UNIVERSITI PUTRA MALAYSIA

MULTI-WAVE LENGTH BRILLOUIN-ERBIUM FIBER LASER UTILIZING BISMUTH-OXIDE ERBIUM DOPED FIBER INCORPORATING HIGH AND LOW NONLINEAR FIBERS

RAMZIA SALEM

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By

RAMZIA SALEM

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

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DEDICATION

This work is dedicated to the loving memory of my late parents and to my beloved supporting sisters and brothers, nieces and nephews and last but not least to my loving husband and my lovely kids, Rania and Rayan.

Abstract of 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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Chair: Mohd Adzir Bin Mahdi, PhD

Faculty: Engineering

Multiwavelength fiber lasers are of great interest in the wavelength division multiplexing systems. To accommodate for the exponential growth in internet, the transmission capacity has to be enhanced in terms of the number of channels. In order to achieve this aim, one approach is to reduce the channel spacing between the wavelengths. The other approach is to increase the gain bandwidth restricted by erbium doped fiber amplifier. Since the bandwidth is dependent on the Er^{3+} structure in glass material, many fiber amplifiers have been developed to broaden the gain bandwidth. Bismuth-based erbium-doped fiber (Bi-EDF) demonstrates fundamental properties showing broadband emission range and can be doped with Er^{3+} without experiencing the negative results of ion-quenching and clustering effects compared to silica-based glass allowing the erbium concentration to be more than 3000 ppm. This dissertation presents

experimental design and development of multiwavelength Brillouin-erbium fiber laser (MWBEFL) sources operating in the L-band transmission window utilizing 2.49 m Bi-EDF. Three different laser designs have been realized by utilizing stimulated Brillouin scattering (SBS) effect in optical fibers to generate multiple lasers. Two types of special fibers, photonic crystal fiber (PCF) with high nonlinearity and large effective area fiber (LEAF) with low nonlinearity, are being investigated individually. These two types of fibers are then merged together to investigate the laser's performance parameters.

The first design for multiwavelength laser comb comprises of Bi-EDF and 50 m photonic crystal fiber in a ring cavity configuration. This fiber laser is solely pumped by a single 1455 nm Raman pump laser to exploit its higher power delivery compared to that of a single mode laser diode pump. At 264 mW pump power and 1 mW Brillouin pump (BP) power, 38 output channels in the L-band have been realized with optical signal-to-noise ratio above 15 dB and Stokes lines spacing of 0.08 nm. The laser exhibits a tuning range of 12 nm and produces stable Stokes lines across the tuning range between Brillouin pump wavelengths of 1603 and 1615 nm. The tuning range of 12 nm is considered high since very short length, 50 m PCF is used. However, due to the spectral broadening of the laser lines caused by four-wave mixing (FWM) effect associated with high nonlinear fibers, the optical signal-to-noise ratio (OSNR) is degraded and the tuning range is limited to only 12 nm.

Another multiwavelength laser comb using 2.49 m Bi-EDF with different lengths of LEAF in a ring cavity configuration has been developed. The Bi-EDF is used as the linear gain medium and LEAF is used as the non-linear gain medium for SBS. Out of the four different lengths, the longest length of 25 km LEAF exhibits the widest tuning range of 44 nm (1576 to 1620 nm) in the L-band at 264 mW pump power and 5 mW Brillouin pump power. In addition, a total of 15 output channels are achieved with total average output power of –8 dBm from this laser structure. All Brillouin Stokes signals exhibit high peak power of above –20 dBm per signal and their OSNR of greater than 15 dB. The Bi-EDF based MWBEFL is also characterized with 22 km Vascade® L1000, another type of LEAF, as the Brillouin gain medium. This fiber generates more Stokes lines than the 25 km LEAF with higher Stokes lines output power. However, the tuning range achieved is 38 nm compared to 44 nm for 25 km LEAF.

