Raman amplifiers for telecommunications: Physical principles to systems

Mohammed N. Islam
Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor
(734)647-9700; fax (734)647-2718; email: mni@umich.edu

ABSTRACT

This paper describes the design and implementation of wide-band Raman amplifiers for fiber-optic telecommunications systems. All-Raman amplifiers permit 100nm wide systems over spans of over 1500km due to the low noise figure and reduced nonlinear system penalties. First, the enabling technologies for realizing 50-100nm transmission systems are reviewed. Then, the focus is on the key building block for wideband systems, namely the all-Raman optical amplifier. The advantages and challenges of all-Raman wideband amplifiers (WBA) are first reviewed. Then, Section 3 describes the physical principles and engineering design rules for construction of all-Raman WBAs that satisfy gain and noise figure performance requirements of typical long-haul and ultra-long-haul fiber-optic transmission systems. Exemplary wideband system experiments are described in Section 4, and then the paper is summarize and concluded in Section 5.

Keywords: Raman amplifiers, Fiber optic telecommunications, Optical Amplifiers, Wideband Communication.

1. ENABLING TECHNOLOGIES FOR WIDEBAND SYSTEMS

Several technologies are required to realize practical and economical wideband systems. Consider for example, the key components for 100 nm bandwidth systems. (Smaller bandwidth systems still require the same components or sub-systems, but with less stringent performance requirements.) First, wideband amplifiers are required. Second, broadband components such as multiplexers and demultiplexers are required. The pass band for couplers and other passive components needs to be larger than the actual bandwidth being used by the channels because in a cascaded system a spectrally dependent transfer function decreases in bandwidth as a cascade of components is traversed.
A third component that is critical for wideband systems is gain equalizers and gain flattening filters. Again, in a system consisting of a cascade of spans (e.g., a 1500 km system may have 19 spans each 80 km long), any non-uniformity in the gain spectra of the amplifiers is accentuated as more and more amplifiers are traversed. For example, a 0.5 dB gain variation can grow to well over 5 dB at the end of a system, resulting in substantial variation in signal strength between channels. Variations in signal strength between channels can require a large dynamic range at the receivers and lead to unwanted gain saturation, cross-talk between channels, and substantial variation in bit error rate performance for different channels. From a design perspective, the worst performing channel limits the overall system performance. Therefore, the best design will have roughly equally performing channels. Gain equalizers and gain flattening filters are typically utilized to equalize channels. In erbium-doped fiber amplifiers (EDFAs), a bandwidth greater than 10-15 nm can only be achieved with gain equalizing devices. In Raman amplifiers, gain shape can be more flat, reducing constraints on gain equalization. However, gain equalization in Raman amplifiers is still beneficial and is especially useful in wideband amplifiers. For uniform signal traffic and time-invariant components, a static gain equalizer can be utilized; if, on the other hand, the traffic is time varying or component characteristics vary with time, then a dynamic gain equalizer may be required. For example, if a system utilizes dynamic optical add/drop multiplexers or optical cross-connects, dynamic gain equalizers may be required. Various devices can be configured for static gain equalization. Examples include waveguide notch filters, Mach Zender interferometers, dielectric filters, and fiber Bragg gratings. Dynamic gain equalizers have been realized with acousto-optic filters and with micro-electromechanical systems (MEMS), liquid crystal, or thermo-optic switch arrays integrated with a dispersive element such as a diffraction grating.

Another essential component for wideband systems operating at 10 Gb/s or higher bit rates comprises dispersion compensating and dispersion slope compensating modules. Examples of dispersion compensators include dispersion compensating fiber (DCF), chirped fiber Bragg gratings, higher-order mode fibers, and virtually imaged phased array

Active and Passive Optical Components for WDM Communications IV, edited by
Achyut K. Dutta, Abdul Ahad S. Awwal, Niloy K. Dutta, Yasutake Ohishi, Proc. of SPIE
Vol. 5595 (SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.580682

micro-optic devices. As system bandwidth increases, it is not adequate to match the dispersion magnitude at the center of the band, as is commonly done in systems with less than 30 nm bandwidth. The dispersion slope of the compensator must also be matched to the dispersion slope of the transmission fiber in order to achieve compensation over a wide spectral band. The quantity to be matched is then the relative dispersion slope $RDS = S/D$, the ratio of dispersion slope S to dispersion D. Manufacturers of dispersion compensating fiber are aware of the need for dispersion slope compensation, and slope-compensating fibers are now becoming available for most deployed transmission fiber types.

