APPENDICES :

OUTPUT OF THIS DISSERTATION

Appendix A : Papers Published

Below is the list of papers that were published or presented out of this research, locally as well as internationally. These papers describe various effects that was observed during research and the progress of this research in whole.

International Conferences (with Proceeding)

1. M.K.Abdullah, V.Sinivasagam, Teyo,T.C and H.Ahmad, "*Development of EDFL-Brillouin Laser at TMPRC*", International Meeting of Frontier Physics (IMPF '98).
2. V.Sinivasagam, M.K.Abdullah, F.Isnin and H.Ahmad, "*Multiple Signal Generation in a BEFL system*", IMPF '98, Mines Resort Hotel, K.L.
3. P.Poopalan, M.A.Mahdi, M.K.Abdullah, V.Sinivasagam, N.P.Tan and H.Ahmad, "*Csacaded Fiber Amplifiers as Digital Memory Devices*", 1998 International Wireless and Telecommunication Symposium, ITM Resort Hotel, Shah Alam.
4. Teyo,T.C, M.K.Abdullah, F.Isnin, V.Sinivasagam and H.Ahmad, "*Optimization of the Reflectivity in Er^{3+}-Yb^{3+} Codoped Fiber Laser Design for Maximum Power*", IMFP '98, Mines K.L.
5. V.Sinivasagam, M.K.Abdullah, F.Isnin and H.Ahmad, "*EYDFL Giving Higher Efficiency and Smaller Power Flucuation as Compared to EDFL*", IEEE International Conference on Semiconductor Electronics, ICSE '98.
6. M.K.Abdullah, V.Sinivasagam, N.P.Tan, P.Poopalan, M.A.Mahdi and H.Ahmad, "*Effects of EDF length and Lasing Oscillation Reflectivity on the Performance of a Hybrid Brillouin-Erbium Fiber Laser System*", IWTS '98.

7. V.Sinivasagam, M.K.Abdullah, F.Isnin and H.Ahmad, "*The use of Er^{3+}-Yb^{3+} codoped fiber in improving the performance of a ring fiber laser*", XV International Conference on Solid State Science, Dec.'98, Hotel Seri Malaysia, Sepang.
8. M.K.Abdullah, F.Isnin, V.Sinivasagam, Teyo, T.C and H.Ahmad, "*Back-reflection and Pump Instability Effects on a Fiber Laser System*", ICSE '98.
9. M.K.Abdullah, V.Sinivasagam, F.Isnin and H.Ahmad, "*Multiple Channel Optical Coherent Source Employing SBS in Silica Fibers*", XV International Conference on Solid State Science, Dec.'98, Hotel Seri Malaysia, Sepang.
10. M.K.Abdullah, V.Sinivasagam and H.Ahmad, "*An Optical Channel Doubler Using Brillouin Fiber Laser(BEFL)*", 1st East Asian Conference on LiSLO, 16th-18th March '99, Hotel Equatorial, Bangi.
11. M.K.Abdullah, V.Sinivasagam and H.Ahmad, "*Reflectivity and EDF lengths effects in a BEFL system*", 1st East Asian Conference on LiSLO, 16th-18th March '99, Hotel Equatorial, Bangi.

National Conferences/Presentations (with Proceeding)

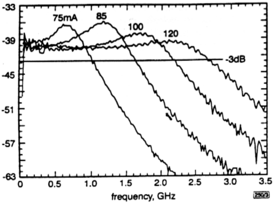
1. P.Poopalan, S.Vasagavijayan, N.P.Tan, M.A.Mahdi, M.K.Abdullah and H.Ahmad, "*Dual-Stage Optical Amplifier as All-Optical Digital Devices*", 1997 IEEE National Symposium on Microelectronics, Nov. '97, Nikko Hotel, Bangi.
2. S.Vasagavijayan, F.Isnin, M.K.Abdullah and H.Ahmad, "*Analysis of an EDFL and EYDFL System on the Tuning Range and Output Power*", 2nd National Conference on Telecommunication Technology, UPM Serdang.

