Photon Netw Commun
DOI 10.1007/s11107-008-0130-5

Experimental assessment of some Raman fiber amplifiers solutions for coarse wavelength division multiplexing applications

D. Sperti · P. S. André · B. Neto · A. M. Rocha · A. Bononi · F. da Rocha · M. Facão

Received: 3 October 2007 / Accepted: 1 April 2008

Abstract Raman amplification will, in a closer future, penetrate into the access network, bringing new challenges and difficulties to be overcome. In this article, we present the performance assessment of Raman amplification solutions suitable for Coarse Wavelength Division Multiplexing (CWDM) access networks applications. For this purpose, a pumping scheme with three lasers allows a bandwidth of 78 nm which is suitable for four CWDM channels. For this scheme, the gain and noise figure dependence with the pumping configuration was evaluated. The gain equalization was experimentally obtained based on a previously developed model using the Genetic Algorithm (GA) for pump allocation. A comparative study of Raman amplification in different types of Raman fibers (single mode fiber and dispersion shifted fiber) is also presented as well as the use of composite links. Those applications were tested in a local network and the obtained results comply with the modeling foreknowledge, showing the feasibility of Raman amplification over CWDM networks.

Keywords Raman fiber amplifiers · Access networks · Coarse wavelength division multiplexing · Broadband amplification · Pump allocation

1 Introduction

The increasing demand of broadband applications will soon outgrow the capacity of first generation access networks. Wavelength Division Multiplexing (WDM) seems to be a good solution to extend the capacity of optical networks without drastically changing the present fiber infrastructure. Actually, this technology can provide a virtual point-to-point link to each end user over Passive Optical Networks (PON) with simple Media Access Control protocols. This procedure enables the upgradeability of security levels and simplifies the network management [1]. Nowadays, WDM exists in two formats: Dense WDM (DWDM) working in the C and L spectral windows, allocating a maximum of 150 channels spaced by 100 GHz [2], and Coarse WDM (CWDM) working on the O, E, S, C, and L spectral windows, allocating a maximum of 18 channels spaced by 20 nm [3].

CWDM presents several cost benefits related to the use of affordable components. Due to the wide channel spacing, it is no longer necessary to stabilize the temperature of

---

D. Sperti · P. S. André · B. Neto (✉) · A. M. Rocha · A. Bononi · F. da Rocha · M. Facão
Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
e-mail: bneto@av.it.pt

D. Sperti
e-mail: sperti@av.it.pt

P. S. André
e-mail: pandre@av.it.pt

A. M. Rocha
e-mail: amrocha@av.it.pt

A. Bononi
e-mail: alberto.bononi@unipr.it

M. Facão
e-mail: mfacao@ua.pt

D. Sperti · A. Bononi
Facoltà di Ingegneria, Università Degli Studi di Parma, V.le G.P. Usberti, 69/A - Campus Universitario, 43100 Parma, Italia

P. S. André · B. Neto · A. M. Rocha · M. Facão
Departamento de Física, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

F. da Rocha
Departamento de Electrónica e Telecomunicações e informática, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
e-mail: frocha@det.ua.pt

laser sources and filters. However, there are some important issues such as the lack of an efficient optical amplification over such a wide bandwidth. A possible upgrade for a network is to first use CWDM and then insert DWDM channels in the C-band without disturbing the existing transmission, but optical amplification is still a matter of concern [1]. The key challenge for the amplification in CWDM systems is the large optical spectrum that the amplifier must cover.

Raman Fiber Amplifiers (RFA) are emerging as a promising technology owing to the theoretical possibility to obtain gain at any spectral region. Thus, a wide and flat spectral gain is achievable, thanks to the combination of several pumping lasers operating at specific powers and wavelengths. The composite amplification is determined from the mutual interactions among the pumps and signals, and gain spectra as wide as 100 nm were obtained using multiple pumping lasers [4]. Initially, the expensive high-power pumping lasers needed for Raman amplification have discouraged commercial interest in that kind of solution. By the last decade of the twentieth century, the Erbium Doped Fiber Amplifier (EDFA) seemed to be the most convenient reasonable choice, but the astonishing growing demand in terms of transmission capacity has saturated the entire spectral band of the EDFA. Hopefully, the development and commercialization at a reasonable cost of high-power pump laser will renew the interest in Raman amplification, which appears as a good solution for broadband applications, such as CWDM.

Another relevant aspect in the evolution of the optical networks is the heterogeneity of the fiber structure, being possible to find in the same link spans with the different fiber types. This could be due to several aspects, such as operational condition, upgrade strategy or even difficulty to replace old spans with the same type of fiber. Therefore, the study of Raman amplification in composite link could give guidelines for the real network behavior.

