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Gain characteristics of a 210 km hybrid Raman/erbium-doped fiber amplified loop

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Abstract

As an alternative to using gain flattening filters or other optical devices that add attenuation to balance the gain in the optical spectrum, we have studied the effects of combining gain from Raman amplifiers and erbium-doped fiber amplifiers (EDFAs) in a fiber recirculating loop. We have shown a parameter range for which the gain profile is flat, and have analyzed the variation of the gain tilt as a function of the individual contributions of the Raman and EDFA amplifiers.

Keywords: EDFA; Raman amplification; Gain tilt compensation

1. Introduction

For wavelength-division multiplexed (WDM) transmission, the spectral variation of the amplifier gain can result in significant transmission impairments due to gain tilt and ripple. A common technique for reducing these effects is to use passive devices that attenuate selected channels. However, in addition to adding loss to the system, this approach increases the number of components required and therefore the overall system cost. Another approach is to combine different gain sources with differing spectral characteristics, which when added together result in flattened, ripple-free gain over some bandwidth [1–4].

In this article we present an experimental and simulation study in which we use distributed Raman amplification and erbium-doped fiber amplifier (EDFA) gain media together to eliminate the gain tilt, removing the need for extra components that add excess loss. We used a 210 km recirculating loop to investigate the gain tilt present in a 7 nm signal bandwidth using five equally-spaced non-return-to-zero (NRZ) channels between 1547 and 1553.4 nm when varying the amount of EDFA and Raman gain. In contrast to previous studies of a similar system [4], our loop is significantly simplified, utilizing only a single-wavelength Raman pump and no gain-flattening or equalizing filters. After the signal has propagated 1700 km, we find that the gain is flat over a 7 nm bandwidth, with a ripple of less than 0.5 dB. We also present a parameter study showing the sensitivity of the gain, gain tilt, and optical signal-to-noise ratio (OSNR) to the balance of Raman and EDFA gains. Channels that experience excess Raman gain maintain their power over longer lengths due to the distributed nature of the Raman gain. Hence, these channels experience higher self-phase modulation and have a greater tendency for their spectra to broaden than those channels for which the EDFA contributes more gain.

2. Experimental setup and amplifier model

The transmitter in this experiment consists of five continuous wave (CW) lasers, each of which is modulated by

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an electro-optic modulator (EOM) driven with a $2^{23}-1$, 10 Gb/s NRZ pseudorandom bit sequence. The input power is −3 dBm per channel. The recirculating loop consists of six segments, each of which is composed of a 10 km spool of single-mode fiber (SMF)-28 followed by a dispersion compensation module (DCM), which compensates both the dispersion and dispersion slope of the entire segment, followed by another spool of 25 km of SMF-28 fiber. After this spool, the Raman pump laser at 1455 nm is injected backward into the segment using a WDM coupler. The last component in each segment is an EDFA that boosts the signal before it continues to the next segment (see Fig. 1). The DCM was placed between the 10 and 25 km SMF-28 spools to balance the optical signal-to-noise ratio degradation and nonlinear impairments resulting from the distributed Raman amplification [5]. Our segments were limited to 35 km, so as to maintain high OSNR over long transmission distances and to avoid large power variations as a function of transmission distance, yielding a high-performance system. After the sixth segment, there is a booster EDFA that compensates for the loss of the loop switch and the 3 dB coupler.

The output signal is captured using a triggered optical spectrum analyzer (OSA). The traces are captured after 1 and 8 round trips (or 1700 km), and the signal tilt and mean power of the channels is extracted from the traces for several values of the EDFA and Raman pump powers. To measure the mean channel powers, we record the power levels and wavelengths at the channels centers. We perform a linear regression on the 5 points that we obtained in this way to extract the signal tilt. To measure the OSNR, we use the midpoint in wavelength between two adjacent channel wavelengths and read the power level at that point. Using the 4 points for the noise power level, we perform a linear regression to measure the noise level and its tilt. The OSNR is calculated by subtracting the signal power

