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ACHIEVING GAIN FLATTENING WITH ENHANCED BANDWIDTH FOR LONG HAUL WDM SYSTEMS

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A hybrid amplifier consisting of one stage of Erbium Doped Fiber Amplifier and two stages of RAMAN amplifiers is constructed. Two RAMAN fibers are cascaded in series to suppress the intensity noise due to double Rayleigh scattering. Backward pumping is applied at all stages in order to increase the gain of Erbium Doped Fiber Amplifier and to decrease the polarization dependent gain of Raman fiber amplifier. Gain Flattening is achieved for the entire C-band and L-band. The simulation results showed that the hybrid amplifier has the average Gain of more than 24 decibels in the wavelength range between 1530–1605 nanometers, with the Noise Figure of less than 6 decibels. The Gain of the Erbium Doped Fiber Amplifier and RAMAN was optimized to minimize the ripple value as low as 0,7 decibels with an output power of 14,076 decibel-milli.

Keywords: *Raman fiber amplifier, hybrid amplifier, Erbium Doped Fiber Amplifier, Decibels, Decibel-milli, Noise Figure, Wavelength Division multiplexing, Gain Flattening Filter.*

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1. Introduction

Different techniques exist to enhance the flattened gain bandwidth of fiber amplifiers such as using gain equalizers (GEQ's), new host materials and connecting EDFA and thulium – doped fiber amplifiers in parallel configuration [1–4]. The techniques also include an EDFA, a GEQ and an RFA in serial configuration [5]. One possible way to increase the Gain Bandwidth is to combine numerous amplifiers with different Bandwidth Gain's and construct a hybrid amplifier [6]. These amplifiers could either be connected in series or parallel configuration. In parallel configuration WDM signals that serve as an input to the amplifiers are demultiplexed by the WDM coupler into numerous wavelength band groups. After amplification, these signals are again multiplexed through a WDM coupler [7]. On the contrary a very wide seamless Gain Band is observed for the amplifiers joined together in series configuration, because they do not need any WDM couplers. So connecting an EDFA amplifier in series with an RFA is an effectual approach because RFA can give any gain band by appropriately choosing the pump wavelengths and powers.

Thus, in order to add spectral shaping flexibility in broadband applications a high output power EDFA can be used with RFA [8]. The main bottleneck in such configuration lies in correctly setting up pump wavelengths and pump powers for RFA's. Optimization of the pump wavelength and pump power can make the gain spectrum extremely flat [9]. However RAMAN amplifiers are modeled by non-linear coupled equations with pump-pump and pump-signal interactions and there is no simple relation between wavelength, gain and power of the multiple pump lasers that can be found without seriously compromising the accuracy of the results [10].

The main aim of this work is to optimize EDFA+RAMAN hybrid amplifiers for long haul WDM systems. Fig. 1 shows the setup, used for the purpose of simulation. WDM channels serve as an input to the 5m EDFA amplifier pumped by a laser source. Two 25 km Raman fibers, pumped by a laser array and single pump laser