In this work, a methodology for the design of broadband RFA for CWDM applications is presented. The article is organized as follows: in Sect. 2, the Raman amplification theory is presented. This section also focuses on the use of two different types of optical fibers, standard single mode fiber (SMF) and dispersion shifted fiber (DSF), in Raman applications. In Sect. 3, a draft of the use of Raman amplification in access networks is presented with a procedure to enlarge the gain bandwidth and flatten its profile that makes use of Genetic Algorithms (GA). The experimental results are presented enhancing the effect of changes in the pumping power and configuration in the system performance. Comparative results of the use of DSF and SMF in fiber links are presented, as well as the use of composite links. The gain flattening results obtained from the GA simulations are also compared with the experimental ones. Finally, in Sect. 4 the main conclusions are drawn.

2 Raman amplification theory

Modeling of power evolution in multipump Raman amplifiers, in steady state, is based on a unified treatment of information carrying signals, pumping signals, and amplified spontaneous emission (ASE). The modeling accounts the major interactions that include the pump-to-pump, signal-to-signal, and pump-to-signal power transfer, attenuation, Rayleigh backscattering, spontaneous Raman scattering, and their temperature dependence. The effects that were excluded are anti-Stokes generation, polarization dependent gain, time dependence, and nonlinear index effects. For a system with N_p pumping signals, N_s information carrying signals and N_ASE spectral components, the power evolution along the fiber distance is given by the following set of $N_\mathrm{p} + N_\mathrm{s} + 2N_\mathrm{ASE}$ coupled differential Eqs., [5]:

$$\begin{aligned}\pm\frac{dP_i^{\pm}}{dz} = \Bigg[&-\alpha_i + \sum_{j=1}^{i-1} g_{ji}\left(P_j^{+} + P_j^{-}\right)\\ &- \sum_{j=i+1}^{m}\frac{\upsilon_i}{\upsilon_j} g_{ij}\left(P_j^{+} + P_j^{-}\right) - 2h\upsilon_i \sum_{j=i+1}^{m} g_{ij}\Gamma\\ &\times\left(1+\left(\exp\frac{h\left(\upsilon_i-\upsilon_j\right)}{k_\mathrm{B}T}-1\right)^{-1}\right)\Delta\upsilon\Bigg] P_i^{\pm}\\ &+\gamma_i P_i^{\mp} + h\upsilon_i\sum_{j=1}^{i-1} g_{ji}\Gamma\left(P_j^{+} + P_j^{-}\right)\\ &\left(1+\left(\exp\frac{h\left(\upsilon_j-\upsilon_i\right)}{k_\mathrm{B}T}-1\right)^{-1}\right)\Delta\upsilon\end{aligned} \tag{1}$$

The ± signs stand for the forward or backward propagating waves, being α_i and γ_i the coefficients of attenuation and Rayleigh backscattering of the ith wave at frequency υ_i, respectively. h and k_B are the Planck's and Boltzmann's constants, respectively, whereas T is the fiber absolute temperature. The Raman gain efficiency, g_{ij} [$\mathrm{W}^{-1}\mathrm{m}^{-1}$], accounts for the strength of the signal coupling via stimulated Raman scattering. This quantity varies according to the fiber types, depending upon their effective area, A_eff, and Raman coefficient, g_R, as follows:

$$g_{ij} = \frac{g_R\left(\upsilon_i - \upsilon_j\right)}{\Gamma A_\mathrm{eff}} \tag{2}$$

From (2) it is clear that gain efficiency can be varied by using different types of fiber. For comparison, SMF and DSF present different values of Raman gain efficiency because they differ in both effective area and Raman coefficient. Since, DSF presents a smaller area and a higher Raman coefficient than SMF, its Raman efficiency is sensibly improved, as depicted in Fig. 1.

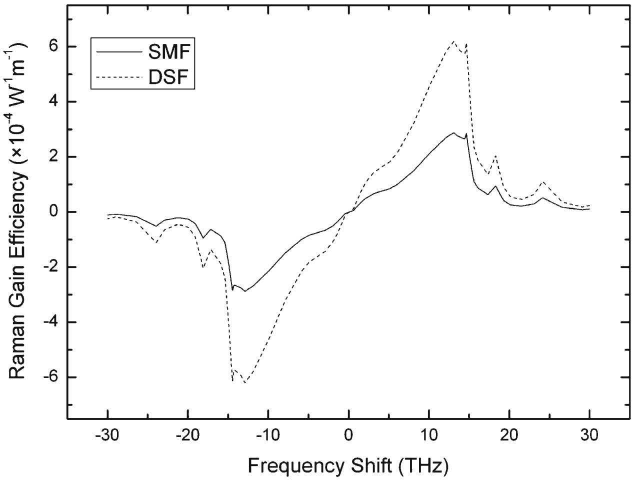


Fig. 1 Raman gain efficiency profiles for a 1,510-nm pump in two different types of fiber: SMF and DSF [6]