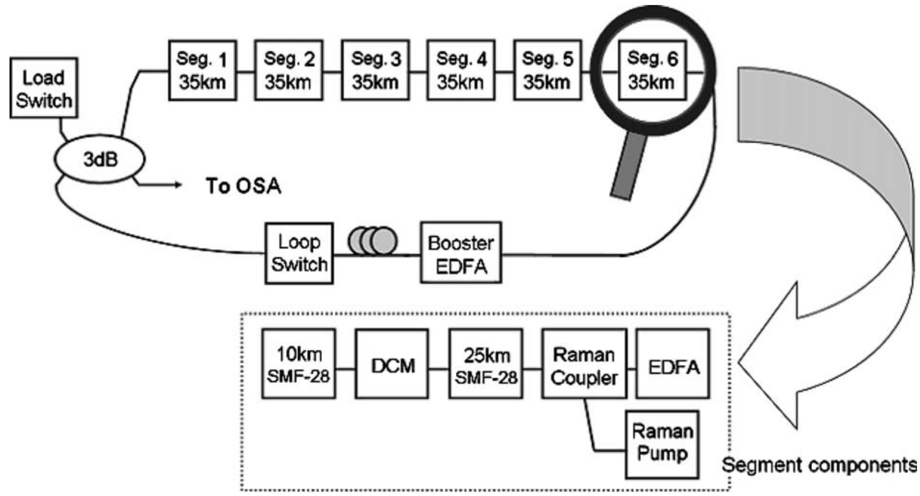

Fig. 1. Schematic of our 210 km recirculating fiber-optic loop.

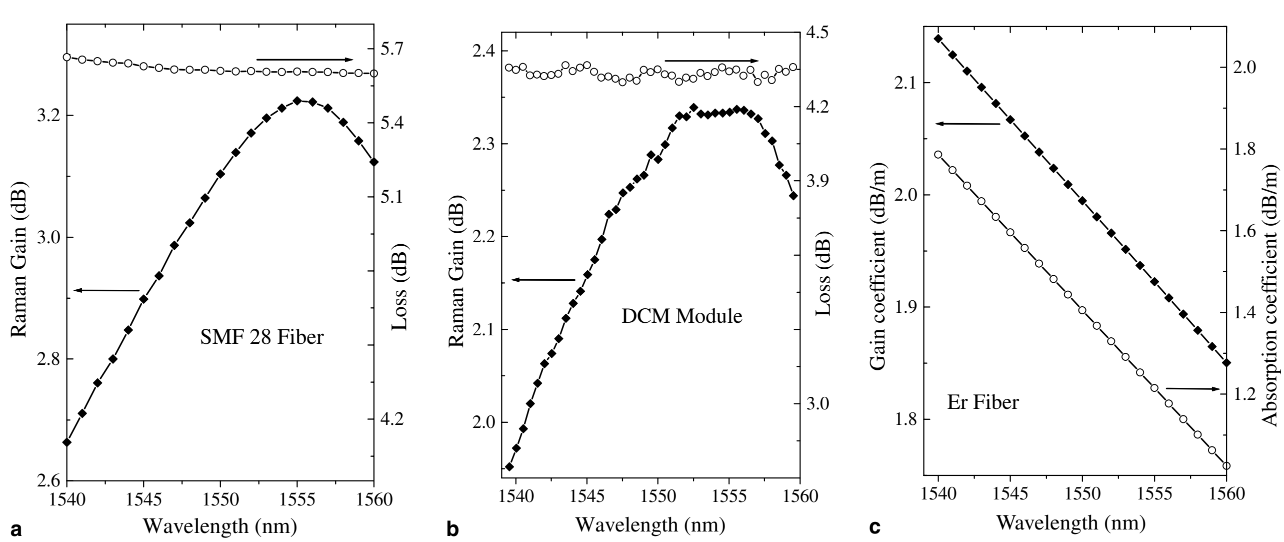

Fig. 2. Gain and loss characteristics of the fiber in the loop: (a) gain and loss for the SMF-28, (b) gain and loss for the DCM and (c) gain and absorption coefficients of the erbium fiber used in the EDFAs in the loop.

from the noise power given by the calculated regression at the channel wavelength.

