa dengan mengoptimumkan dimensi laser, IM dan tindak balas FM dengan amplitud puncak yang rendah, operasi kekerapan rata yang tinggi dan kestabilan pada suhu yang tinggi boleh diperolehi.

Ciri paling penting bagi laser semikonduktor yang digunakan dalam sistem komunikasi optik adalah kemampuannya beroperasi dengan keamatan gangguan relatif yang rendah. Dalam kertas kerja keempat, kami kemukakan suatu analisis komprehensif mengenai ciri-ciri relatif keamatan gangguan (RIN) laser FGFP, yang diterbitkan di Jurnal Kuantum Elektronik IEEE. Jurnal ini diindeks oleh ISI Thomson Saintifik dengan *Impact Factor* 2010 sebanyak 2.48. Dalam kertas ini, analisis secara numerical telah dilakukan dengan membangunkan satu set persamaan laser mod tunggal tak berkadar terus. Ia menunjukkan bahawa dengan mengoptimumkan laser, tahap keamatan gangguan relatif daripada FGFP laser boleh dikurangkan dengan ketara.

Akhirnya, ciri-ciri gangguan fasa laser semikonduktor adalah penting dalam menilai prestasi sistem komunikasi optik yang koheren. Oleh kerana sifat kuantum proses laser, keluaran laser menunjukkan fasa dan keamatan yang turun naik. Kertas kelima membincangkan ciri-ciri fasa gangguan laser FGFP yang diterbitkan dalam Jurnal Optik Moden. Jurnal ini diindeks oleh ISI Thomson Saintifik dengan *Impact Factor* 2010 sebanyak 0.988. Dalam kertas ini, analisis berangka telah dilakukan dengan mengubahsuai ungkapan umum persamaan fasa gangguan laser. Melalui analisis yang komprehensif, keputusan dengan jelas menunjukkan bahawa melalui pengoptimuman laser, kadar fasa gangguan laser FGFP telah melalui penambahbaikan yang ketara.

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First and foremost, I wish to acknowledge the Creator of the entire world, who all the knowledge is with Him. The infinite thanks to Him that from His mercy and kindness forgave me the knowledge.

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I certainly appreciate the extremely friendly environment that I had to work in. My colleagues in Photonics and Fiber Optics Systems Laboratory, UPM, were always willing to lend a hand or a sympathetic ear for fruitful discussions, and chats, which have contributed towards the completion of this thesis. Working with all of you is a good experience that could never be forgotten.

Finally, last but not least, I thank my father, my mother and my wife for their unconditional love, support and constant encouragement. It is with them that I share this great accomplishment.

I certify that a Thesis Examination Committee has met on …… to conduct the final examination of Hisham K. Hisham AL Musawi on his thesis entitled "Optimum Design of Fiber Grating Fabry-Perot Laser for Dense Wavelength Division Multiplexing Systems" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date:

DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

HISHAM K. HISHAM AL MUSAWI

Date:

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