3. Teyo,T.C, M.K.Abdullah, F.Isnin, S.Vasagavijayan and H.Ahmad, "*Optimization of Reflectivity in Erbium Fiber Laser Design for Maximum Output Power*", NCTT'98, UPM Serdang.
4. F.Isnin, M.K.Abdullah, Teyo,T.C, S.Vasagavijayan and H.Ahmad, "*The effects of filter positioning on a tunable fiber laser system*", NCTT'98, Idea Tower, UPM.
5. V.Sinivasagam, M.K.Abdullah and H.Ahmad, "*The effect of EDFL lasing gain on a multi-wavelength BEFL (MWBEFL) system*", NSM'99, Pan Pacific Hotel, Pangkor.
6. Teyo Tuan Chin, S.Vasagavijayan, F.Isnin, M.K.Abdullah and H.Ahmad, "*Erbium-Ytterbium Co-Doped Fiber Lasers and Cascaded Systems*", NSM'99, Pan Pacific Hotel, Pangkor, Perak.

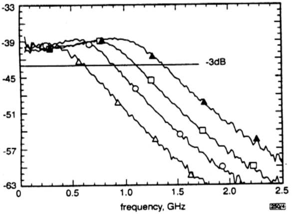
International Paper (Inserted)

1. V.Sinivasagam, M.K.Abdullah, F.Isnin, P.Poopalan and H.Ahmad, "*Stokes Signal Saturation in a Tunable BEFL System*", Electronics Letters, vol34, no.18, Sept. '98.

nder small signal modulation,
ency (ω^2) and the damping factor (γ) of such a damped har-
onic oscillation is linearly proportional to the photon density in
e cavity. The slope of the linear fitting results in differential gain
efficient (dg/dn), which is ~ 1.2×10^{-16} (cm²) for our 635nm low-
vergence laser diode. The gain coefficient is very much wave-
ngth dependent due to the lower carrier confinement in the short
avelength region. A gain coefficient of ~3.5×10^{-16} (cm²) has
en obtained from our 650nm low-divergence singlemode laser
ode fabricated by similar design and processing. Those numbers
e comparable with other reported results [4].



ig. 3 *Modulation response of low-divergence ridge waveguide 635nm inglemode laser at 20°C, showing device nearly free of parasitics*



ig. 4 *Modulation response of device at 50°C, with maximum band-vidth of 1.4GHz at –3dB*

△ 130mA
○ 140mA
□ 150mA
▲ 170mA

For optical storage applications, the devices need to be capable of operating at elevated temperatures of 50–60°C. We measured he modulation response at 50°C, and found a 1.4GHz –3dB bandwidth at this elevated temperature (Fig. 3), which is suitable for data storage applications where high data rates and high-frequency noise reduction techniques may require a speed of ~1GHz.

In summary, we have fabricated nearly parasitic-free low-divergence ridge waveguide 635nm singlemode lasers, which demonstrated a maximum bandwidth of 2.7GHz at 20°C and 1.4GHz at 50°C at –3dB under the electrical bias condition. A maximum differential gain of 1.2×10^{-16} (cm²) and 3.5×10^{-16} (cm²) has been obtained for 635 and 650nm low-divergence laser diodes, respectively.

29 June 1998

Electronics Letters Online No: 19981211

Bo Lu, E. Vail, J.S. Osinski and B. Schmitt (*SDL Inc., 80 Rose Orchard Way, San Jose, CA 95134, USA*)

E-mail: blu@sdli.com

1 OSINSKI, J.S., and LU, B.: 'Developments in red lasers for optical data storage'. 1997 Conf. Lasers and Electro-Optics, Baltimore, MD, 19 May 1997, Paper CMH4

2 HIROYAMA, H., NISHIDA, T., UETANI, T., BESSHO, Y., SHONO, M., SAWADA, M., and IBARAKI, A.: 'High-power 630nm-band AlGaInP laser diodes with strained-compensated single quantum well active layer'. 1997 Conf. Lasers and Electro-Optics, Baltimore, MD, 22 May 1997, Paper CThF1

3 MIYASAKI, F., HOTTA, H., UENO, Y., SAWANO, H., YAMAMOYO, M., TSUJI, M., KOBAYASHI, K., MAKITA, K., NYU, T., and YAMAZAKI, S.: 'High speed light sources and detectors for gigabit-per-second plastic-optical-fiber transmission'. OFC'95 Tech. Dig., 1995, pp. 257–258