2. ADVANTAGES & CHALLENGES OF ALL-RAMAN WIDEBAND AMPLIFIERS

Raman amplification provides a simple, single platform for long-haul (typically 300-600 km long) or ultra-long-haul (typically greater than 600 km) fiber-optic transmission systems, and the current trend suggests extensive deployment of Raman amplification in the future. There are numerous reasons for the current trend. First, distributed Raman amplification alone or in combination with lumped Raman amplification can improve noise figure and reduce system penalties arising from fiber non-linearities. In optically amplified transmission systems, the principal limitations usually arise from amplifier noise and fiber non-linearities. In particular, the range of allowed signal levels is determined by two factors: the minimum signal level is determined by the signal-to-noise ratio (SNR) required to achieve a prescribed bit error rate; the maximum signal level is determined by impairments arising from non-linear propagation effects in optical fiber. Raman amplification eases the constraints arising from both of these limitations and improves performance. First, distributed Raman amplification (DRA) reduces the excursion of the signal power level in comparison to purely lumped amplification. The low signal power swing reduces the signal impairments arising from fiber non-linearity, while the higher minimum signal level reduces the SNR degradation.

A second advantage of Raman amplification is that gain can be obtained in any spectral region and over a wide spectral band. The location and width of the gain band are determined by the pump wavelength location and distribution. Whereas typical single-band EDFAs have less than 40 nm of bandwidth, Raman amplifiers can easily achieve 100 nm of continuous bandwidth, and heroic experiments have shown bandwidths of up to 136 nm in a single amplifier. The present generation of Raman amplifiers employs several pump laser diodes operating at different wavelengths. As a rule of thumb, the Raman gain bandwidth for each pump laser is about 20 nm. Therefore, by using approximately five properly spaced pump wavelengths, a gain bandwidth of approximately 100 nm is typically achieved. Note that the location and number of pump wavelengths are determined not only by the gain bandwidth, but also by gain flatness requirements: the flatter the gain spectrum required, the greater the number of wavelengths required.

A third advantage of Raman amplification is that gain and dispersion compensation can be integrated in a lumped amplifier. Such an amplifier can have higher power conversion efficiencies at high channel counts than EDFAs. Most systems operating at line rates of 10 Gb/s (OC-192) or higher require dispersion compensation, commonly implemented using dispersion compensating fiber. Dispersion compensating fiber turns out to be an efficient fiber type for Raman amplification, and the Raman gain coefficient can be as much as an order of magnitude larger in DCF than in standard single-mode fiber. Hence, gain and dispersion compensation can be integrated in the same unit. Moreover, the efficiency of Raman amplification in DCF can exceed that of EDFAs pumped at 1480 nm for channel counts exceeding about 200.

Beyond the advantages of Raman amplification enumerated above, additional features of Raman amplification enable simple, practical implementation in deployed fiber-optic systems exist. Some of these features include:

- All-silica components: all of the components and fiber types for Raman amplifiers can be based on fused-silica, and all of the parts as well as the amplifiers can be spliced into existing systems;
- Higher system reliability: in a multiple-pump amplifier, Raman amplification can be more reliable because a pump failure can be compensated by increasing the power of surviving pumps;
- Simpler channel equalization: because gain shape can be smoother in a Raman amplifier than in an EDFA, gain equalization techniques can be considerably simpler;
- Simple adjustment of gain flatness: since the gain shape in Raman amplifiers can be tailored by the pump power, simple adjustment of gain flatness can be made by adjusting the pump power levels, an important feature in, for example, a transmission system using optical add/drop multiplexers or optical cross-connects;

- Large gain and power levels: because the Raman amplifier is relatively weakly saturated even at high powers, gain and output power levels can be increased by simply increasing pump power, and output powers in the watt range have been reported from Raman amplifiers;
- Large power dynamic range for flat gain operation: unlike an EDFA where the gain shape changes as the pump power is changed (i.e., as inversion level is changed), the gain shape of a Raman amplifier can be maintained flat over a large dynamic range of pump power and amplifier gain.