In order to simulate the experimental results, we developed a full amplifier model for both the Raman and EDFA contributions. We used a shooting algorithm to solve the backward-pumped Raman amplifier equations [6]. We describe wave propagation in a backward-pumped, multiple-wavelength fiber Raman amplifier using a system of coupled equations that includes the effects of spontaneous Raman scattering and Rayleigh back-scattering [7,8]. The pump-to-pump, pump-to-signal, and signal-to-signal Raman interactions are considered in the coupled equations,

$$\pm\frac{dP_k}{dz}=-\alpha_k P_k+\sum_{j=1}^{m+n} g_{jk}P_jP_k, \tag{1.a}$$

$$\pm\frac{dP_{ASE,k}}{dz}=-\alpha_k P_{ASE,k}+\sum_{j=1}^{m+n} g_{jk}P_j(P_{ASE,k}+h\nu_k\Delta\nu F_{jk}), \tag{1.b}$$

$$-\frac{dP_{SRB,k}}{dz}=-\alpha_k P_{SRB,k}+\sum_{j=1}^{m+n} g_{jk}P_jP_{SRB,k}+\kappa P_k, \tag{1.c}$$

$$\frac{dP_{DRB,k}}{dz}=-\alpha_k P_{DRB,k}+\sum_{j=1}^{m+n} g_{jk}P_jP_{DRB,k}+\kappa P_{SRB,k}, \tag{1.d}$$

where n is the number of pump waves and m is the number of signal waves. The values P_k, ν_k, and a_k describe, respectively, the power, frequency, and attenuation coefficients for the kth wave, where $k = 1, 2, \ldots, m+n$. The quantities $P_{ASE,k}$, $P_{SRB,k}$, and $P_{DRB,k}$ are the powers corresponding to amplified spontaneous emission (ASE) noise, single Rayleigh backscattering (SRB), and double Rayleigh backscattering (DRB), respectively. The gain coefficient g_{jk} describes the power transferred by stimulated Raman scattering between the jth and kth waves and is given by $g_{jk} = (1/2A_{eff})g_j(\nu_j - \nu_k)$ for $\nu_j > \nu_k$ and $g_{jk} = -(1/2A_{eff})(\nu_k/\nu_j)g_k(\nu_k - \nu_j)$ for $\nu_j < \nu_k$. Here, A_{eff} is the fiber effective area and $g_i(\Delta\nu)$ is the Raman gain spectrum experienced by a signal spaced in frequency $\Delta\nu$ away from the pump. The Raman gain in our transmission fiber for the pump wavelength $\lambda_0 = 1455$ nm, is plotted in Figs.2(a) and (b). The temperature-dependent term contributing to ASE noise is given by $F_{jk} = N_{phon} + 1$ for $\nu_j > \nu_k$, $F_{jk} = -N_{phon}$ for $\nu_j < \nu_k$, where $N_{phon} = [\exp(h|\nu_j - \nu_k|/k_BT)-1]^{-1}$. Here, the parameters T, k_B, and h are the temperature of the system, Boltzmann's constant, and Planck's constant, respectively. For a fiber span of length L, the boundary conditions are defined at $z = 0$ for the signal waves $P_k(0) = P_{k0}$ $(k = 1, 2, \ldots, m)$ and at $z = L$ for the backward propagating waves. The Rayleigh backscattering coefficients, κ, used in the simulations are 6×10^{-5} and 5×10^{-4} km^{-1} for SMF-28 and DCM, respectively [8]. Also, polarization effects have been neglected in Eqs. (1).

This set of coupled ordinary differential equations is used to find the power variation in a Raman amplifier with Raman scattering and Rayleigh back-scattering [9]. Temperature-dependent ASE, single Rayleigh backscattering, and double Rayleigh backscattering are included in the model, as these noise sources affect the OSNR and, to a lesser extent, the gain.