4 MORITZ, A., WIRTH, R., HEPPEL, S., GENG, C., KUHN, J., SCHWEIZER, H., and SCHOLZ, F.: 'Intrinsic modulation bandwidth of strained GaInP/AlGaInP quantum well lasers', *Appl. Phys. Lett.*, 1997, **71**, pp. 650–652

5 LU, B., OSINSKI, J.S., VAIL, E., PEZESHKI, B., SCHMITT, B., and LANG, R.J.: 'High power 635nm low-divergence ridge waveguide singlemode lasers', *Electron. Lett.*, 1998, **34**, pp. 272–273

6 LAU, K.Y., and YARIV, A.: 'Ultra-high speed semiconductor lasers', *IEEE J. Quantum Electron.*, 1985, **21**, pp. 121

Stokes signal saturation in tunable BEFL system

V. Sinivasagam, M.K. Abdullah, F. Isnin, P. Poopalan and H. Ahmad

The Stokes shifted signal with 7nm tunability generated by a hybrid Brillouin/erbium fibre laser (BEFL) system was investigated. The results show that there is a saturation point after which further increment of Brillouin pump power will no longer increase the Stokes signal power. This saturation point determines the optimum Brillouin pump power needed for a specific BEFL configuration. A brief discussion on the methodology of determining the saturation point and selecting the best Brillouin pump power for a particular BEFL system is given. The results show that this is a promising technique for suppressing the stimulated Brillouin scattering effect, especially in areas that use high signal power.

Introduction: The importance of multiplexing/demultiplexing using wavelength division multiplexing (WDM) techniques in optical communication has prompted researchers to investigate multiple optical sources operating in the 1550nm long-haul optical communication window [1]. Besides the deployment of laser diodes, fibre lasers are a promising choice of light source due to their various advantages [2, 3], one of which is their ability to provide tunability features. The Brillouin/erbium fibre laser (BEFL) provides multiple optical sources that are closely spaced (~10GHz) for potential use in dense WDM systems. This design functions by utilising the Brillouin gain in singlemode fibre (SMF) and the linear gain in erbium-doped fibre (EDF).

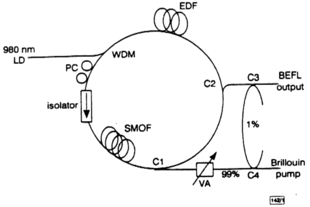
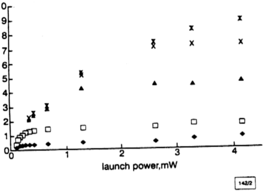


Fig. 1 *Experimental setup of BEFL system*

VA: variable attenuator, PC: polarisation controller
EDF = 7m, SMOF = 0.5km,
C1, C2, C3 = 50/50 coupler, C4 = 1/99 coupler

nt: In this Letter we present an observation on the gnal power saturation of the BEFL system. The variation okes signal power with launch power is discussed for varim laser diode (LD) powers. Launch power (LP) is the unched into the SMF by the Brillouin pump. The experitup is as shown in Fig. 1, whereby a tunable source was he Brillouin pump and a programmable attenuator conpower.

itput of the system is a tunable Stokes shifted signal with ity easily exceeding 5nm, as compared to existing systems ists of components used are as stated in Fig. 1. A 980nm ed as the pump source for the EDF and the latter is con- n a loop that carries the generated Stokes signal from the en pumped by the Brillouin pump. This amplified Stokes gnal propagates in the counter clockwise direction with to Fig. 1, and part of the signal is extracted using a al coupler and is monitored on an optical spectrum ana- SA). With all other parameters such as EDF and SMF eflectivity, cavity loss and length fixed, the output is mon- varying the Brillouin pump power with an attenuator at LD powers. For each fixed laser diode power, the pump power was increased and the peak power of the gnal was taken from the OSA at a 1nm span with a reso- 0.05nm. The maximum launch power used in this experi- as 4.16mW while the maximum LD power used was



xperimental results showing Stoke signal saturation

ver:
mW
mW
3mW
5mW
1mW

ording to Fig. 2, an increment in launch power into the ncreases the Stokes signal peak power until a point beyond t no longer increases. This point is defined here as the satu- point, which denotes the optimum launch power and the um Stokes power obtainable from a BEFL system at a LD power. Simultaneous increments in LD power and LP he saturation point to shift towards the right, as in Fig. 1. turation points at 22.74 and 100.75mW of LD power are at nd 5.16mW of LP, respectively.