Despite a significant list of desirable features, Raman amplification is beset by numerous challenges that dictate amplifier design and architecture. First, gain flatness of a wideband Raman amplifier can be significantly affected by pump-to-pump interactions as well as inter-band and intra-band Raman gain tilt (i.e., transfer of energy from short-wavelength signals to longer wavelength signals through the Raman effect). Second, as the signal band in a wideband Raman amplifier approaches the longest wavelength pump band, the noise figure of the amplifier increases because of thermal noise. Finally, in a Raman amplifier it is important to consider the electrical noise figure as well as the optical noise figure. Because the upper state lifetime associated with Raman amplification is short and long fiber lengths are typically used in Raman amplifiers, additional noise sources contribute to the electrical noise figure. Multi-path interference (MPI) arising from double-Rayleigh scattering, coupling of pump fluctuations to signals, and pump-mediated signal cross-talk increase the electrical noise figure with minimal effect on the optical noise figure as usually determined from amplified spontaneous emission (ASE) measurements.

3. DESIGN OF WIDEBAND RAMAN AMPLIFIERS

This section describes design techniques to overcome many of the physics limitations in achieving a 100nm Raman amplifier.

3.1 Electrical Noise Figure

It is important to account for the electrical noise figure as well as the optical noise figure in Raman amplifiers. Optical noise figure primarily depends on signal-spontaneous emission beating. The optical noise figure of a Raman amplifier is generally better than that of an EDFA. This is because whereas the noise figure of an EDFA degrades if the amplifier is not completely inverted, a Raman amplifier always acts as a completely inverted amplifier. However, several additional effects such as multi-path interference (MPI) from double-Rayleigh scattering (DRS) and pump-signal RIN transfer contribute to the electrical noise figure. Electrical noise figure is therefore generally higher than optical noise figure if the additional effects contribute significantly to amplifier noise performance.

Some simple amplifier architectures make it possible to achieve an electrical noise figure roughly equal to the optical noise figure. The electrical noise figure can be 5 to 6 dB in commercial wideband Raman amplifiers, comparable to the electrical noise figure of commercial EDFAs. Because of MPI penalties from DRS, wideband Raman amplifiers are typically sectioned into multiple stages, where each stage is separated by an isolator. For an amplifier comprising discrete and distributed stages, the MPI penalty is usually larger in the discrete stages. This is because discrete stages are usually constructed of DCF, which has a higher gain coefficient and a higher DRS coefficient than transmission fiber. Although the MPI penalty needs to be computed for each particular design, one rule of thumb is that it is difficult to simultaneously obtain pump-on/pump-off gain of more than 15 dB and DRS cross-talk of less than –15 dB (corresponding to a Q penalty of less than 1 $dB_{20}Q$) in a single stage. By using isolators between stages, the build up of DRS is minimized, and high-gain, low MPI amplifiers can be constructed.
The easiest way to deal with the short upper-state lifetime of Raman amplifiers is to introduce an effective lifetime equal to the transit time through the fiber by propagating pump and signal waves in opposite directions. This leads to a signal profile that is most amplified from Raman amplification at the end of the fiber length. Since there is loss before gain in the fiber, the resulting noise figure is not optimal, although coupling of pump fluctuations to the signal is avoided.

3.2 Pump-to-pump Interactions

The Raman effect in the gain fiber leads to power exchange between the pumps, which must be properly accounted for to obtain the correct gain profile. The Raman effect transfers energy from shorter wavelength pumps to longer wavelength pumps. For example, if equal frequency spacing and equal amplitude pumps are used in a wideband Raman amplifier, the resulting gain is tilted upward as a function of wavelength [Kidorf99]. Depending on the signal powers and bandwidth of the signal bands, there can also be transfer of energy from short to long signal wavelengths, further accentuating the gain tilt.

Several techniques can be used to achieve flat gain spectra in the presence pump-to-pump interactions. The basic idea is to increase the spectral density at short pump wavelengths. If equally spaced pump frequencies are used, the amplitudes of long-wavelength pumps can be reduced compared to the shorter wavelength pumps (pump power pre-emphasis). Alternately, for unequally spaced pumps, the pump separation can be increased to the longer wavelength side. In a practical system, a combination of these two techniques is actually used.

