
**UNIVERSITI PUTRA MALAYSIA**

# *TUNABLE MULTIWAVELENGTH BRILLOUIN ERBIUM FIBER LASER DESIGNS FOR HIGH CAPACITY OPTICAL COMMUNICATION SYSTEM*

**ABDULMOGHNI ALI WAZA'A AL-ALIMI**

# TUNABLE MULTIWAVELENGTH BRILLOUIN ERBIUM FIBER LASER DESIGNS FOR HIGH CAPACITY OPTICAL COMMUNICATION SYSTEM

**By**

**ABDULMOGHNI ALI WAZA'A AL-ALIMI**

**Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy**

**July 2014**

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**DEDICATIONS**

*To my parents, wife,* my
daughter Nuha, and son Ali,
*Thank you for every thing*

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

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**JULY 2014**

**CHAIRMAN: MOHD HANIF YAACOB, PhD**
**Faculty: Engineering**

This work presents the design and development of a single laser source for multiple wavelengths generation in C-band transmission window to meet the demand from optical communication systems for high transmission rate. The single laser source consists of Brillouin and erbium doped fiber (EDF) gain mediums. The combination of stimulated Brillouin scattering (SBS) effect and EDF gain medium in the same laser cavity forms Brillouin erbium fiber laser (BEFL). The effect of SBS inside an optical fiber is used to initialize Stokes lines and the EDF gain medium is used to compensate the cavity loss as well as to enhance the BEFL performance.

Based on the Brillouin-erbium combination, four novel laser configurations have been designed, namely BEFL with nonlinear fiber loop mirror (NOLM), with single pass amplified Brillouin pump (BP) power, with double pass post-amplified BP power and with virtual mirror. These configurations were developed to overcome substantial limitations in the existing BEFL system.

One of the limitations of the conventional BEFL is the requirement for high threshold power to generate the first Stokes line and the requirement of high EDF pump power to generate a large number of Stokes lines. Therefore, it is a huge challenge to design a BEFL cavity to reduce these requirements. To address this problem, the author proposed the first system that is BEFL with NOLM. A low threshold power was achieved by utilizing the high reflectivity feature of NOLM. The developed BEFL with NOLM exhibited a low threshold power ranging from 2 mW to 3 mW and 26 stable Stokes lines with wavelength spacing of 0.089 nm (10.5 GHz), which were obtained at low EDF pump power of 25 mW.

The second limitation of BEFL is the standard single mode fiber (SSMF) distance requirement for several kilometers or even longer to improve the number of Stokes lines generation. In this work, two new linear cavity BEFL configurations with amplified BP power techniques were successfully designed to enhance the number of Stokes lines in a short length of SSMF. In these configurations, the BP power is amplified once and twice in the EDF gain medium before inserting the Brillouin gain. The second and third configurations are based on single pass (SP) pre-amplified and double pass (DP) post-amplified BP power, respectively. Both BEFL based on SP and DP techniques have improved the number of Stokes lines generation inside the short length of SSMF. Up to 33 and 42 Stokes lines were generated inside SSMF

length of 600 m by utilizing SP and DP techniques, respectively. Also, these techniques are able to suppress the built-up of the self lasing over a wide range.

The main disadvantage of the conventional BEFL is the existence of self lasing cavity modes together with the generated Stokes lines as the Brillouin wavelength tuned away from the EDF peak gain. This undesirable self lasing limits the tuning range of the BEFL and number of Stokes lines as well. The fourth BEFL design is proposed with the concept of virtual mirror to eliminate the self lasing over a wide tuning range, which resulted in the improvement in the BEFL tuning range. Also, the new design improves the number of Stokes lines by inducing four wave mixing (FWM) inside the Brillouin gain medium. In this new BEFL configuration, the virtual mirror was utilized to prevent the self lasing cavity modes from circulating inside the cavity. Therefore, the generated Stokes lines were tuned throughout the whole C-band from 1532.2 nm to 1572.2 nm with the average number of 100 Stokes lines. Up to 160 channels can be tuned over a tuning range of 26 nm from 1539 nm to 1565 nm. The generated Stokes lines of this BEFL have wavelength spacing of 0.076 nm and individual peak powers of greater than -8 dBm for the first nine Stokes lines. In addition, this BEFL design overcomes the requirement of BP power adjustment in conjunction with the adjustment of the EDF pump power in the linear cavity. As a result, the tunability of the generated Stokes lines is limited only by amplification bandwidth of linear gain medium.

Different design parameters such as EDF pump power, BP power, BP wavelength and SSMF length were used to characterize and optimize the four BEFL systems. The effects of these design parameters on the BEFL system performance such as threshold power, number of Stokes lines, total output power, self lasing cavity modes, stability and tuning range, have been analyzed and discussed.

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

**PEMBANGUNAN LASER FIBER BRILLOUIN ERBIUM BOLEH TALA PANJANG GELOMBANG BERBILANG**

**Oleh**

**ABDULMOGHNI ALI WAZA'A AL-ALIMI**

**JULAI 2014**

**PENGERUSI: MOHD HANIF YAACOB, PhD**
**Fakulti: Kejuruteraan**

Kerja ini mengenai rekaan dan pembangunan sumber laser tunggal untuk penjanaan panjang gelombang berbilang dalam tetingkap penghantaran jalur-C bagi memenuhi permintaan kadar penghantaran tinggi dalam sistem komunikasi optik. Sumber laser tunggal tersebut terdiri daripada medium gandaan Brillouin dan fiber terdop erbium (EDF). Kombinasi kesan serakan Brillouin terangsang (SBS) dan medium gandaan EDF di dalam rongga laser yang sama membentuk laser fiber Brillouin erbium (BEFL). Kesan SBS di dalam fiber optik telah digunakan untuk memulakan garisan Stokes dan medium gandaan EDF telah digunakan untuk mengimbangi kehilangan rongga serta meningkatkan prestasi BEFL tersebut.