When an amplification scheme has to be designed, the proper selection of the fiber must be accounted for. In distributed amplification, the fiber losses are counterbalanced along the transmission, since the amplification fiber is the one used for transmission. For discrete amplification, a link with a different type of fiber can be used, as well as a composite link. Nevertheless, the fundamental issue is to increase the gain efficiency.

The use of multipump amplification schemes instead of single pump has proved to be valuable for CWDM systems since gain exists at any wavelength as long as the pump wavelength is properly chosen, multiple pumps will provide gain spectra that are broader and flatter. A flat spectral gain profile is achievable with the combination of several pumping lasers operating at specific powers and wavelengths. The technique that selects the appropriate wavelengths and power levels of the pumps is known as pump allocation. Among the numerical optimization methods available to perform this task, Genetic Algorithms (pure or associated with other search methods) appear as a suitable solution [7].

3 Raman amplification in access networks

3.1 Single pump versus multipump

An important feature to properly design an amplification scheme is the evaluation of the information channels bandwidth that is needed and the channel spacing. In CWDM, both bandwidth and channel spacing are large, therefore, we have to choose the most adequate pumping scheme that produces a flat spectrum gain as large as possible. The higher the number of pumps the larger and flatter is the gain bandwidth. Nevertheless, there are economic issues that prohibit the use of an arbitrary number of pumps. Hence, we have to find a balance between system performance and cost.

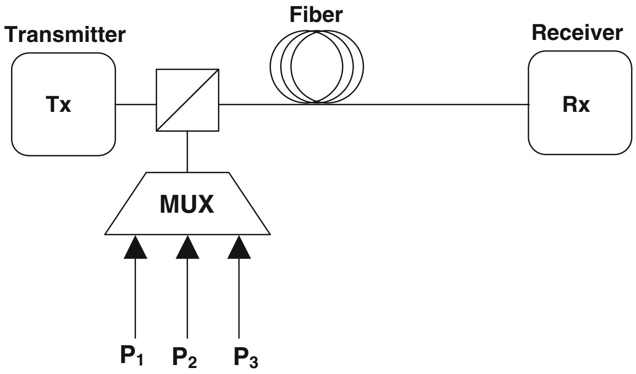


Fig. 2 Scheme of the used experimental setup

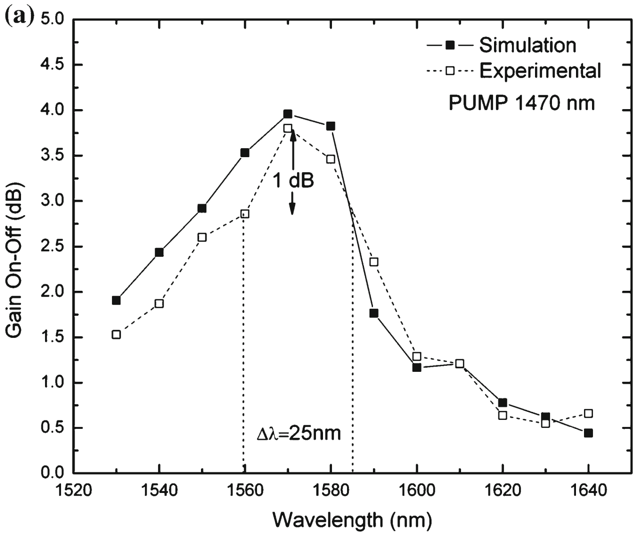
In order to demonstrate a proper pumping scheme (one, two, or three pumps), some experiments were carried out. An optical multiplexer with a set of three CW high power lasers was used as a pumping unit, being one, two, or three lasers used in each experiment. The copropagating pumps are centered at 1,470, 1,490, and 1,509 nm, each one with an output power of 158 mW. The propagation medium is a span of SMF fiber with 40 km, were $\alpha = 0.22$ dB/km, and $A_{\text{eff}} = 80\,\mu\text{m}^2$. The experiments were carried out with the measurement of the on/off gain for each scheme, using a forward pumping configuration. The scheme depicted in Fig. 2 reproduces the implemented experimental setup.