Different measured Raman gain profiles are used in modeling the Raman amplification in the SMF and the DCM. These profiles are shown in Fig. 2(a) and (b). The length of the DCM fiber is 6.6 km, and the loss at 1455 nm is 0.8 dB/km. The length of the SMF-28 fiber is 25 km, and the loss at 1455 nm is 0.4 dB/km. The Raman gain in the SMF-28 is measured while backward pumping the 25 km piece with a pump power of 175 mW. In the case of the DCM, the Raman pump is first sent through a 25 km long SMF-28 fiber spool to emulate actual loop conditions. Our Raman model was validated by comparison with previously published results by Perlin and Winful [10,11] and with a simulation of 8 pump waves and 100 signal waves published by Kidorf et al. [6,9].

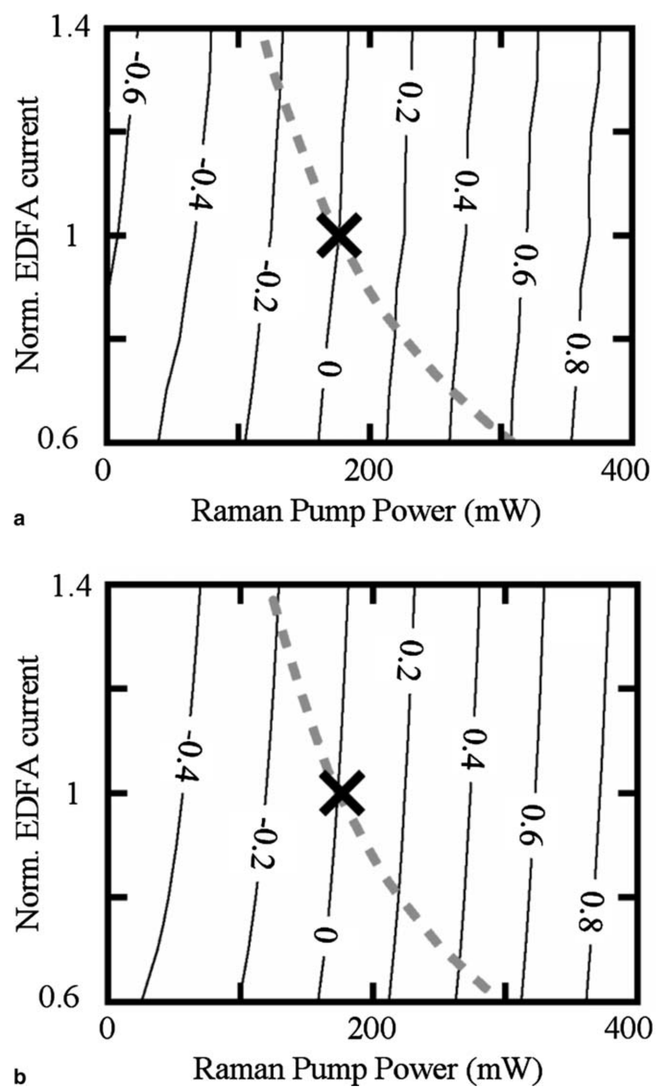

Fig. 3. Contour plots of the signal tilt in dB/nm: (a) experimental values and (b) simulated values, as a function of the Raman pump power and Δ_{EDFA}. The X denotes the pump values for which the system is transparent (net gain is 0 dB) and has no tilt. The dashed curve represents an average of −3 dBm per channel.

To model the EDFAs, we solved the erbium rate equations for a homogeneously-broadened two-level system with noise to obtain the gain and noise profiles of the erbium-doped fibers [12]. For the model, we measured the gain and absorption coefficients of an erbium fiber using the cutback method [13,14]. The gain and absorption coefficients are almost linear within our signal spectrum range, as shown in Fig. 2(c). We define the gain coefficient as the gain in dB per meter when a large pump power is used. We define the absorption coefficient as the loss in dB per meter when the pump is turned off. The measured gain and absorption coefficients are 2.1 and 1.8 dB/m, respectively, at 1540 nm, and 1.9 and 1.0 dB/m, respectively at 1560 nm. We propagated the signal and pump waves through the erbium-doped fiber with the wavelength dependence of both the measured emission and absorption coefficients, as shown in Fig. 2(c). Amplified spontaneous emission noise was calculated from the local excited ion population. Both forward- and backward-propagating ASE are included to determine the overall gain and output noise spectrum.