Berdasarkan kombinasi Brillouin-erbium tersebut, empat konfigurasi laser terbaru telah direkabentuk, iaitu BEFL dengan cermin gelung fiber tak linear (NOLM), dengan kuasa pam Brillouin (BP) laluan tunggal terkuat, dengan kuasa BP laluan berganda terkuat dan dengan cermin maya. Konfigurasi-konfigurasi ini dibangunkan untuk mengatasi kelemahan nyata di dalam sistem BEFL sedia ada.

Salah satu kelemahan BEFL konvensional adalah keperluan kuasa ambang yang tinggi untuk menjana garisan Stokes pertama dan keperluan kuasa pam EDF yang tinggi untuk menjana sejumlah besar garisan Stokes. Oleh yang demikian, cabaran yang besar dalam merekabentuk satu rongga BEFL untuk mengurangkan keperluan ini. Untuk mngatasi masalah ini, pengarang telah mencadangkan sistem pertama iaitu BEFL dengan NOLM. Kuasa ambang yang rendah dicapai dengan menggunakan sifat reflektiviti tinggi NOLM. BEFL dengan NOLM yang dimajukan telah menunjukkan kuasa ambang rendah antara 2 mW ke 3 mW dan 26 garisan Stokes yang stabil dengan ruang panjang gelombang 0.089 nm (10.5 GHz), telah dicapai pada kuasa pam EDF serendah 25 mW.

Kelemahan kedua BEFL adalah keperluan jarak fiber mod tunggal standard (SSMF) untuk beberapa kilometer atau lebih jauh dari itu bagi meningkatkan penjanaan bilangan garisan Stokes. Di dalam kerja ini, dua konfigurasi BEFL baru dengan rongga linear serta teknik kuasa BP terkuat telah berjaya direka untuk meningkatkan bilangan garisan Stokes dalam jarak SSMF yang pendek. Dengan konfigurasi ini, kuasa BP dikuatkan sekali dan dua kali di dalam medium gandaan EDF sebelum kemasukan gandaan Brillouin. Konfigurasi kedua dan ketiga ini, masing-masing

berasaskan kuasa BP pra-kuatan laluan tunggal (SP) dan kuasa BP pasca-kuatan laluan berganda (DP). Kedua-dua konfigurasi berasaskan teknik SP dan DP telah meningkatkan penjanaan bilangan garisan Stokes di dalam jarak SSMF yang pendek. Sebanyak 33 dan 44 garisan Stokes telah dijana di dalam SSMF sepanjang 600 m, masing-masing dengan menggunakan teknik SP dan DP. Teknik-teknik ini juga berjaya menekan pembinaan pelaseran sendiri dalam julat yang lebar.

Satu kelemahan utama BEFL konvensional adalah kewujudan mod rongga pelaseran sendiri berserta garisan Stokes yang terjana apabila panjang gelombang Brillouin ditala jauh daripada gandaan puncak EDF tersebut. Pelaseran sendiri yang tidak diingini ini menghadkan julat talaan BEFL tersebut dan juga bilangan garisan Stokes. Rekabentuk BEFL keempat telah dicadangkan dengan konsep cermin maya untuk menghapuskan pelaseran sendiri dalam julat talaan lebar, sekaligus menambahbaikan julat talaan BEFL tersebut. Disamping itu, rekabentuk baru tersebut meningkatkan bilangan garisan Stokes dengan mendorong percampuran empat gelombang (FWM) di dalam medium gandaan Brillouin. Di dalam konfigurasi BEFL baru ini, cermin maya telah digunakan untuk mencegah mod rongga pelaseran sendiri daripada berlegar di dalam rongga tersebut. Jadi, garisan Stokes yang terjana telah ditala sepanjang kesemua jalur-C daripada 1532.2 nm ke 1572.2 nm dengan purata 100 bilangan garisan Stokes. Sehingga 160 saluran boleh ditala melalui julat penalaan 26 nm dari 1539 nm ke 1565 nm. Garisan Stokes BEFL yang terjana mempunyai jarak panjang gelombag 0.076 nm, dan kuasa puncak individu lebih daripada -8 dBm untuk sembilan garisan Stokes terawal. Tambahan daripada itu, rekabentuk BEFL keempat mengatasi keperluan pelarasan kuasa BP bersempena dengan pelarasan kuasa pam EDF di dalam rongga linear. Hasilnya, penalaan garisan Stokes yang terjana telah dihadkan oleh hanya penguatan jalur lebar medium gandaan linear.

Parameter-paremeter rekabentuk berbeza seperti kuasa pam EDF, kuasa BP, panjang gelombang BP dan jarak SSMF telah digunakan untuk menciri dan mengoptimumkan keempat-empat sistem BEFL tersebut. Kesan parameter rekabentuk ini kepada prestasi sistem BEFL tersebut seperti kuasa ambang, bilangan garisan Stokes, jumlah kuasa output, mod rongga pelaseran sendiri, kestabilan dan julat penalaan juga telah dianalisa dan dibincangkan.

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I certify that a Thesis Examination Committee has met on (24th July 2014) to conduct the final examination of (**Abdulmoghni Ali Waza'a Al-Alimi**) on his thesis entitled "**Tunable Multiwavelength Brillouin Erbium Fiber Laser Designs For High Capacity Optical Communication System**" 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**).
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