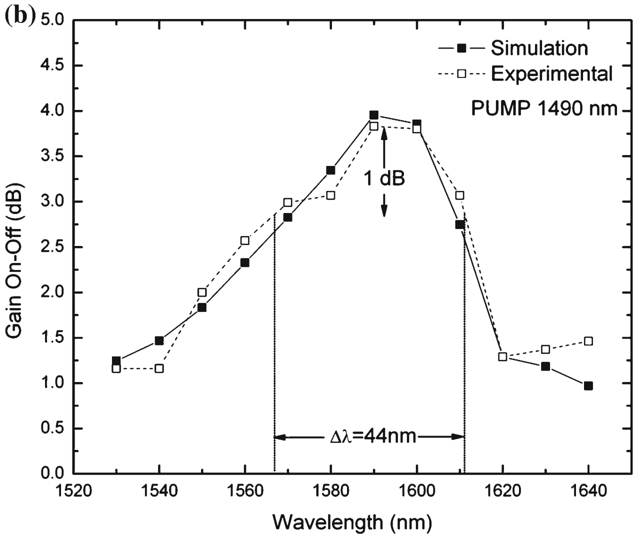
A comb of 12 wavelengths is used, but only three are turned on in each measurement. The three active channels are equally spaced by 20 nm (the CWDM channel spacing), starting with the triplet (1,530, 1,550, 1,570 nm), then rigidly shifting the three wavelengths by 10 nm.

Usually, this kind of measurements are taken with only one active channel but measurements using three active channels simultaneously instead of only one, provide a more accurate assessment of the system performance. For a single pump scheme, both simulation and experimental gain results are displayed in Fig. 3.

We observe that the results comply with the theoretical statement that the gain peak is obtained for a wavelength upshifted from the pump by 100 nm [8]. This peak decays rapidly with the wavelength, decreasing 1 dB for a small wavelength variation. A 1 dB decay is equivalent to a declining of 20% of the maximum gain, in linear units, and used to define the effective gain bandwidth. Therefore, the effective average gain bandwidth is equal to 39 nm, allowing the use of only two active channels for CWDM purposes. It must be noted that all three pumps present the same behavior.

After assessing the system performance using a single pump, we perform the evaluation for multipump schemes, using the three pumps simultaneously. The obtained gain





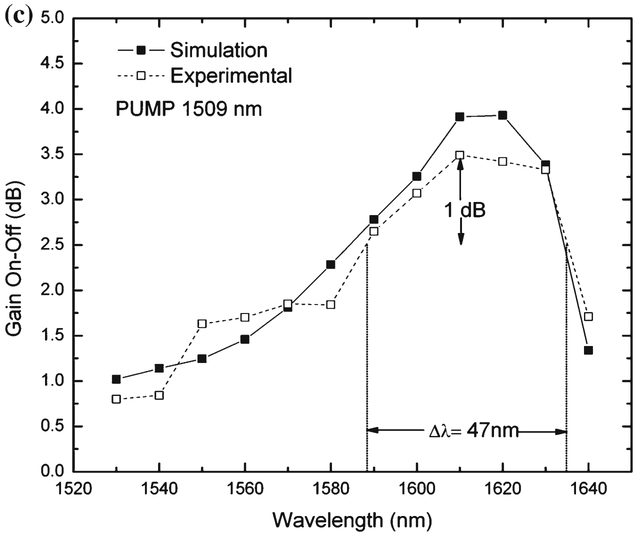


Fig. 3 Gain spectrum for the (**a**) 1,470 nm, (**b**) 1,490 nm and (**c**) 1,509 nm single pump scheme. Only the experimental bandwidth is assigned in the graphs

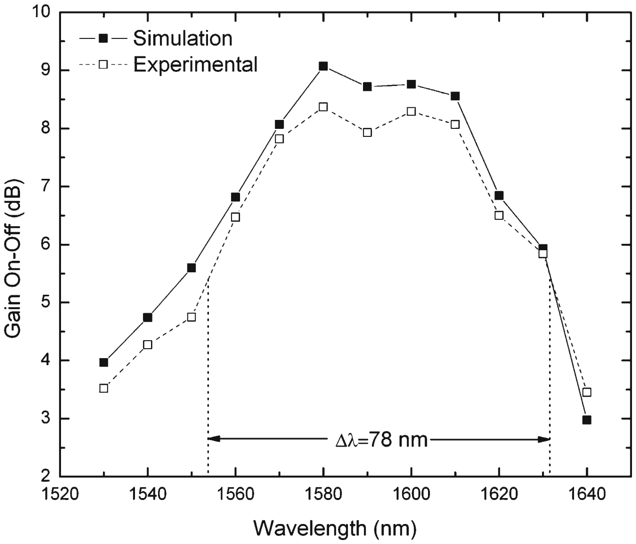


Fig. 4 Gain spectrum for multipump scheme. Only the experimental bandwidth is assigned in the graphs

spectrum is plotted in Fig. 4. As opposed to the single pump case, the deployed gain is higher and broader; being the effective bandwidth equal to 48 nm. A 78 nm bandwidth was measured at 3 dB. Since the channel spacing in CWDM is 20 nm, this pumping configuration allows the allocation of three active channels.