Using only the gain profiles, noise accumulation, and the signal spectra, we were able to compute the final OSNR and tilt after one round trip. These quantities were calculated by simulating the effect of an optical spectrum analyzer with a 0.2 nm optical bandpass filter. Once the spectrum is obtained via the simulated OSA trace, the tilt and OSNR were calculated in the same manner as in the experiment. After solving the Raman equations to obtain the power variation, we also modeled the signal propagation through the fiber by solving the nonlinear Schrödinger (NLS) equation. The loss and gain in the NLS were parameterized by the data obtained from solving the Raman amplifier

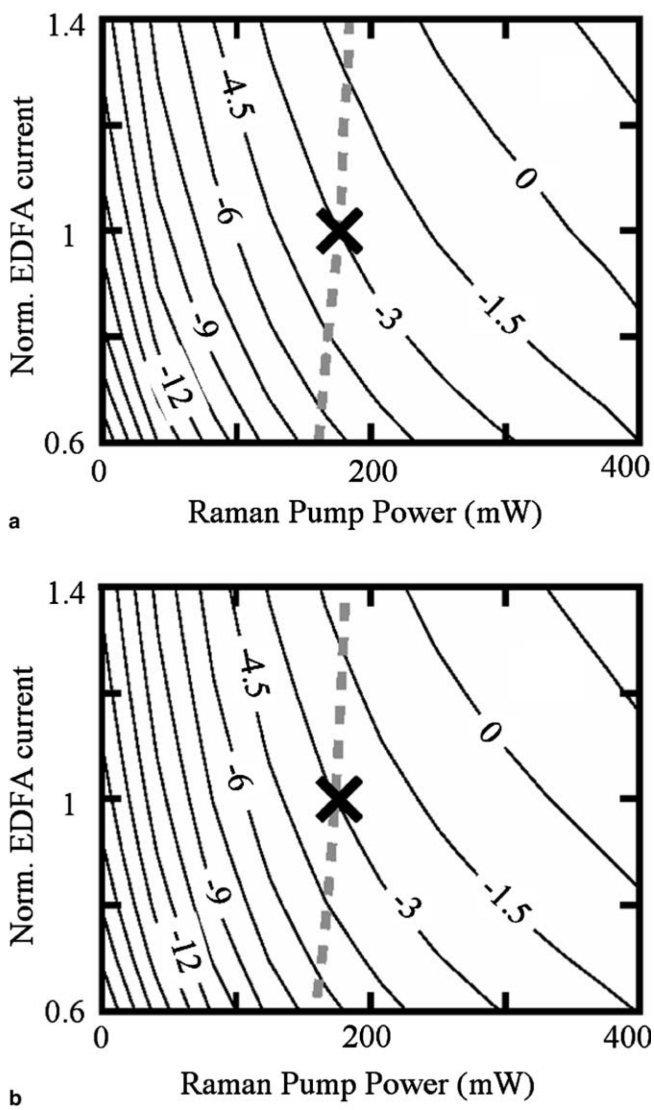

Fig. 4. Contour plots of the mean output power in dBm: (a) experimental values and (b) simulated values, as a function of the Raman pump power and Δ_{EDFA}. The *X* denotes the pump values for which the system is transparent (net gain is 0 dB) and has no tilt. The dashed curve represents the parameter set corresponding to no tilt (see Fig. 3).

