STUDY OF S-BAND OPTICAL AMPLIFIERS AND ITS APPLICATIONS

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Abstract

Currently, existing networks which utilizes Dense Wavelength Division Multiplexing (DWDM) have come to its limitation, with the increase of data traffic extending the operational bandwidth from the C- to the L-band. Although the L-band can sustain current demands, there is a pressing need to explore the S-band region for future needs. One of the important components for operation in the S-band region is the S-band optical amplifier, which requires in-depth investigation and is the scope and objective of this thesis. The work will undertake a nearly comprehensive evaluation of the different types of optical amplifiers such as Erbium Doped Fibers Amplifiers (EDFAs), Depressed-Cladding Erbium-Doped Fibers Amplifiers (DC-EDFAs), Semiconductor Optical Amplifier (SOAs) and Raman Amplifier (RAs). The methodology of this work is to investigate these amplifiers from the aspect of the gain and noise figure at different input signal wavelengths and powers. Further to this, the optical amplifier is configured into a fiber laser and various parameters such as the tuning range, output power and the Side Mode Supression Ratio (SMSR) will be investigated. Various methods are used to tune the wavelength of the fibre lasers, including the Arrayed Waveguide Gratings (AWGs) and Tunable Bandpass Filters (TBFs) as well as Tunable Fibre Bragg Gratings (TBFGs) for different gain media. Significantly important results were obtained from these investigations, including the generation of an SOA based fiber laser with an ultra-wide tuning range of more than 120 nm covering the S-, C- and L- bands.

This thesis also presents another application of the S-band amplifier, which is the multi-wavelength Brillouin fiber laser operating in the S-band region. This application is important for the development cost-effective transmission sources for the DWDM systems. The multi-wavelength fiber laser uses the Brillouin effect, which is a
non-linear optical effect, together with the EDFA, DC-EDFA, SOA and RA to generate a multi-wavelength output in the S-band region. The developed multi-wavelength Brillouin fiber laser has a number of substantial performance improvements over similar designs, including the number of the Stokes lines generated, flat output peak power and also channel spacing.

The studies undertaken and the results obtained in this work can provide important inputs into the design of S-band optical amplifiers for application in future S-band networks. Furthermore, the results obtained in this work are instrumental to the development of tunable S-band fiber laser sources and also multi-wavelength sources for the possibility of usage in DWDM systems.
Abstrak


Pelbagai kaedah digunakan untuk menala panjang gelombang laser gentian, termasuk yang menggunakan parutan Pandu gelombang (AWGs) dan Penapis laluan Boleh Laras (TBFs) serta parutan Bragg Gentian Optik Boleh Laras (TBFGs) untuk media gandaan yang berbeza. Signifikan keputusan penting telah diperolehi daripada penyiasatan, termasuk generasi laser gentian optik berasaskan SOA dengan rangkaian selulur ultrapenalaan lebih daripada 120 nm meliputi jalur- S, C dan L.

Tesis ini juga membentangkan satu lagi aplikasi penguat jalur-S iaitu Brillouin laser gentian optik dengan keluaran pelbagai panjang gelombang pada jalur S-. Aplikasi ini adalah penting bagi sumber pembangunan penghantaran dengan kos yang berkesan
untuk sistem DWDM. Laser gentian optik pelbagai panjang gelombang menggunakan kesan Brillouin, yang juga merupakan kesan optik bukan linear, bersama-sama dengan EDFA, DC-EDFA, SOA dan RA untuk menjana keluaran pelbagai panjang gelombang di rantau jalur-S. Pembangunan pelbagai panjang gelombang Brillouin laser fiber mempunyai bilangan peningkatan prestasi yang besar ke atas reka bentuk serupa, termasuk bilangan garisan Stokes yang terhasil, kuasa output puncak rata dan juga jarak saluran.

Kajian yang dijalankan dan keputusan yang diperolehi dalam kerja-kerja ini boleh memberikan input penting ke dalam reka bentuk penguat optik jalur-S untuk aplikasi dalam rangkaian masa depan jalur-S. Tambahan lagi, keputusan yang diperolehi dalam kerja-kerja ini adalah penting kepada pembangunan sumber jalur-S laser gentian optik boleh laras dan juga sumber pelbagai panjang gelombang bagi kemungkinan penggunaan dalam sistem DWDM.
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List of ISI Publications

1. H. Ahmad, **M. Z. Zulkifli**, N. A. Hassan, and S. W. Harun, S-band Multi-Wavelength Ring Brillouin/Raman Fiber Laser with 20 GHz Channels Spacing, Accepted in Applied Optics 2012