The use of two pumps instead of one also provides a higher and broader gain spectrum but the situation where the effect of the increase in the number of pumps is more evident is the three pumping scheme, as depicted in Fig. 5. In these graphs, the gain spectra obtained by the three pumps configuration and the possible combinations of two pumps are displayed.

These pictures show that the gain profile for the two pumps situation presents an intermediate performance between the three pumps and single pump configurations. The association of the more spectrally aparted pumps (1,470 nm with 1,509 nm) produce a lower valued gain than the other possible associations. Since the Raman gain created by pumps at different wavelengths is due to the partial overlap of each pump gain, only the pumps with closer emitting wavelength can form a consistent composite gain. For more aparted pumps this overlap does not occur and the gain is not reinforced.

3.2 Pump allocation—Optimized Gain

As referred above, the use of a multipump scheme results in a broader gain bandwidth, but the pump allocation is still needed to attain a gain as flat as possible. If the number of pumps and their wavelengths are constrained, the power level can be adjusted. The gain equalization is numerically attained by the minimization of its ripple. Since this process requires the use of multimodal search, robust optimization

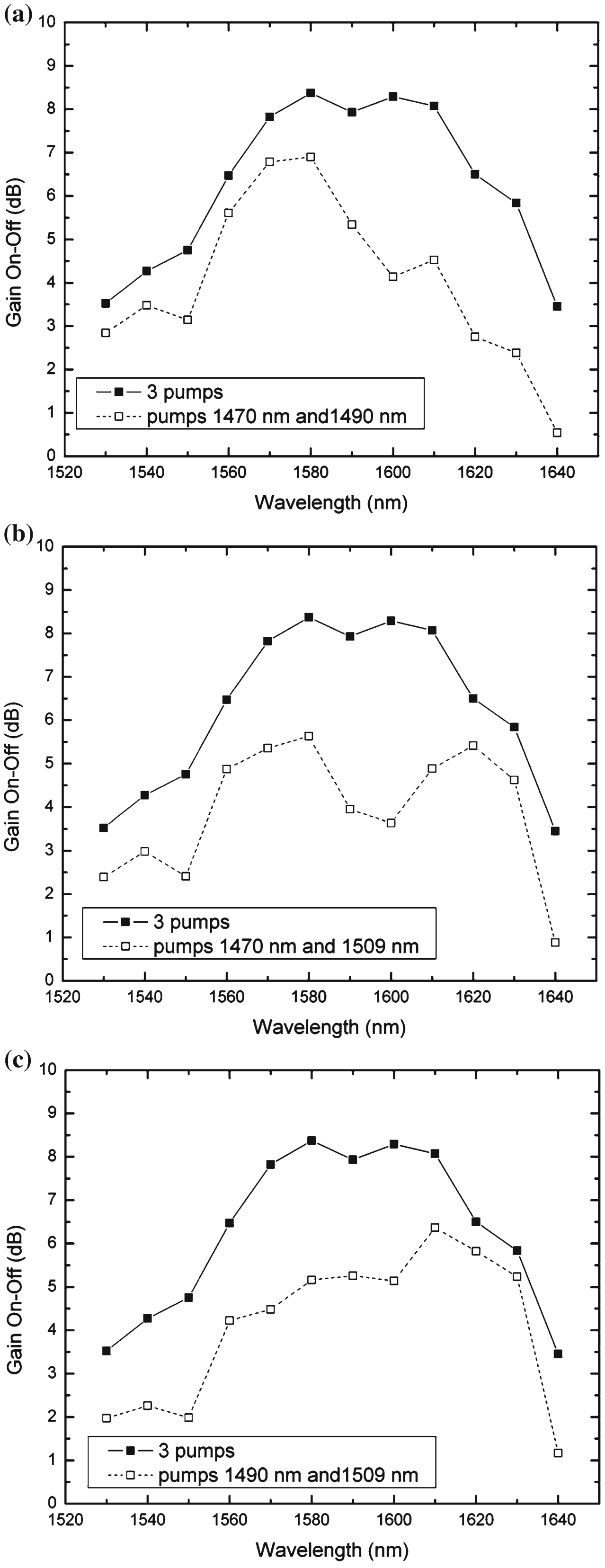


Fig. 5 Comparison between gain spectra obtained with the 3 pumps schemes and the two pumps one at (**a**) 1,470 and 1,490 nm (**b**) 1,470 and 1,509 nm (**c**) 1,490 and 1,509 nm