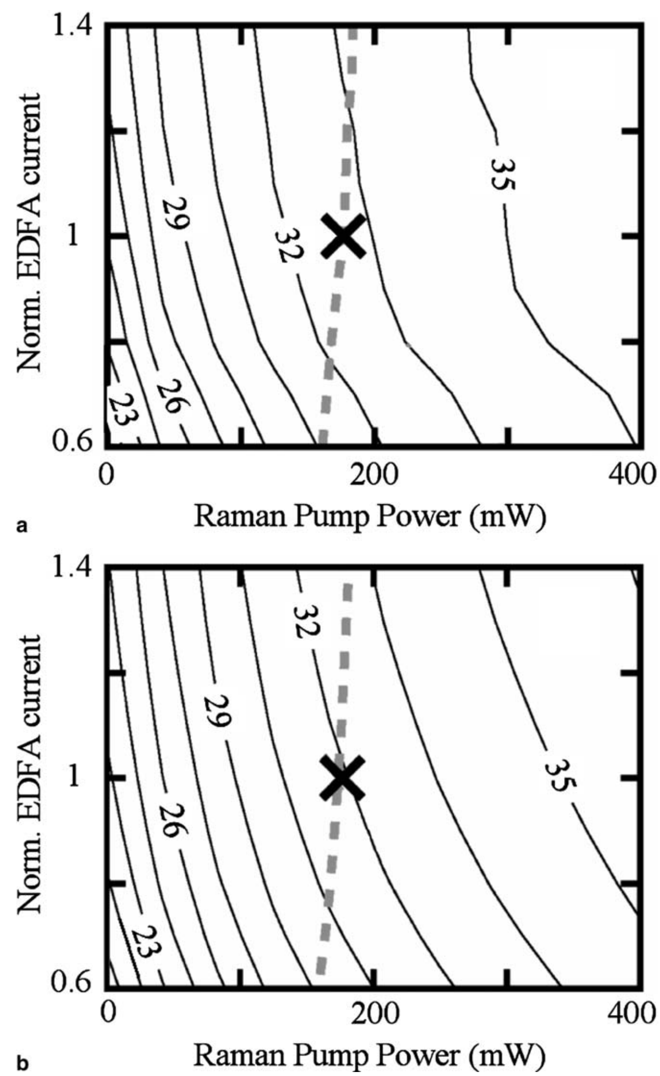

Fig. 5. Contour plots of the OSNR of the center channel in dB: (a) experimental values and (b) simulated values, as a function of the Raman pump power and Δ_{EDFA}. The *X* denotes the pump values for which the system is transparent (net gain is 0 dB) and has no tilt. The dashed curve represents the parameter set corresponding to no tilt (see Fig. 3).

equations. The NLS was required to show spectral broadening of the channels due to self phase modulation, which is not present in the amplifier models themselves.

3. Results: straight-line

We initially investigated the interplay of Raman and EDFA gain in a 210 km straight-line transmission link obtained by breaking open our recirculating loop before the booster EDFA. We found a balance between Raman and EDFA gain by adjusting the amplifier's pump powers for each of the six segments until we obtained 0 dB net gain and no tilt after each segment. We call the corresponding pump current for the EDFA in the *j*th segment $I_{\mathrm{ref}}(j)$ for $j = 1, \ldots, 6$. Then we varied the Raman and EDFA pump powers and measured the spectrum after transmission. In our plots, the EDFA pump current is shown in relative terms as

$$\Delta_{\mathrm{EDFA}} = \frac{I(j) - I_{\mathrm{trans}}(j)}{I_{\mathrm{ref}}(j) - I_{\mathrm{trans}}(j)}, \qquad (2)$$

where $I_{\mathrm{trans}}(j)$ is the pump current at which the *j*th EDFA is transparent for an input power of −11 dBm per channel, corresponding to the power when operating in the loop mode. As a result of this normalization, Δ_{EDFA} is 0 when the *j*th amplifier provides 0 dB gain and 1 when the amplifier is set to balance the loss of the dispersion map and the gain tilt of the Raman amplification. In our results, the Raman pump power is expressed as the power injected into each segment, in mW. Fig. 3 shows contour levels of the net gain tilt in dB/nm after one pass through our 210 km fiber loop as a function of the normalized EDFA current, Δ_{EDFA}, and the Raman pump power per segment, obtained from (a) experiment and (b) simulation. In this figure, the dashed curve corresponds to the parameter set for which the mean of the channel's output power is equal to the input value of each channel, −3 dBm. Along this curve, only the point denoted by the *X* corresponds to 0 dB net gain for all channels (no tilt), and there is a nonzero tilt over the channels at all other points on the same curve. In Fig. 4, we show the mean of the channels' output powers as a function of EDFA and Raman pump power. We note that there is excellent agreement between experiment and theory in Figs. 3 and 4. Although the EDFAs provides close to 70% of the total gain in each dispersion map, we observe that the tilt is strongly affected by the variation of the Raman pump power. Fig. 5 shows contour levels of the OSNR of the center channel for the same conditions as Fig. 3. The dashed curves in Figs. 4 and 5 correspond to the parameter set for which there is no tilt.