The third structure of MWBEFL incorporating cascaded PCF and two different lengths of LEAF individually is demonstrated. In this design, the tuning range is enhanced significantly reaching 54 nm from 1566 -1620 nm, at 264 mW pump power and 5 mW BP power, without a trace of self-lasing throughout, utilizing 22 km Vascade® L1000 along with 50 m PCF. Five output channels can be tuned along the whole region of 54 nm. Although this design provides high tuning range, but the number of output channels is reduced. At Raman pump power of 395 mW and 5 mW BP power, up to 9 channels can be widely tuned over 49 nm. The channels exhibit high output power and high stability with average power fluctuation of 0.34 dB over 60 minutes time span. The effect of FWM is reduced thus enhancing the OSNR by 5.2 dB due to the suppression of turbulent waves effect owing to the larger core size in LEAF.

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

LASER GENTIAN BRILLOUIN-ERBIUM PELBAGAI JARAK GELOMBANG MENGGUNAKAN GENTIAN TERDOP BISMUTH-OKSIDA ERBIUM BERSAMA GENTIAN TIDAK LINEAR TINGGI DAN RENDAH

Oleh

RAMZIA SALEM

September 2011

Pengerusi: Mohd Adzir Bin Mahdi, PhD

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Laser gentian pelbagai jarak gelombang adalah sangat menarik dalam sistem multipleks divisyen jarak gelombang. Bagi memenuhi perkembangan eksponensial internet, kapasiti transmisi telah diperbaiki dari segi bilangan saluran. Untuk mencapai sasaran ini, satu cara adalah mengurangkan jarak pemisahan saluran antara jarak gelombang. Cara yang lain adalah meningkatkan lebar jalur yang dihadkan oleh penguat gentian terdop erbium.Memandangkan lebar jalur bergantung kepada struktur Er3+ dalam bahan gelas, banyak penguat gentian dibangunkan untuk meluaskan lebar jalur. Gentian terdop erbium berasaskan bismusth (Bi-EDF) mendemonstrasikan ciri-ciri asas yang menunjukkan lingkungan pancaran jalur lebar dan boleh didopkan dengan Er3+ tanpa menghadapi keputusan negatif penghapusan ion dan kesan pengelompokan berbanding gelas berasaskan silika lalu membenarkan konsentrasi ion erbium

untuk melebihi 3000 ppm. Disertasi ini membentangkan rekabentuk dan pembangunan eksperimental punca laser gentian Brillouin-erbium pelbagai jarak gelombang (MWBEFL) menggunakan 2.49 m Bi-EDF yang beroperasi di tingkap transmisi L-band. Tiga rekabentuk laser berlainan telah diwujudkan dengan menggunakan kesan penyerakan Brillouin terangsang (SBS) dalam gentian optik bagi menghasilkan laser yang banyak. Dua jenis gentian khas disiasat secara individu iaitu, gentian kristal fotonik (PCF) dengan ketidaklinear yang tinggi dan gentian kawasan efektif besar (LEAF) dengan ketidaklinear yang rendah. Kedua-dua gentian ini kemudiannya digabungkan bersama untuk menyiasat parameter prestasi laser itu.

Rekabentuk pertama bagi laser sikat pelbagai jarak gelombang mengandungi Bi-EDF dan 50 m PCF dalam konfigurasi rongga cincin. Laser gentian ini adalah dipamkan sendirian oleh satu laser pam Raman 1455 nm bagi mempergunakan penghantaran kuasa yang tinggi berbanding pam diod laser mod tunggal. Pada kuasa pam 264 mW dan 1 mW kuasa pam Brillouin (BP), 38 saluran hasilan dalam L-band diwujudkan dengan nisbah isyarat kepada gangguan optikal (OSNR) di atas 15 dB dan jarak pemisahan garisan Stokes pada 0.08 nm. Laser itu menunjukkan lingkungan talaan sebanyak 12 nm dan menghasilkan garisan Stokes yang stabil merentasi lingkungan talaan di antara jarak gelombang pam Brillouin pada 1603 dan 1615 nm. Lingkungan tallan 12 nm ini dikira tinggi memandangkan PCF 50 m yang sangat pendek digunakan. Walau bagaimanapun, oleh kerana peluasan spektral garisan laser itu disebabkan kesan pencampuran empat-gelombang (FWM) yang dikaitkan dengan gentian tidak linear yang tinggi, OSNR berkurangan dan lingkungan talaan dihadkan kepada hanya 12 nm.