Another completely different approach to reducing the effects of pump-to-pump interaction is to arrange for the pumps not to encounter one another altogether. For example, if the pumps are time-modulated and then multiplexed or timed so that they do not overlap, then they are not simultaneously in the gain fiber and do not interact. One example of this approach has been demonstrated by Fludger *et al.* [Fludger02].

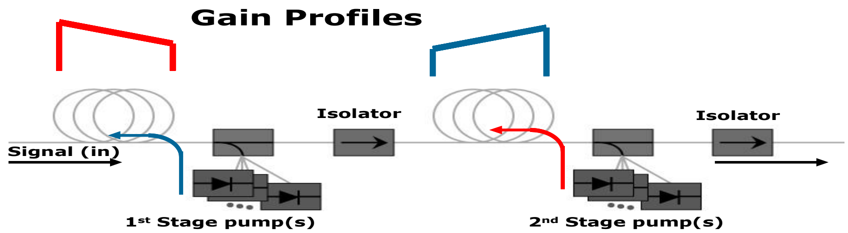

Fig 3.3.1. Block diagram of a two-stage Raman amplifier with complementary gain spectra. The gain of the first stage decreases as wavelength increases, while that of the second stage increases with wavelength .

3.3 Thermally-induced Phonon Noise

Thermal noise from the thermally induced phonons is particularly important in wideband Raman amplifiers. In the telecommunications band around 1550 nm, the peak of the Raman gain at 13.2 THz corresponds to a separation of approximately 100 nm between pump and signal. Thus, for a 100 nm bandwidth amplifier, the short-wavelength end of the signal band is close to the long-wavelength pumps, and the contribution of thermal noise to the short-wavelength noise figure can be as much as 3 dB at room temperature. Therefore, the thermally induced phonons are a significant limitation for any Raman amplifier with about 70 nm or more of bandwidth.

To mitigate the effect of the thermally induced phonon noise, one strategy is to amplify the vulnerable signals first. In other words, if the most vulnerable signals are amplified first, the signal-to-noise ratio will remain high throughout the amplifier because the signal remains strong. Since the most vulnerable signals are those closest to the pumps in wavelength (i.e., the shortest-wavelength signals), gain for the shortest wavelength signals can be made high at the input of the amplifier. However, as discussed earlier, there is also a need to have an equalized gain shape across the band to obtain roughly equivalent behavior for all channels. A method for accommodating both of these requirements is to use a multi-stage amplifier, each with a gain slope. The first stage has a gain that decreases from short to long wavelengths, while the second stage has an approximately complementary slope. Thus, net gain shape after the two stages is substantially flat. This concept can also be extended to any number of stages.

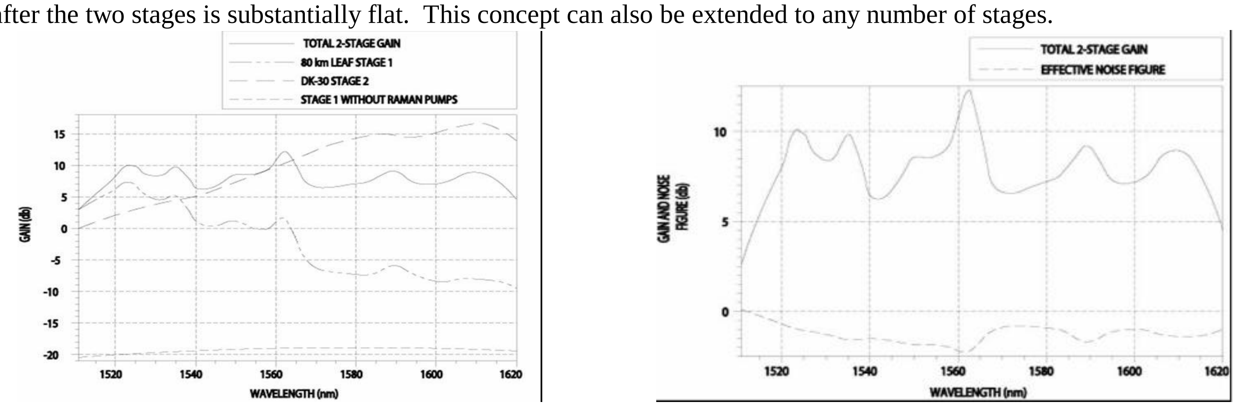

Fig. 3.3.2. Gain spectra for a hybrid DRA/discrete Raman amplifier pair: (a) gain spectra of DRA (stage 1) and discrete sections, loss spectrum of stage 1 fiber, and composite gain spectrum; (b) composite gain and effective noise figure spectra. The DRA stage comprises 80 km of large effective area fiber (LEAF) and the discrete stage comprises 4.9 km of dispersion compensating fiber (DK-30).