se results can be further explained according to the operat- inciple of the system. The Stokes shifted signal power ses at the expense of launch power and this increase is sig- t, especially below the saturation point. As the launch is increased, the amount of Stokes signal generated es due to Brillouin gain provided by the SMF. This increase ted by the length of the SMOF which acts as the gain m for the Stokes signal. As the launch power is increased d the saturation point, the Stokes shifted signal does not ence any increment as the amount of Stokes signal generated fixed SMF length has reached its saturation level.

erring to Fig. 2, the saturation point increases and shifts ds the right (the saturation power increases) as the LD is increased. This is because, at low LD powers, not all Er^{3+} re excited and therefore the extra length of EDF causes re- ption of the Stokes signal, which reaches the saturation point nuch lower launch power. However, when the LD power is increased further, more Er^{3+} ions are excited, thereby reducing the unpumped EDF length; thus, there is less re-absorption and a greater Stokes signal is amplified whereby it reaches the saturation point at a much higher launch power. Fig. 3 shows the efficiency of the BEFL system against LD power at every saturation point for a specific launch power. The efficiency increases from 1.82 to 6.94% as the LD power is increased, which further explains that re-absorption of the Stokes signal occurs at low LD power and reduces at high LD power for which the efficiency remains almost constant. The Stokes signal was tunable around a 7nm range and the tuning range is limited by the EDF lasing gain profile [5].

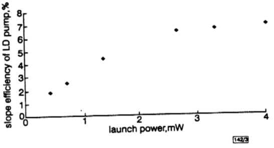


Fig. 3 *LD pump efficiency at respective launch power*

Conclusion: We have demonstrated that there is an optimum launch power needed in a BEFL system, and discussed ways of determining this optimum launch power. Operating the BEFL beyond this saturation point does not benefit the system, but only causes other nonlinear effects to take place, thus degrading the performance. In our BEFL configuration we have successfully obtained up to 8.85mW of Stokes signal peak power and a conversion efficiency of 6.94% for the 980nm LD pump. Further studies are being carried out to increase the tuning range of the Stokes signal and its potential use in suppressing the SBS effect in fibre based optical communications.

29 July 1998
Electronics Letters Online No: 19981266

V. Sinivasagam, M.K. Abdullah, F. Isnin, P. Poopalan and H. Ahmad (*Telekom Malaysia Photonics Research Centre, Department of Physics, University of Malaya, Kuala Lumpur, Malaysia*)

E-mail: khazani@rndtm.com.my

References

1 GILES, R., and TINGYE LI.: 'Optical amplifiers transform long-distance lightwave telecommunications', *Proc. IEEE*, 1996, **84**, (6), pp. 870–883
2 COCHLAIN, C.R.O., and MEARS, R.J.: 'Broadband tunable single frequency diode pumped erbium doped fibre laser', *Electron. Lett.*, 1992, **28**, (2), pp. 124–126
3 IWATSUKI, K., OKAMURA, H., and SARUWATARI, M.: 'Wavelength tunable single frequency and single polarisation Er-doped fibre ring laser with 1.4kHz linewidth', *Electron. Lett.*, 1990, **26**, pp. 2033-2035
4 COWLE, G.J., and STEPANOV, D.YU: 'Multiple wavelength generation with Brillouin/erbium fiber laser', *IEEE Photonics Technol. Lett.*, 1996, **8**, pp. 1465–1467
5 ABDULLAH, M.K., SINIVASAGAM, V., MAHDI, M.A., POOPALAN, P., and AHMAD, H.: 'Wavelength synchronization requirement in BEFL system'. OC'98, Kuala Lumpur, 1998, pp. 91–97

Appendix B : Exhibited Prototype Model

A prototype model of the multi-wavelength BEFL (MWBEFL) was developed and exhibited at the International Invention, Innovation, Industrial Design & Exhibition (ITEX '98) recently is shown below. This compact casing dimension is 9.5″× 4.3″× 0.5″ and was designed for robust application.

The prototype model of the MWBEFL system