Satu lagi laser sikat pelbagai jarak gelombang menggunakan 2.49 m Bi-EDF dengan LEAF berbeza kepanjangan dalam konfigurasi rongga cincin telah dibangunkan. Bi-EDF digunakan sebagai perantara penambah linear dan LEAF digunakan sebagai perantara penambah tidak linear bagi SBS. Daripada 4 panjang yang berbeza, LEAF yang terpanjang pada 25 km menunjukkan lingkungan talaan yang terluas sebanyak 44 nm (1576 to 1620 nm) dalam L-band pada kuasa pam 264 mW dan BP 5 mW. Sebagai tambahan, sejumlah 15 saluran hasilan dicapai dengan purata kuasa hasilan pada -8 dBm bagi struktur laser ini. Semua isyarat Stokes Brillouin menunjukan kuasa puncak yang tinggi melebihi -20 dBm bagi setiap isyarat dan OSNR melebihi 15 dB. MWBEFL berasaskan Bi-EDF ini turut dikaji sifatnya dengan 22 km Vascade L1000, sejenis LEAF lain, sebagai perantara penambah Brillouin. Gentian ini menghasilkan lebih garisan Stokes berbanding 25 km LEAF dengan kuasa hasilan garisan Stokes yang lebih tinggi. Walau bagaimanapun, lingkungan talaan yang dicapai adalah 38 nm berbanding 44 km bagi 25 km LEAF.

Struktur ketiga MWBEFL menggabungkan PCF berturutan dan dua kepanjangan LEAF yang berbeza didemonstrasikan secara individu. Dalam rekabentuk ini yang menggunakan 22 km Vascade L1000 disamping 50 m PCF, lingkungan talaan telah ditingkatkan dengan jelas, mencapai 54 nm dari 1566 kepada 1620 nm, pada kuasa pam 264 mW dan BP 5 mW tanpa sebarang tanda lasing sendirian. 5 saluran hasilan boleh ditala sepanjang seluruh kawasan 54 nm itu. Walaupun rekabentuk ini memberikan lingkungan talaan yang luas, tetapi bilangan saluran hasilan berkurangan. Pada kuasa pam maksimum, 395 mW kuasa pam dan 5 mW kuasa BP, sehingga 9 saluran hasilan boleh ditala seluas 49 nm. Saluran-saluran itu menunjukkan kuasa hasilan dan kestabilan yang tinggi dengan purata perubahan kuasa sebanyak 0.34 dB dalam sela masa 60 minit. Kesan FWM dikurangkan lalu OSNR diperbaiki sebanyak 5.2 dB kerana peredaman gelombang bergolak disebabkan saiz teras yang lebih besar di dalam LEAF.

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them enough for standing by me and believing in me. Without their love and support, this dissertation would not have come true.

Approval Sheet 1

I certify that an Examination Committee has met on _______________ to conduct the final examination of **Ramzia Abdulmalik Salem** on her degree thesis entitled **"Multiwavelength Brillouin-Erbium Fiber Laser Utlilizing Bismuth-Oxide Erbium Doped Fiber incorporating High and Low Nonlinear Fibers"** in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Examination Committee were as follows:

Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Faculty of Engineering
University Putra Malaysia
(Internal Examiner)

Faculty of Science
University Putra Malaysia
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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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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.

RAMZIA SALEM

Date: 8 September 2011

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