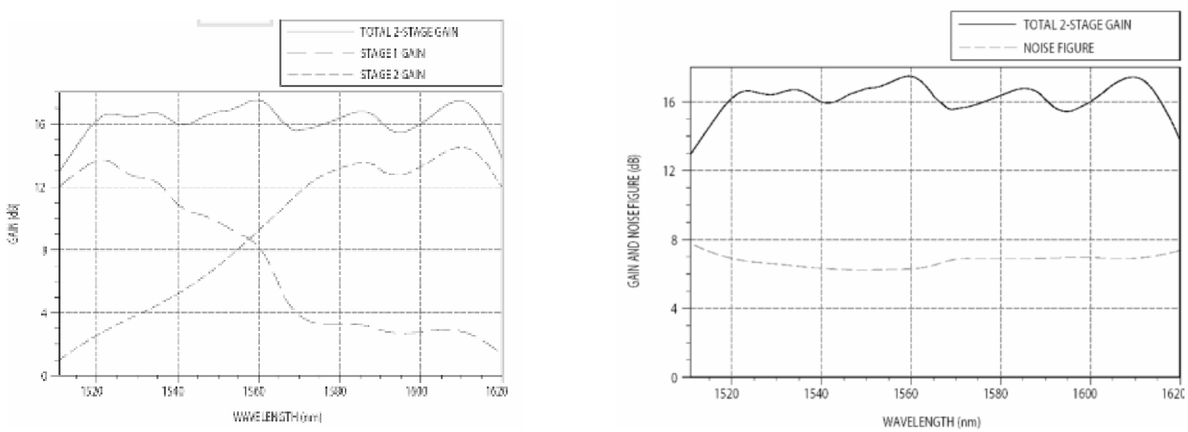

Fig. 3.3.3. Gain spectra for a two-stage discrete Raman amplifier with complementary stage gains: (a) stage gain and composite gain spectra; (b) composite gain and effective noise figure spectra. Gain fibers are 3.4 km and 3.1 km of dispersion compensating fiber (DK-21 and DK-19) for the first and second stages, respectively.

As an example of using gain slope in multiple stages to mitigate the thermally induced phonon noise limitation, consider the design illustrated in Fig. 3.3.1. The figure shows a block diagram of a two-stage Raman amplifier and gain profiles associated with each stage. The first stage is a DRA, while the second stage is a discrete Raman amplifier. Each pump module consists of a plurality of pump wavelengths, the pump light is coupled into the gain fiber through WDM couplers, and the pump waves propagate in a direction opposite to that of the signal.

For this configuration, the calculated gain and noise figure are illustrated for two different cases in Figs. 3.3.2 and 3.3.3. Figure 3.3.2 shows the results for a hybrid amplifier (DRA followed by a discrete Raman amplifier), while Fig. 3.3.3 shows the results for a two-stage discrete Raman amplifier. For example, Figs. 3.3.2a and 3.3.3a show the gain profile in the first stage, the gain profile in the second stage and the composite gain. Conforming to the intended design, the first stage gain decreases towards long wavelengths, and the second stage has an approximately complementary slope, which yields an approximately flat overall gain profile. Figures 3.3.2b and 3.3.3b show both the gain and the noise figure. The noise figure is approximately flat across the full 100 nm range from 1520 to 1620 nm. In the case of the discrete Raman, the actual noise figure is shown in Fig. 3.3.3b. In the case of the distributed Raman amplifier, the effective noise figure is shown in Fig. 3.3.2b. The amplifier noise figure NF = SNR_{in} / SNR_{out}, where SNR_{in} is the signal-to-noise ratio of the input signal and SNR_{out} is the signal-to-noise ratio of the output signal. Amplifier noise figure is always greater than one for any realizable amplifier. Effective noise figure for a distributed optical amplifier is the noise figure required of a discrete amplifier placed at the end of the transmission fiber used in the distributed amplifier to produce the same final SNR as the distributed amplifier. It can be, and in practice often is, less than 1 (negative value in dB) for distributed amplifiers over at least a portion of their operating wavelength range