12 H.Ahmad, A.A Latif, S.F Norizan, M.Z Zulkifli, S.W Harun, “Flat and compact switchable dual wavelength output at 1060 nm from ytterbium doped fiber laser with an AWG as a wavelength selector”


32 H. Ahmad, M.Z Zulkifli, A.A Latif, K. Thambiratnam, S.W Harun, “Bidirectional S-band continuous wave operation in a depressed-

H. Ahmad, M.Z Zulkifli, A.A Latif, K. Thambiratnam, S.W. Harun
Dual wavelength fibre laser with tunable channel spacing using an SOA and dual AWGs, Journal Of Modern Optics Volume 56, Issue: 16, pp1768-1773, 2009


H.Ahmad, H.C Ooi, A.H Sulaiman,K Thambiratnam, M.Z Zulkifli

List of Conferences

Plenary Speaker


Oral and Poster Presentations

1  H. Ahmad, M. Z. Zulkifli, K. Thambiratnam, M. Yasin and S.W. Harun “Non-Contact Micro And Sub-Mirco Thickness Measurement Using Fiber Optic Displacement Sensor”, 8th International Symposium on Modern Optics and Its Applications, 4-7 July 2011, Institut Teknologi Bandung, Bandung, Indonesia


4  M Z Zulkifli and H Ahmad, “Switchable Fiber laser”, Topical Meeting On Laser and Optoelecronic, 7-10 February 2009, The
Andaman Langkawi, Malaysia

5 M. Z. Zulkifli, “Flat output and Switchable Fiber laser Using AWG and Broadband FBG, International meeting on Frontiers of Physic 2009, 12-16 Januari, Awana Genting Highland, Malaysia

List of Awards

1 **Best Phd Candidate With Highest Cumulative ISI Impact Factor,**
University of Malaya Excellence Award 2011, 12 December 2011, Universiti of Malaya, Kuala Lumpur, Malaysia

2 **Full Sponsorship by UNESCO and ICTP,** Winter College on Optic and Imaging Science, 24 January- 11 Fabuary 2011, ICTP, Trieste, Italy

3 **Bronze Medal,** Ready-To Market, (Physical Science and Engineering), “Low Cost Tunable Laser Diode”, 1-3 April 2010 Innovation and Creativity Expo 2010 Universiti Malaya

4 **Gold Medal,** “Novel O-band Tunable Fiber Laser Using an Array Waveguide Grating”, 1-3 April 2010 Innovation and Creativity Expo 2010, Universiti Malaya

5 **Gold Medal,** Ready-To Market, (Physical Science and Engineering) “Erbium Doped Fiber Amplifier Experiment Kits”, 1-3 April 2010 Innovation and Creativity Expo 2010 Universiti Malaya

6 **Gold Medal,** “An All-Optical Frequency Up/Down Converter Utilizing Stimulated Brillouin and Raman Scattering in Truewave
Reach Fiber and Dispersion Compensating Fiber for Radio Over Fiber Application”, 1-3 April 2010 Innovation and Creativity Expo 2010 Universiti Malaya