4. Results: loop mode

When we propagate the channels over 1700 km in the recirculating loop, the accumulation of the tilt is severe and could lead in extreme cases to dropout of channels that

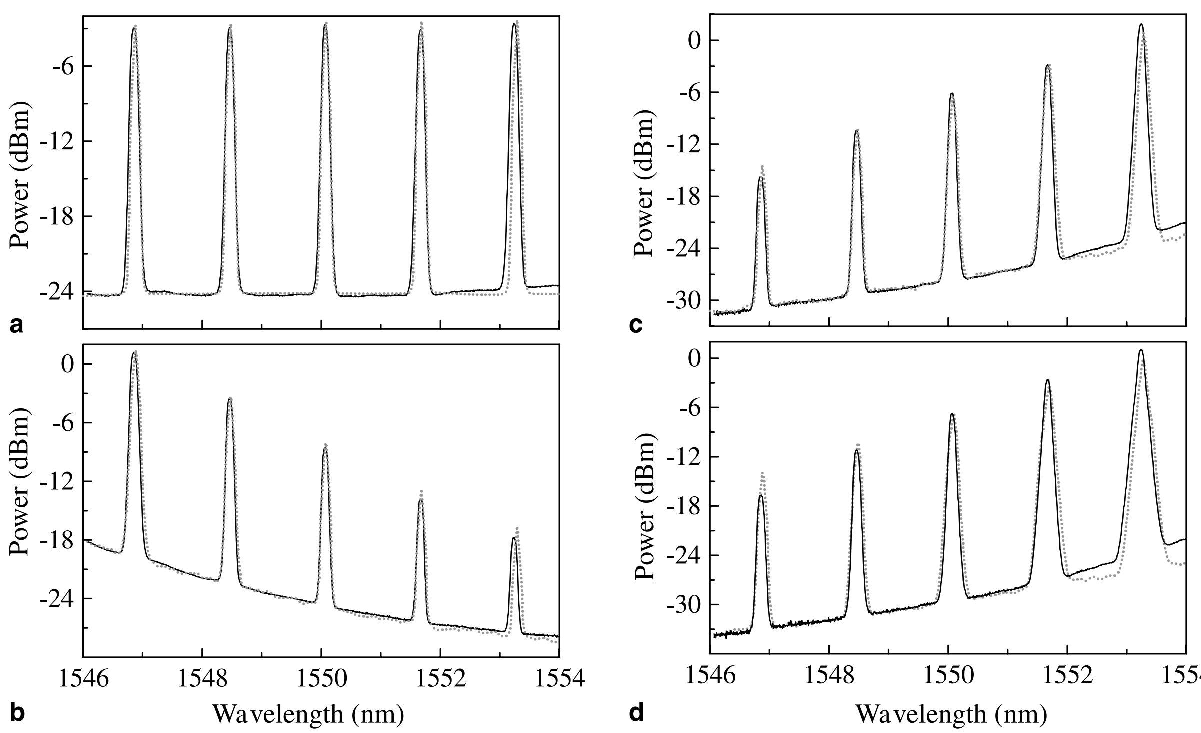

Fig. 6. Spectra for four different settings of the Raman pump power and Δ_{EDFA} after 1700 km of propagation. Experimental results are shown as solid curves while theoretical results are shown as dotted curves. In (a) the pump values are set so that the system has 0 dB net gain and no tilt. In (b), there is excess EDFA gain. In (c), excess Raman gain is used to compensate the lower EDFA gain. In (d), we show channel broadening when increasing the amount of Raman and EDFA gain.