3.4 Zero Dispersion Wavelength

Four-wave mixing impairments in Raman amplifiers are most pronounced in dispersion shifted fibers for which the zero-dispersion wavelength falls within the pump band or between the pump and signal bands. In fibers for which the dispersion wavelength falls within the pump band, four-wave mixing between pump waves can generate sidebands within the signal band and severely degrade optical SNR (OSNR) for some channels. In fibers for which the zero-dispersion wavelength falls between the pump and signal bands, non-degenerate four-wave mixing between pump and signal waves generates sidebands that fall in the signal band. In both cases, the power in the sidebands depends on how close the longest wavelength pumps are to the zero-dispersion wavelength. This is because phase matching over long lengths of fiber is necessary for significant four-wave mixing to occur and is easily achieved when one of the pump wavelengths coincides with the zero-dispersion wavelength of the fiber.

Four-wave mixing presents a cross-talk problem when the frequencies of the sidebands coincide with channel frequencies. For example, in single-band transmission using C band only or L band only, pump-pump four-wave mixing products do not typically fall within the signal band. On the hand, in wideband systems where both C- and L-band transmission are used, the longest wavelength pumps are typically close enough to the signal band that four-wave mixing products fall within the signal band and can interfere with some channels.

Several methods can be used to mitigate the effects of four-wave mixing. One technique is simply to allocate band gaps in the signal band where sidebands occur. Since four-wave mixing efficiency is strongly dependent on phase matching, employing fiber with high local dispersion tends to reduce the cross-talk level. (In many cases, the DRA section within which four-wave mixing is troublesome employs pre-existing transmission fiber and the associated dispersion properties are predetermined.) Increasing pump frequency spacing, particularly for pump wavelengths close to the zero-dispersion wavelength, can also be used. Increasing pump frequency separation increases dispersive walk-off between the pump waves, reducing phase matching and four-wave mixing efficiency. In addition, reducing the power of long-wavelength pumps is also effective. Note that four-wave mixing efficiency is at least a quadratic function of pump power and Raman amplification further increases efficiency so that the dependence of sideband intensity on pump intensity is a power function with index greater two. Where Raman gain is high, the index can exceed four [Bromage02]. Therefore, decreasing pump power can significantly reduce four-wave mixing. In reducing the power at long pump wavelengths, gain and gain flatness can be kept unchanged by maintaining the spectral power density of the long-wavelength pumps.

Another approach to mitigation of FWM employs pump amplitude modulation to prevent interaction between the pumps involved in pump-pump FWM. The offending pumps are time modulated and multiplexed in such a manner that different pump wavelengths occupy separate time slots.

3.5 Pump Power Adjustment to Control Gain and Noise Figure Shape

The behavior of Raman amplifiers differs significantly from rare-earth doped amplifiers such as EDFAs with regard to the change in noise figure shape in response to a change in pump power. In an EDFA, changing the pump power has the effect of changing the level of inversion. The noise figure in an EDFA is minimum for a completely inverted amplifier, and the noise figure increases as the level of inversion is decreased (i.e., the spontaneous emission factor increases). On the other hand, in a Raman amplifier the gain shape and noise figure shape can be controlled by the pump powers.

Management of Raman gain tilt is required in almost all wideband, amplified systems. While present in any DWDM system, Raman gain tilt is most problematic in systems spanning near or above 100 nm of gain bandwidth. This tilt management is less complicated with an “all-Raman” system as monitoring of the signal wavelengths can occur across the entire band at just two positions, immediately before amplification and directly after amplification (Fig. 3.5.1). Dynamic adjustment of any measured tilt (or other gain affecting event, such as channel drops or additions) can be made through the straightforward adjustment of the Raman pump power levels. The very nature of Raman amplification permits this ability to “shape” the gain spectrum. Monitoring and adjustment of a split-band amplifier is more intricate, as a number of monitoring points need to be used together with different gain adjustments for the discrete amplifiers.