Table 1 Simulation and experimental gain using pump allocation

λ_{signal} (nm)	$G_{\text{simulation}}$ (dB)	$G_{\text{experimental}}$ (dB)	ΔG (dB)
1,570	7.05	7.08	0.03
1,590	7.05	7.12	0.07
1,610	7.05	7.20	0.15

algorithms are required. Our methodology is based upon a hybrid combination of the Genetic Algorithm with the Nelder–Mead simplex method. The use of a hybrid GA instead of a simple GA enhances the efficiency of the searching process, making it suitable for practical use [9]. First, the optimization using the hybrid GA was numerically implemented and only then the experiments were performed. Thus, the same pumps centered at 1,470, 1,490, and 1509 nm are used in the copropagating scheme depicted in Fig. 2, being the information carrying signals represented by a set of three CW lasers, centered at 1,570, 1,590, and 1,610 nm, respectively. The numerical gain target was set equal to 7 dB due to the limitation on the maximum pump powers. The obtained power levels for pumps at 1,470, 1,490, and 1,509 nm are equal to 128.08, 64.94, and 146.87 mW, respectively. Table 1 shows the simulated and experimental optimized power pumps and the gain for each channel. Experimental and simulated gain results show a good agreement.

3.3 Comparison SMF versus DSF

The heterogeneity of the fiber structure could lead to situations where a link is constituted by the concatenation of several spans with different fiber types, being necessary to understand the performance imposed by their different gain characteristic as shown in Fig. 1. The experiments make use of SMF and DSF fiber with a length equal to 8.8 km. The DSF fiber presents a smaller effective area and higher Raman gain coefficient when compared with a SMF and consequently it is possible to achieve higher levels of Raman gain. This experiment was carried out as previously, by changing only the type of fiber. The powers for the pumps are set equal to 158 mW each. In Fig. 6 the gain spectra of SMF and DSF are reported. As expected from the Raman efficiency data depicted in Fig. 1, the DSF induces an improvement in the on/off gain value when compared with a SMF with same length.

The different behaviors of SMF and DSF fibers enable further studies, like the use of composite links (DSF + SMF). In the analyzed setup, two configurations were used, differing in the position of the fibers: in the first configuration the DSF fiber (8.8 km) is placed closer to the transmitter and a 40 km SMF fiber span closer to the pumps, and in the second configuration the fiber order is reversed. The pumps centered at

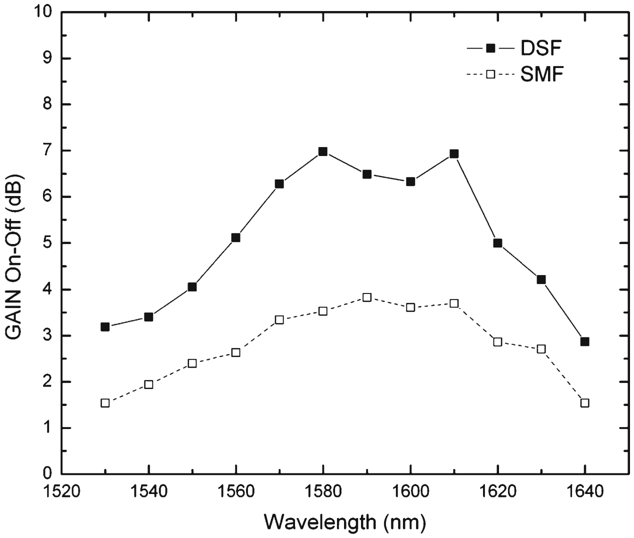


Fig. 6 On/off gain for a SMF fiber of 8.8 km and for DSF fiber of 8.8 km

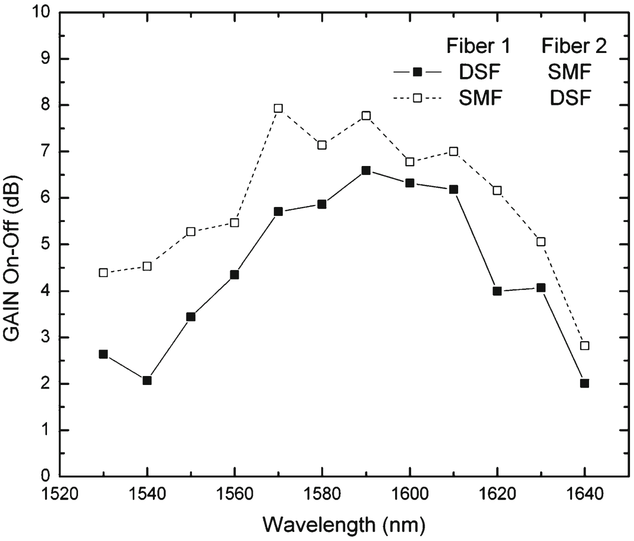


Fig. 7 On/off gain for a composite link: SMF fiber of 40 km and for DSF fiber of 8.8 km

1,470, 1,490, and 1,509 nm are used in a counterpropagation scheme with power levels equal to 158 mW.