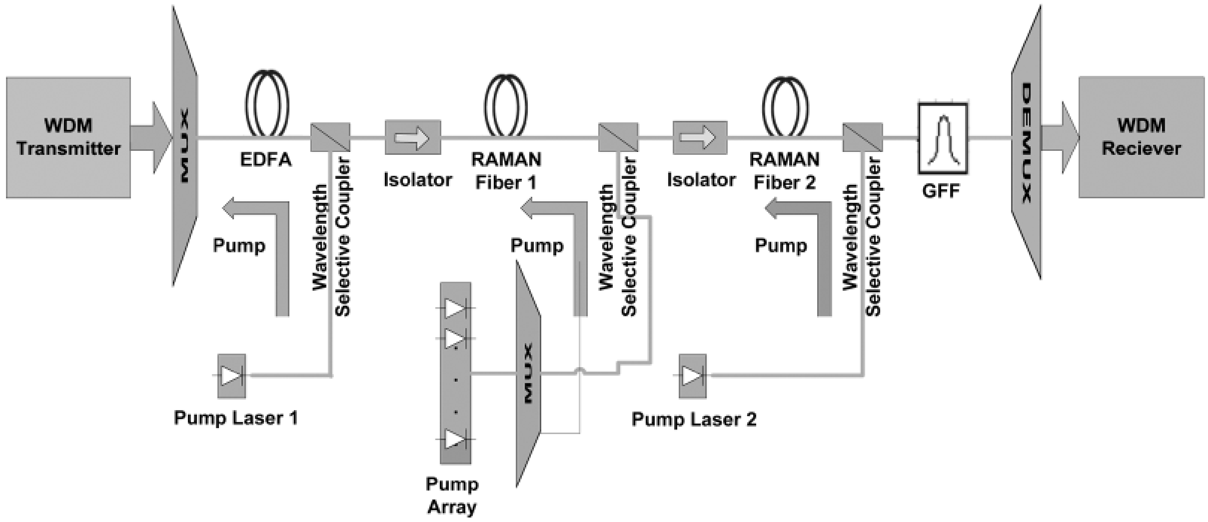

Fig. 1. Simulation Setup.

source respectively, follow the EDFA. Finally gain equalization is achieved with the help of a transmission filter also known as the Gain Flattening Filter (GFF). Backward pumping is used at all stages to increase the gain of EDFA and to decrease the polarization dependent gain (PDG) of RFA [11].

2. Hybrid Amplifiers Fundamentals

To compensate for the fiber losses in long-haul WDM systems, optical amplifiers are considered as indispensable optical components [12, 13]. Since EDFA's have very wide gain bandwidth, they can enable WDM based optical networking by amplifying all channels simultaneously without crosstalk and signal distortion. EDFA's are suitable to operate at the conventional C-band in the wavelength range from 1530 to 1565 nm [12]. Since the C band for EDFA's is fully utilized, the need for wider optical bandwidth requires that the EDFA technology should develop beyond its present limits. Thus to enhance the number of WDM channels and to broaden the optical bandwidth, optical amplifiers that operate in the L-band region are employed. Such amplifiers can work in the wavelength region from 1570 to 1605 nm. EDFA has a very low gain in the L-band region and hence a long length of erbium-doped fiber is required in most of the L-band EDFA's to pump up its gain. Also the noise figure (NF) of an L-band EDFA is much greater than a C-band EDFA [14]. On the other hand RFA's are characterized as an emerging technology for high capacity and long distance density wavelength division multiplexed (DWDM) systems. By using the correct pumped wavelengths, RFA's can amplify not only the C-band, but also the S-, L- and other bands [13]. RFA's have several advantages such as wide gain bandwidth and low noise figure (NF). They also provide flexibility while selecting a gain medium. Thus, L-band optical amplifiers are better to adopt RFA rather than L band EDFA [1]. The gain of an EDFA is given by [15]

$$G_{\mathrm{EDFA}} = (\tau\sigma_{\mathrm{em}}P_{abc}F)/(h\upsilon_{\rho}A_{\mathrm{eff}}\eta_p), \qquad (1)$$

where τ is the upper-state lifetime, σ_{em} is the emission cross-section, P_{abc} is the absorbed pump power, F is the overlap integral between the pump and signal fields in the transverse dimensions, $h\upsilon_P$ is the pump photon energy, A_{eff} is the fiber core area and η_{p} is the fractional pump energy. The gain of a RFA is defined as [15]

$$G_{\mathrm{RAMAN}} = [\exp(P_0 g_R L_{\mathrm{eff}})]/A_{\mathrm{eff}}, \qquad (2)$$

where P_0 is the pump power at the amplifier input, g_R is the Raman gain coefficient as a function of the wavelength difference between signal and pump, and L_{eff} is the pump effective length.