are at one wavelength extreme, while channels at the other extreme are over-amplified. In Fig. 6 we show the output spectra after 1700 km, obtained for different EDFA and Raman gain settings. Experimental results are shown as solid curves while theoretical results are shown as dotted curves. The agreement between theory and experiment is excellent in all plots. In Fig. 6(a), we show the case of no tilt, in which the gain has been balanced in each segment. If we have excess gain from the EDFA, the tilt will be negative, and the OSNR of the longer wavelength will be reduced. We show such a case in Fig. 6(b), in which Δ_{EDFA} is 1.3 and the Raman pump power is 50 mW. If there is excess Raman gain, the channel with the shortest wavelength has a reduced OSNR, as shown in Fig. 6(c) and (d). In these plots we show two spectra, both of which have a tilt of about 3 dB/nm, but with different amounts of EDFA gain. In Fig. 6(c) the normalized EDFA current is 0.7, and the Raman pump power is 250 mW, while in Fig. 6(d) the normalized EDFA current is 1.3, and the Raman pump power is 240 mW. When the EDFA gain increases, the OSNR of all the channels increases, but at the expense of nonlinear broadening of the channel with the longest wavelength. This broadening occurs primarily due to the presence of the Raman gain, which sustains higher channel power at longer wavelengths over more fiber length than with the EDFAs alone. The increase of the nonlinearity observed for larger fractions of Raman gain is due to the higher span-averaged signal power [5].

5. Conclusion

The gain profile in WDM systems must be carefully equalized during propagation or after short distances, which typically requires the use of additional gain flattening filters or multiple wavelength Raman pumps, adding to the cost of a fiber optic link. However, for applications in which a smaller channel bandwidth is sufficient, we have shown that the gain equalization can be done using a simplified arrangement of an EDFA and single-pump distributed Raman amplification. We have shown that over-amplification is less harmful if the gain is lumped (using EDFAs) than if it is distributed (Raman gain). Increasing the distributed gain to avoid losing OSNR on the shorter wavelengths increases the accumulated nonlinearity of the channels where the Raman gain is maximum, which leads to broadening of the longer wavelengths. Using these results, we have also validated a full amplifier model that shows excellent agreement with the experimental results for a wide range of system parameters. We have used the amplifier model along with a full nonlinear propagation model to accurately predict the spectral broadening observed in the experiment.

Acknowledgement

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References

[1] H. Takara, H. Masuda, K. Mori, K. Sato, Y. Inoue, T. Ohara, A. Mori, M. Kohtoku, Y. Miyamoto, T. Morioka, S. Kawanishi, Electron. Lett. 39 (2003) 382.
[2] H. Masuda, S. Kawai, IEEE Photon. Technol. Lett. 11 (1999) 647.
[3] S. Kawai, H. Masuda, K. Suzuki, K. Aida, IEEE Photon. Technol. Lett. 11 (1999) 886.
[4] C.B. Clausen, S. Ten, B. Cavrak, C.R. Davidson, A.N. Pilipetskii, M. Nissov, E.A. Golovchenko, R. Ragbir, K. Adams, in: European Conference on Optical Communication 2001, We.F.1.2.
[5] R. Hainberger, T. Hoshida, T. Terahara, H. Onaka, IEEE Photon. Technol. Lett. 14 (2002) 471.
[6] J. Hu, B.S. Marks, Q. Zhang, C.R. Menyuk, J. Opt. Soc. Am. B 22 (2005) 2083.
[7] S.E. Miller, A.G. Chynoweth, Optical Fiber Telecommunication IVA, Academic Press, New York, 1979.
[8] J. Bromage, J. Lightwave Technol. 22 (2004) 79.
[9] H. Kidorf, K. Rottwitt, M. Nissov, M. Ma, E. Rabarijanona, IEEE Photon. Technol. Lett. 11 (1999) 530.
[10] J. Hu, B.S. Marks, C.R. Menyuk, J. Lightwave Technol. 22 (2004) 1519.
[11] V. Perlin, H. Winful, J. Lightwave Technol. 20 (2002) 250.
[12] C.R. Giles, E. Desurvire, J. Lightwave Technol. 9 (1991) 271.
[13] E. Desurvire, Erbium-Doped Fiber Amplifiers: Principles and Applications, John Wiley & Sons Inc., New York, 1994.
[14] C.R. Giles, C.A. Burrus, D.J. DiGiovanni, N.K. Dutta, G. Raybon, IEEE Photon. Technol. Lett. 11 (1991) 363.