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<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
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<td>AWG</td>
<td>Arrayed Waveguide Grating</td>
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<tr>
<td>BEFL</td>
<td>Brillouin Erbium Fiber Laser</td>
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<tr>
<td>BDFL</td>
<td>Brillouin Doped Fiber Laser</td>
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<tr>
<td>Bi-EDFA</td>
<td>Bismuth/Erbium Doped Fiber Amplifier</td>
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<tr>
<td>BP</td>
<td>Brillouin Pump</td>
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<tr>
<td>CIR</td>
<td>Circulator</td>
</tr>
<tr>
<td>CB</td>
<td>Conduction Band</td>
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<tr>
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<td>Conventional Band</td>
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<td>CWDM</td>
<td>Coarse WDM</td>
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<td>Continuous Wave</td>
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<td>DC</td>
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<td>DCF</td>
<td>Dispersion Compensating Fiber</td>
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<td>Depressed Cladding-Erbium Doped Fiber</td>
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<td>DFB</td>
<td>Distributed Feedback</td>
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<td>Distribute Raman Amplifier</td>
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<tr>
<td>FBG</td>
<td>Fiber Bragg Grating</td>
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<tr>
<td>FWHM</td>
<td>Full-Width Half-Maximum</td>
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<td>FWM</td>
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<td>Fabry-Perot SOA</td>
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<td>GFF</td>
<td>Gain Flattening Filter</td>
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<tr>
<td>HiBi-FLM</td>
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<td>Abbreviation</td>
<td>Description</td>
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</tr>
<tr>
<td>HRA</td>
<td>Hybrid Raman Amplifier</td>
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<td>ISO</td>
<td>Isolator</td>
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<td>ITU</td>
<td>International Telecommunication Union</td>
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<td>L-band</td>
<td>Long-Band</td>
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<tr>
<td>LD</td>
<td>Laser Diode</td>
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<td>MCVD</td>
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<td>Optical Channel Selector</td>
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<td>Optical Power Meter</td>
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<tr>
<td>OSA</td>
<td>Optical Spectrum Analyzer</td>
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<tr>
<td>OTDM</td>
<td>Optical Time Domain Division Multiplexing</td>
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<tr>
<td>PC</td>
<td>Polarization Controller</td>
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<td>PCF</td>
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<td>PLC</td>
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<td>S-band</td>
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<td>SA</td>
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<td>Stimulated Brillouin Scattering</td>
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<td>SLM</td>
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<td>Acronym</td>
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<td>SMF</td>
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<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<td>SPM</td>
<td>Self-Phase Modulation</td>
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<td>Transverse Electric</td>
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<td>Tunable Fiber Bragg Grating</td>
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<td>TM</td>
<td>Transverse Magnetic</td>
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<td>TFBG</td>
<td>Tunable Fiber Bragg Grating</td>
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<td>TDM</td>
<td>Time Division Multiplexing</td>
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<td>TW-SOA</td>
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<td>VB</td>
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<td>WSC</td>
<td>Wavelength Selective Coupler</td>
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<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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<td>XPM</td>
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</tbody>
</table>
Nomenclature

\( A \)  
Fiber core area

\( A_{\text{eff}} \)  
Effective core area

\( A_{\text{mf}} \)  
Mode field diameter

\( \beta \)  
Modal propagation constants

\( f \)  
Optical frequency

\( f_0 \)  
Center frequency

\( r \)  
Core radius

\( R \)  
Radius of curvature

\( c \)  
Speed of light

\( E_p \)  
Young’s modulus of the Perspex

\( E_{p}^{s} \)  
Young’s modulus of the spring steel

\( \epsilon \)  
Strain

\( h \)  
Planck’s constant

\( P_{s,\text{out}} \)  
Output signal power

\( P_{s,\text{in}} \)  
Input signal power

\( P_{\text{ASE}} \)  
ASE noise power

\( G \)  
Gain

\( G_0 \)  
Small signal gain

\( G_{\text{max}} \)  
Maximum value of small-signal gain

\( G_{\text{TE}} \)  
TE mode gain

\( G_{\text{TM}} \)  
TM mode gain

\( g_R \)  
Raman gain coefficient

\( g_B \)  
Brillouin gain coefficient

\( g_{th} \)  
Gain Threshold

\( I_{\text{sat}} \)  
Saturation intensity

\( I_s(0) \)  
Incident pump intensity at fiber position \( z=0 \)

\( n \)  
Index of refraction/ refractive index

\( \varnothing \)  
Azimuthal coordinates of a cylindrical

\( L_{\text{coh}} \)  
Coherent length
<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$L_{int}$</td>
<td>Pump interaction length</td>
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<td>$\eta_{EB}$</td>
<td>Cross efficiency of Brillouin/Erbium</td>
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<td>$\eta_B$</td>
<td>Brillouin Efficiency</td>
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<td>$\eta_E$</td>
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<td>$\eta_p$</td>
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<td>$P_{th}$</td>
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<td>$SNR_{in}$</td>
<td>Signal-to-noise ratio input</td>
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<td>$SNR_{out}$</td>
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<td>$t_s$</td>
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<td>$\tau_{sp}$</td>
<td>Spontaneous life time of the ion in the metastable state</td>
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<td>$V_a$</td>
<td>Velocity of Acoustic wave</td>
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<td>$v_B$</td>
<td>Frequency shift</td>
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<td>$v$</td>
<td>Frequency of the light</td>
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<td>$N_T$</td>
<td>Total dopant concentration</td>
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<td>$R$</td>
<td>Radiative transitions</td>
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<td>$N_{eff}$</td>
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<td>Effective refractive indices in the free propagation region</td>
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<td>Stimulated emission coefficients of the signal</td>
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<td>$W_{2l}$</td>
<td>Stimulated emission coefficients of the pump</td>
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<td>Population density</td>
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<td>Cut-off wavelength</td>
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<td>$\lambda_0$</td>
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<td>$n_{sp}^\pm$</td>
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<td>$n_{eq}^\pm$</td>
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<td>Index difference</td>
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