Thus the overall gain of a hybrid amplifier consisting of one stage of EDFA and two stages of RFA's is given by,

$$G_{\mathrm{total}} = G_{\mathrm{EDFA}}G_{\mathrm{RAMAN1}}G_{\mathrm{RAMAN2}}. \qquad (3)$$

Noise figure (NF) of EDFA is given by [16]

$$NF(\lambda) = [1 + \lambda^3 P_{\mathrm{ASE}}(\lambda)/(hc^2\Delta\lambda)]/G, \qquad (4)$$

where h is the Planck's constant, G is the EDFA gain, and c is the speed of light in vacuum. The equivalent noise figure (NF_{eq}) for the RFA which is derived from the Friis Formulation is given by [17]

$$NF_{\mathrm{eq}} = 1/G_R + 2P_{\mathrm{ASE}}/(B_0 G_R h\upsilon), \qquad (5)$$

where B_0 is optical measurement bandwidth and $h\upsilon$ is the photon energy.

3. Simulation Setup and Results

EDFA+RAMAN hybrid fiber amplifiers present an enabling technology for future long haul density wavelength division multiplexing (DWDM) systems. EDFA+RAMAN hybrid amplifiers are designed in such a way so as to maximize the span length and/or to minimize the fiber non-linearity impairments [18]. In our experiment we have used the approach used by Martini *et al* [20] except that, we have used the single pump sources and pump arrays for EDFA and Raman stages instead of utilizing the pump residual power. Since simulation has become an important tool for finding out more adequate configurations before they can be implemented experimentally, numerical simulation is employed in order to obtain the Global Performance of EDFA+Raman hybrid amplifiers setup configurations. Also the experiment was performed for the entire span length of 1530–1605 nm in comparison with [19].

The simulation setup shown in Fig. 1 consists of a 16 channel WDM transmitter with each channel carrying a 10 Gbps signal with a power of –20 dBm per channel in the wavelength range of 1530–1605 nm with 5 nm spacing. WDM channels served as an input to the 5 m EDFA pumped by a laser diode. Since commercial RAMAN pump lasers with power ratings less than 300 mW are available with affordable prices so a laser array consisting of 8 laser diodes is used as a pumping source for the first stage of 25 km RAMAN fiber. The second stage of 25 km RAMAN fiber is pumped by a single laser diode. The two RAMAN fibers are employed to suppress the intensity noise due to double Rayleigh scattering [21]. Since interaction between channels and pumps are very complicated, therefore it is very important to give good estimated initial values, especially to the pump wavelengths. Thus for accurately estimating the pump channel locations a general guideline is given in [22]. The wavelengths and powers of the laser diodes used for the pumping purpose are given in Table 1, 2.

A thin film 2 port Gain Equalization Filter or Gain Flattening Filter (GFF) with the operating wavelength range in the C/L band is used for the purpose of Gain Equalization. Generally there are two types of Gain Flattening Filters namely Dynamic Gain Flattening Filter (DGFF) and Static Gain Flattening Filter (SGFF).The DGFF in contrast with the SGFF accommodates for the variations of gain over time. Also the outstanding ripples of gain originating from one of the stages of DGFF cannot move into later amplification stages. Also by using a DGFF, network reconfigurability can be facilitated by eliminating the variations in gain caused by dropping and adding of channels.

Dynamic gain flattening filters (DGFF) generally come in two different types namely Channel by Channel and Continuous Envelope. Each wavelength channel is independently adjusted with the help of a channel-by- channel equalizer in the spectrum. The basic theme here is that the DWDM signals must be demultiplexed into individual channels in order to impose the required attenuation for every channel. After

Table 1. Pump powers and wavelengths for the laser diodes

Pump Sources	Wavelength, nm	Power, mW
Pump Laser	1465	100
Pump Array, 8 pumps	1435, 1442,5, 1450, 1457,5, 1465, 1480, 1495, 1510	50, 48, 46, 50, 170, 180, 190, 200
Pump Laser 2	1505	200

Table 2. Pump powers and wavelengths for the laser diodes after applying the optimization

