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

Pada masa ini, rangkaian sedia ada yang menggunakan Dense Division Pemultipleksan (DWDM) telah pun terhad, dengan peningkatan trafik data jalur lebar melanjutkan operasi dari jalur-C kepada jalur-L. Walaupun jalur-L boleh menampung keperluan semasa, terdapat keperluan mendesak untuk meneroka kawasan jalur-S untuk keperluan masa depan. Salah satu komponen penting bagi operasi di rantau jalur-S adalah penguat optik jalur-S, yang memerlukan penyiasatan yang mendalam dan juga adalah skop dan objektif tesis ini. Kerja ini akan menjalankan penilaian yang hampir menyeluruh kepada jenis penguat optik seperti Penguat Gentian Optik Berdop Erbium (EDFAs),Penguat Gentian Optik Berdop Erbium Dengan Rekabentuk Pelapisan Ditekan (DC-EDFA), Penguat Optikal Semiconductor (SOA) dan Penguat Raman (RA). Kaedah kerja ini adalah untuk menyiasat penguat-penguat ini dari aspek gadaan dan nilai hingar pada jarak gelombang isyarat input dan kuasa yang berbeza. Selain itu, penguat optik dikonfigurasikan ke dalam laser gentian optik dan pelbagai parameter seperti julat pelarasan, kuasa keluaran dan nisbah penekanan mode isyarat (SMSR) akan disiasat. 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 seluruh ultra-penalaan 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

2 H. Ahmad, **M. Z. Zulkifli**, N. A. Hassan, and S. W. Harun, "Enhancement of Brillouin Stokes Generation in the S-Band Region Using a Combination S-Band Depressed Cladding Erbium Doped Fiber and Semiconductor Optical Amplifier" Laser Physics, Vol. 22, No. 3, pp. 1–7. 2012.

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List of Conferences

Plenary Speaker

1 **M. Z. Zulkifli** and H. Ahmad, “S-band Optical Amplifier, 13th Mindanao National Physics Conference,20-22 October 2011 Andres Bonifacio College, Dipolog City, Philippines

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

2 **M.Z.Zulkifli**, A.A.Latif, S.W Harun and H.Ahmad, “Design the 10 GHz Filter for filtering Multiwavelength Brillouin Fiber Laser”,Winter College on Optic and Imaging Science, 24 January- 11 Fabuary 2011 ICTP, Triaste, Italy

3 H. Ahmad, **M.Z.Zulkifli**, A.A. Latif and S.W.Harun, “O-Band Multi-Wavelength Fiber Laser , 7th InternationalSymposium on Modern Optics and Its Applications, 2009 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

7 **Silver Medal**, "Tunable Multiwavelenth Fiber Laser using AWG and FBG",13-15 Januari 2009 Ekspo Penyelidikan, Rekacipta & Inovasi 2009 Universiti Malaya, Kuala Lumpur, Malaysia

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Acronyms

ASE	Amplified Spontaneous Emission
AWG	Arrayed Waveguide Grating
BEFL	Brillouin Erbium Fiber Laser
BDFL	Brilloiun Doped Fiber Laser
Bi-EDFA	Bismuth/Erbium Doped Fiber Amplifier
BP	Brillouin Pump
CIR	Circulator
CB	Conduction Band
C-band	Conventional Band
CWDM	Coarse WDM
CW	Continuous Wave
DC	Direct Current
DCF	Dispersion Compensating Fiber
DC-EDF	Depressed Cladding-Erbium Doped Fiber
DC-EDFA	Depressed Cladding-Erbium Doped Fiber Amplifier
DC-EDFL	Depressed Cladding Erbium Doped Fiber Laser
DFB	Distributed Feedback
DRA	Distribute Raman Amplifier
DRS	Double Rayleigh Scattering
DWDM	Dense WDM
EDF	Erbium Doped Fiber
EDFA	Erbium Doped Fiber Amplifier
EDFL	Erbium Doped Fiber Laser
FBG	Fiber Bragg Grating
FWHM	Full-Width Half-Maximum
FWM	Four Wave Mixing
FP-SOA	Fabry-Perot SOA
GFF	Gain Flattening Filter
HiBi-FLM	High Birefringence Fiber Loop Mirror