The obtained gain is displayed in Fig. 7. By looking at the gain spectra, we observe that the profile is higher in the second configuration. This behavior was expected, as DSF fiber has a higher Raman gain and is placed nearer the pumps. However, this could result in an extra signal quality degrading, due to the excitation of nonlinear effects on the DSF fiber.

4 Conclusions

In this article, the Raman pump allocation configuration for CWDM transmission system is presented. We demonstrate that the multipump configuration, in addition to presenting a broader and flatter spectral gain than the single pump configuration, is also able to guarantee the compensation of the fiber attenuation losses. For that very reason, the multipump configuration is preferable to the single pump, for large channels spacing applications such as CWDM, being possible to support amplification in three CWDM channels with three pumping lasers. Since the latter also require the use of equalized gain bandwidth, we have shown that the pump power allocation computed by hybrid Genetic Algorithms is efficiently feasible, exhibiting good agreement with experimental results. The effect of composite links was studied, showing an increase on the gain when the DSF fibers are located closer to the pumps.

Finally, we show that the simple equations that describe the Raman amplification can be implemented for CWDM signals, producing results comparable with the experimental ones, resulting, therefore, on an efficient planning tool.

Acknowledgments This work was supported by the POSC program, financed by the European Union FEDER fund and by the Portuguese scientific program. The authors express their gratitude to the projects ARPA (POSI/EEA-CPS/55781/ 2004) and TECLAR(POCI/A072/ 2005).

References

[1] Amplification in CWDM Systems, BTI Photonic Systems (http://www.btiphotonics.com)

[2] Internation Telecommunications Union, ITU -T G.694.1 (http://www.itu.int)

[3] Internation Telecommunications Union, ITU -T G.694.2 (http://www.itu.int)

[4] Kidorf, H., Rottwitt, K., Nissov, M., Ma, M., Ribarijaona, E.: Pump interactions in a 100-nm bandwidth Raman amplifier. IEEE Photon. Tecnol. Lett. **11**(5), 530–532 (1999)

[5] Karásek, M., Kanka, J., Honzátko, P., Peterka, P.: Time-domain simulation of power transients in Raman fibre amplifiers. Int. J. Num. Model. Electron. Network Dev. Fields **17**(2), 165–176 (2004)

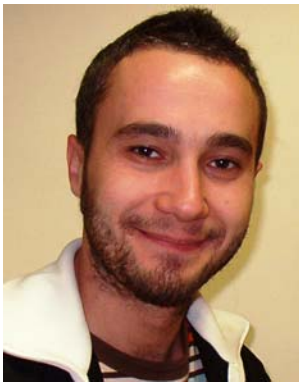
[6] Stolen, R.H., Ippen, E.P.: Raman gain in glass optical waveguides. Appl. Phys. Lett. **22**, 276–278 (1973)

[7] Neto, B., Junior, S., Teixeira, A.L.J., André, P.S.: Efficient simulation of Raman amplifiers propagation equations and spectral gain with optimization techniques. In: European Conference on Networks and Optical Communications (NOC), vol. 1, pp. 381–386. Berlin, Germany, (2006)

[8] Bromage, J.: Raman amplification for fiber communication systems. IEEE/OSA J. Lightwave Technol. **22**, 79–93 (2004)

[9] Neto, B., Teixeira, A.L.J., Wada, N., André, P.S.: Efficient use of hybrid Genetic Algorithms in the gain optimization of distributed Raman amplifiers. Opt. Express **15**(26), 17520–17528 (2007)

Author Biographies



D. Sperti was born in Lucera, Italy in January 1980. He graduated in Telecommunication Engineering in 2004 from the University of Parma. Approved experimental thesis with the maximum one of the votes regarding "Comparative Analysis of the performance of receivers for optics communications IM/DD", supported by use of the software OPTSIM for the simulation of systems of optic communications. From September 2006 to May 2007 he had made his specialization Thesis at the Instituto de Telecomunicações—Aveiro, about Raman Amplification. He has been co-author of "Optical Fibers Research Advances", editor: Jurgen C. Schlesinger and has written some articles about Raman Amplification. Now, he is finishing his study in Optical Communiction at University of Parma.