Pump Sources	Wavelength, nm	Power, mW
Pump Laser 1	1458,91	91,2012
Pump Array, 8 pumps	1430,599, 1437,846, 1444,967, 1454,552, 1465,354, 1482,255, 1493,366, 1510	46,78, 48,52 43,04, 66,85, 154,76, 191,90 173,04, 187,67
Pump Laser 2	1503,24	209,887

that the channels are multiplexed back again in the DWDM transmission line. Predetermined configuration of channels like spacing of channels, wavelength range, bit rate, etc are needed for the channel-by-channel equalizers and each wavelength is treated individually by them. Also in rapidly growing DWDM systems upgradability and scalability could be limited by a fixed channel approach. In addition, use of a multiplexer and demultiplexer pair for the case of channel-by-channel equalizer results in the occurring of power penalties in the transmission system which also can result in signal distortion due to additional spectral dispersion and bandwidth narrowing. On the other hand adjustments are made on the basis of continuous and smooth filter function by using a continuous envelope equalizing filter. Since the gain profile from Raman or EDFA optical amplifier is effectively smooth, these filters can be used to give ideal spectral shaping for today's optical amplifiers. The commonly used building blocks to construct envelope gain equalizers are the Fourier filters and notch filters. The filter used in our experiment is a DGFF continuous envelope equalizer having 16 independent notches and produces a ripple as high as 1,18 dB, before applying the optimization. The results shown below are before applying the accurate numerical methods.

The whole hybrid amplifier is then taken in to account through accurate numerical methods [9]. The pump powers and wavelengths found after optimization are listed in Table 2.

After applying the optimization, ripple values less than 0,8 dB, an average Gain of 24 dB, an output power of 14,076 dBm, and a NF less than 6 dB in the 75-nm gain band was observed.

4. Comparison of Results

Analysis of the simulation results before and after applying the optimization shows that a better ripple value and power is observed after applying the optimization. As can be seen in Fig. 2: Gain Profiles, before applying the optimization a maximum Gain of 25,5523 dB and a minimum Gain of 24,3625 dB was observed after passing through the gain flattening filter (GFF). So the ripple value which is calculated as $G_{\max} - G_{\min}$ comes out to be 1,1897 dB. Also the maximum value of Noise Figure (NF) was observed to be 5,25 dB, as can be seen in Fig. 2: Gain Profiles and total Power was found to be 14,056 dBm. After applying the optimization as can be seen in Fig. 3: Gain Profiles, and after passing through the GFF a maximum Gain of 25,3612 dB and a minimum Gain of 24,5916 dB was observed, so the ripples value comes out to be 0,76 dB. The value of NF and Total Power was observed to be 5,20 and 14,076 dBm respectively.

The results showed that although there is a significant improvement in the ripple value but the NF and total Power were not much affected. This is because we have started with the good estimated values for the pump wavelengths and power's, before applying the optimization [23].

5. Conclusion

A hybrid amplifier comprising of one stage of Erbium Doped Fiber Amplifier (EDFA) and two stages of RAMAN amplifiers is presented. Two RAMAN fibers are cascaded in series to suppress the intensity noise due to double

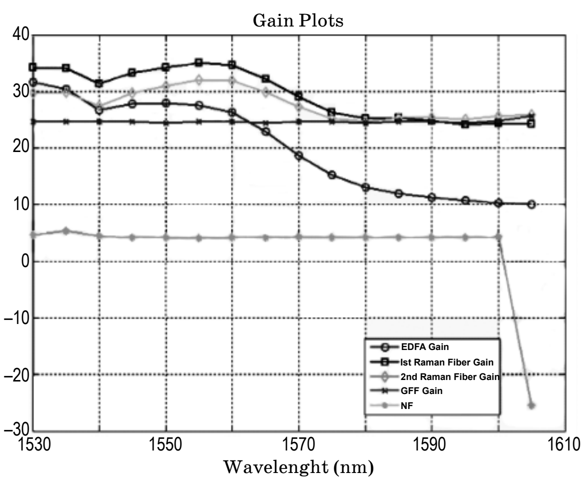

Fig. 2. Gain Profiles.