HRA	Hybrid Raman Amplifier
ISO	Isolator
ITU	International Telecommunication Union
L-band	Long-Band
LD	Laser Diode
MCVD	Modified Chemical Vapor Deposition
MWBDCEDFL	Multi-wavelength Brillouin/Depressed Cladding Erbium Doped Fiber Laser
MWBEFL	Multi-wavelength Brillouin/Erbium Doped Fiber Laser
MWBRFL	Multi-wavelength Brillouin/Raman Fiber Laser
MWBSOAFL	Multi-wavelength Brillouin/SOA Fiber Laser
MWFL	Multi-Wavelength Fiber Lasers
NF	Noise Figure
OC	Optical Circulator
OCS	Optical Channel Selector
OPM	Optical Power Meter
OSA	Optical Spectrum Analyzer
OTDM	Optical Time Domain Division Multiplexing
PC	Polarization Controller
PCF	Photonic Crystal Fibers (PCFs),
PDG	Polarization Dependence Gain
PLC	Planar Lightwave Circuit
PMF	Polarization Maintaining Fiber
RA	Raman Amplifier
RP	Raman Pump
RFL	Raman Fiber Laser
RFSA	Radio Frequency Spectrum Analyzer
S-band	Short Band
SA	Saturable Absorber
SBS	Stimulated Brillouin Scattering
SRS	Stimulated Raman Scattering
SLMs	Sagnac Loop Mirrors
SLM	Single Longitudinal Mode

SMF	Single Mode Fiber
SMSR	Sidemode Suppression Ratio
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SOAFL	Semiconductor Optical Amplifier Fiber Laser
SPM	Self-Phase Modulation
TE	Transverse Electric
TBF	Tunable Bandpass Filter
TLS	Tunable Laser Source
TMZF	Tunable Mach-Zehnder Filter
TFBG	Tunable Fiber Bragg Grating
TM	Transverse Magnetic
TFBG	Tunable Fiber Bragg Grating
TDM	Time Division Multiplexing
TW-SOA	Traveling Wave Semiconductor Optical Amplifier
VB	Valance Band
WSC	Wavelength Selective Coupler
WDM	Wavelength Division Multiplexing
XPM	Cross-Phase Modulation .

Nomenclature

A	Fiber core area
A_{eff}	Effective core area
A_{mf}	Mode field diameter
β	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	Young's modulus of the spring steel
ε	Strain
h	Planck's constant
$P_{s,out}$	Output signal power
$P_{s,in}$	Input signal power
P_{ASE}	ASE noise power
G	Gain
G_0	Small signal gain
G_{max}	Maximum value of small-signal gain
G_{TE}	TE mode gain
G_{TM}	TM mode gain
g_R	Raman gain coefficient
g_B	Brillouin gain coefficient
g_{th}	Gain Threshold
I_{sat}	Saturation intensity
$I_s(0)$	Incident pump intensity at fiber position z=0
n	Index of refraction/ refractive index
$\emptyset$	Azimuthal coordinates of a cylindrical
L_{coh}	Coherent length

L_{int}	Pump interaction length
η_{EB}	Cross efficiency of Brillouin/Erbium
$\eta_{B,}$	Brillouin Efficiency
η_E	Erbium Efficiency
η_p	Ratio of emission to absorption cross section at pump
η_s	Ratio of emission to absorption cross section at signal
P	Polarization
P_{out}	Output power
P_{sat}	Saturation power
P_{th}	Brillouin threshold
ρ_o	Peak dopant density
ρ_e	photo-elastic coefficient of silica fiber
p_{12}	Longitudinal elasto-optic coefficient,
ε_o	Vacuum permittivity
SNR_{in}	Signal-to-noise ratio input
SNR_{out}	Signal-to-noise ratio output
σ_e	Total emission cross section
σ_a	Absorbtion coefficient
t_p	Thickness of the Perspex
t_s	Thickness of the Spring Steel
τ_{sp}	Spontaneous life time of the ion in the metastable state
V_a	Velocity of Acoustic wave
v_B	Frequency shift
v	Frequency of the light
N_T	Total dopant concentration
R	Radiative transitions
N	State of population
NR	Non-radiate transitions
N_{eff}	Effective refractive indices in the waveguide array
N_f	Effective refractive indices in the free propagation region
W_{12}	Stimulated emission coefficients of the signal

W_{21}	Stimulated emission coefficients of the pump
N	Population density
λ_c	Cut-off wavelength
λ_0	Zero dispersion wavelength
λ_B	Bragg wavelength
$n_{sp}^{\pm}$	Spontaneous emission factor
$n_{eq}^{\pm}$	Equivalent input noise
Δ	Index difference
Δv	Bandwidth of optical amplifier
Δv_e	Emission bandwidth of the ASE spectrum
Δv_{sp}	Bandwidth of the noise
$\Delta \lambda_B$	Brillouin wavelength shift
Δv_B	Full width at half maximum of Brillouin
Γ	Confinement factor
α_s	Absorption coefficients at signal
α_p	Absorption coefficients at pump
w_a	Frequency of scattered wave
w_s	Frequency of acoustic wave
ω_o	Modal spot size