P. S. André (S′1998, M′2003) was born in Luanda, Angola, in April 1971. He graduated in Physics Engineering in 1996 and the Ph.D. in Physics in 2002, both from the University of Aveiro, Portugal. In the same year, he joined the Instituto de Telecomunicações—Aveiro as Researcher. He is also an Assistant Professor at the University of Aveiro, teaching Physics. His current research interests include the study and simulation of optoelectronics components, transparent performance monitoring, multi-wavelength optical communications systems, and networks. Paulo André is a member of the Portuguese Physics Society (SPF), the Portuguese Materials Society (SPM), Optical Society of America (OSA), and of the Institute of Electrical and Electronics Engineers (IEEE).

B. Neto was born in Montbéliard, France, in March, 1975. She graduated in Physics in 2002 from the Science Faculty of the University of Porto, and received the M.S. degree in 2005 from the University of Aveiro, with a work thesis on the topic of chromatic dispersion compensation. At present, she is a Ph.D. student at the University of Aveiro researching for the Instituto de Telecomunicações—Aveiro in the area of alternative techniques for Raman fiber amplifiers. Her research interests include the study of optical amplifiers and software development.

A. M. Rocha was born in Portugal, in August 1978. She received the engineering degree in physics from the University of Aveiro in 2002. From 2003 to 2004, she was a member of the technical staff at the mechanics department of the University of Aveiro. From 2005 to 2006 she joined Teka Portugal, S.A. and the physics department of the University of Aveiro working on the optimization of microwave oven door seals. Now, she is with Instituto de Telecomunicações—Aveiro researching in the area of alternative techniques for Raman amplifiers. At present, she is a Ph.D. student in physics engineering at the University of Aveiro.

A. Bononi was born in La Spezia, Italy in 1963, received his Laurea Degree in Ingegneria Elettronica (Honors) from the *Università degli Studi di Pisa* in April 1987. He received his Masters of Arts and Ph.D. degrees in Electrical Engineering from *Princeton University*, NJ, USA, in 1992 and in 1994, respectively. He is an Associate Professor of *Telecommunications* since March 2001 in the *Dipartimento di Ingegneria dell'Informazione* of the *Università di Parma*, where he served as an Assistant Professor since May 1995. His *research* interests range from the study and performance evaluation of broadband optical networks, both packet- and circuit-switched, to the design of wavelength division multiplexed (WDM) long-haul terrestrial and submarine optical transmission systems, with emphasis on the study of optical amplifiers, both fiber-based (EDFA, Raman) and semiconductor-based, on the study of polarization mode dispersion (PMD), and on the optimization of dispersion maps for WDM nonlinear fiber propagation.

F. da Rocha was born in Mozambique. He received the M.Sc. degree in telecommunication systems and the Ph.D. degree in electrical engineering both from University of Essex, Essex, U.K., in 1980 and 1983, respectively. He participates actively with the Telecommunications Institute, which is a national R&D nonprofit organization, where he is a member of the Management Committee (Aveiro, Portugal branch) and the National Coordinator for the optical communications area. He has coordinated the University of Aveiro and Telecommunications Institute participation in various projects included in the following European Union (EU) R&D Programs in the area of telecommunications: RACE, RACE II, ACTS, and IST. Over the past few years, he has acted as a Technical Auditor, Evaluator, and Independent Observer for the evaluation of projects submitted to various EU R&D Programs. He has also participated in various project evaluation boards set up by the Engineering and Physical Sciences Research Council (EPSRC), United Kingdom. By invitation of the ACTS Management Committee, he participated in the "Expert Groups on Visionary Research in Communications," which aimed to create a bridge between the activities carried out in the Fourth and the Fifth Framework Programs on EU activities in the field of research, technological development, and demonstration. He is currently a Full-time Professor with the University of Aveiro. He has published about 170 papers, mainly in international journals and conferences. His present research interests include modulation formats and receiver design for very high-capacity (above 40 Gb/s) optical communication systems based on linear and nonlinear transmission and wavelength division multiplexing optical networks.

M. Facão was born in Portugal, on February 8, 1971. She received the Licenciatura degree in Physics in 1993 from University of Aveiro (Portugal) and the Ph.D. degree in Applied Mathematics in 2004 from the University of Edinburgh (U.K.). She is currently an Assistant Professor at the Dep. of Physics of the University of Aveiro. Her research interests include nonlinear evolution equations (equilibrium solutions and stability), nonlinear optics, optical communications.