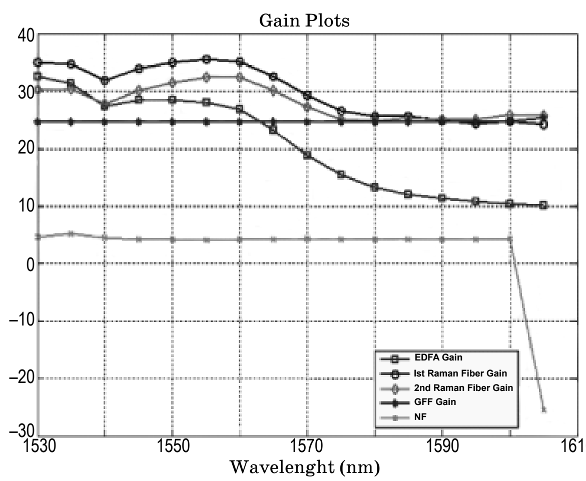

Fig. 3. Gain Profiles.

Rayleigh scattering. Gain Flattening is achieved for the entire C band and L band. We obtain a high gain in the wavelength range from 1530–1605 nm by using hybrid amplifiers. The simulation results show that the ripple values can be minimized to as low as 0,7 dB. The optimized values for the wavelengths and powers of pump sources were obtained by numerical techniques. Gain Equalization is achieved with the help of a Gain Flattening Filter (GFF). Thus a hybrid amplifier with an average Gain of 24 dB, an output power of 14,076 dBm, a ripple value less than 0,8 dB, and a NF less than 6 dB in the 75-nm gain band was achieved.

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REFERENCES

1. *Masuda H., Kawai S.* Wide band and Gain-flattened hybrid fiber amplifier consisting of an EDFA and multiwavelength pumped RAMAN amplifier // IEEE Photonics Technology Letters. 1999. V. 11. № 6. P. 647–649.
2. *Yamada M., Mori A., Kobayashi K., Ono H., Kanamori T., Nishida Y., Ohishi Y.* Low noise and gain-flattened Er^{3+}-doped tellurite fiber amplifier // Tech. Dig. Optical Amplifiers and Their Applications OAA. 1998. P. 103–106, paper TuC2.
3. *Wysocki P.F., Juskins J.B., Espindola R.P., Andrejco M., Vengasarkar A.M.* Broad-band erbium-doped fiber amplifier flattened beyond 40 nm using long-period grating filter // IEEE Photonics Technology Letters. 1997. V. 9. № 10. P. 1343–1345.
4. *Sun Y., Sulhoff J.W., Srivastava A.K., Abramov A., Strasser T.A., Wysocki P.F., Pedrazzani J.R., Judkins J.B., Espindola R.P., Wolf C., Zyskind J.L., Vengsarkar A.M., Zhou J.*A gain-flattened ultra wide band EDFA for high capacity WDM optical communications systems // Tech. Dig. European Conference on Optical Communication. ECOC 1. 1998. P. 53–54.
5. *Kawai S., Masuda H., Suzuki K.-I., Aida K.* Ultrawide, 75-nm 3-dB gain-band optical amplifier utilizing gain-flattened erbium-doped fluoride fiber amplifier and discrete Raman amplification // Electronics Letters.1998. V. 34. № 9. P. 897–898.
6. *Kawai S., Masuda H., Suzuki K.-I., Aida K.* Wide-Bandwidth and Long-Distance WDM Transmission Using Highly Gain-Flattened Hybrid Amplifier // IEEE Photonics Technology Letters. 1999. V. 11. № 7. P. 886–888.
7. *Sakamoto T., Aozasa S.-I., Yamada M., Shimizu M.* Hybrid amplifiers consisting of EDFA and TDFA for WDM signals // Journal of Lightwave Technology. 2006. V. 24. № 6. P. 2287.
8. *Karasek M., Menif M., Bellemare A.* Design of Wideband Hybrid Amplifiers for Local Area Networks // IEE Proc. Optoelectronic. 2001. V. 148. № 3. P. 150–155.
9. *Martini M.M.J., Castellani C.E.S., Pontes M.J., Ribeiro M.R.N., Kalinowski H.J.* Gain Profile Optimization for Raman+EDFA Hybrid Amplifiers with Recycled Pumps for WDM Systems // Journal of Microwaves, Optoelectronics and Electromagnetic Applications. 2010. V. 9. № 2. P. 100–112.
10. *Castellani C.E.S., Cani S.P.N., Segatto M.E.V., Pontes M.J., Romero M.A.* Design methodology for multi-pumped discrete RAMAN amplifiers:case study employing photonic crystal fibers // Optic Express. 2009. V. 17. № 16. P. 14121–14131.
11. *Liaw S.-K., Ho K.-P., Huang C.-K., Chen W.-T., Hsiao Y.-L.* Investigate C+L band EDFA/Raman amplifiers by using the same pump lasers // 6th International Joint Conference on Information and Computing (JCIS2006). JCIS2006 Kaohsoung Taiwan. paper PNC-11.
12. *Sun Y., Srivastava A.K., Zhou J., Sulhoff J.W.* Optical fiber amplifiers for WDM optical networks // Bell Labs Technical Journal. 1999. V. 4. № 1. P. 187–206.
13. *Islam M.N.* Raman Amplifiers for Telecommunications // Journals of Selected Topics in Quantum Electronics. 2002. V. 8. № 3. P. 548–559.
14. *Hwang S., Song K.-W., Song K.-U., Park S.-H., Nilsson J., Cho K.* Comparitive high power conversion efficiency of C- plus L-band EDFA // Electronics Letters. 2001. V. 37. № 25. P. 1539–1541.
15. *Agrawal G.P.* Fiber-Optic Communication Systems // 3rd Edition. John Wiley and Sons, USA. 2002.
16. *Becker P.C., Olsson N.A., Simpson J.R.* Erbium-doped fiber amplifiers fundamentals and technology // Academic Press, 1999. P. 47.
17. *Agrawal G.P.* Nonlinear Fiber Optics // 2nd Edition. Academic press, New York. 1995.

18. *Carena A., Curri V., Poggiolini P.* On the Optimization of Hybrid Raman/Erbium-Doped Fiber Amplifiers // IEEE Photonics Technology Letters. 2001. V. 13. № 11. P. 1170–1172.

19. *Tiwari U., Thyagarajan K., Shenoy M. R.* Simulation and Experimental Characterization of Raman/EDFA Hybrid Amplifier with Enhanced Performance // Optics Communications, ELSEVIER. 2009. V. 82. № 8. P. 1563–1566.

20. *Martini M.M.J., Castellani C.E.S., Pontes M.J., Ribeiro M.R.N., Kalinowski H.1.* Multipump Optimization for RAMAN+EDFA hybrid amplifiers under pump residual recycling // SBMO/IEEE MTT-S International Microwave & Optoelectronics Conference. IMOC. 2009. P. 117–121.

21. *Hansen P.B., Eskildsen L., Stentz A.J., Strasser T.A., Judkins J., DeMarco J.J., Pedrazzani R., DiGiovanni D.J.* Rayleigh scattering limitations in distributed Raman pre-amplifiers // IEEE Photonics Technology Letters. 1998. V. 10. № 1. P. 159–161.

22. *Emori Y., Kado S., Namiki S.* Broadband flat-gain and low-noise Raman amplifiers pumped by wavelength-multiplexed high power laser diodes // Optical Fiber Technology. 2002. V. 8. № 2. P. 107–122.

23. *Yan M., Chen J., Jiang W., Li J., Chen J., Li X.* Automatic design scheme for optical fiber Raman amplifiers backward pumped with multiple laser diode pumps // IEEE Photonics Technology Letters. 2001. V. 13. № 9. P. 948–950.