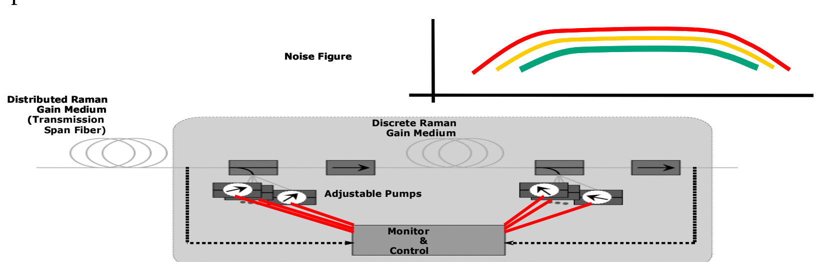

Fig. 3.5.1. Noise figure shaping by pump adjustment and net power monitoring.

Beyond just maintaining gain flatness, it is also desirable to maintain the shape of the noise figure spectrum in an optical communication system against such changes to the system as variations in signal power. This would allow, for example, existing optimization algorithms to continue to be utilized. In addition, in some cases, the peak increase in the noise figure can be lessened by approximately maintaining the shape of the noise figure when system conditions change. Furthermore, maintaining the shape of the noise figure reduces or eliminates the need to monitor and adjust individual channel powers when other channel powers change. In this manner, for example, SNR across the spectrum of amplified wavelengths can be maintained without implementing separate control loops for each channel.

One way to facilitate this feature is to control the pump powers for various wavelengths in a Raman amplifier. The power of one or more long-wavelength pumps can be selectively adjusted to control the noise figure shape.

3.6 High-Reliability Raman Amplifiers

Many conventional optical amplification systems rely solely on erbium-doped amplifiers to increase the reach of the system. When an erbium-doped amplifier is not excited, absorption in the signal band is high. Consequently, when a pump driving an erbium doped amplifier fails, the performance of the entire amplification system can suffer dramatically. To address this problem, erbium doped amplification systems typically require one hundred percent redundancy in the driving pumps. That is, for each driving pump in an erbium-doped system, a normally inactive redundant pump is available to provide the same pump power ordinarily derived from the primary pump. As driving pumps are typically among the most expensive components in an optical amplifier, a one hundred percent redundancy requirement for driving pumps generally results in significant extra amplifier cost.

In a wideband Raman amplifier with multiple wavelength pumps, the interaction between the various pump wavelengths can be used to advantage to make a high-reliability amplifier. As is typically done, the system includes or has access to control or monitoring functionality, operable to detect a failing pump signal. A failing pump signal may result, for example, from a completely failed pump or from a pump that has weakened due to, for example, its age. Upon identifying the failing pump signals, the power of other pump signals are adjusted to at least partially compensate for what would otherwise be a degradation of performance of the amplifier due to the failing pump signal. The degradation in performance for which compensation is desired could be, for example, a distortion of the gain curve for an amplifier or the system, or an increase in the noise figure for the amplifier or the system. Thus, a wideband Raman amplifier provides a significant advantage over a conventional EDFA system in providing a mechanism for ensuring amplifier reliability without requiring one hundred percent redundancy for all driving pumps.

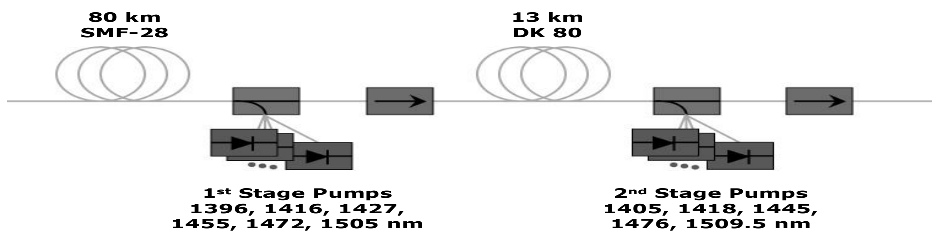

Fig. 3.6.1. Configuration of a high-reliability Raman amplifier using multiple pump wavelengths.

Figure 3.6.1 is a block diagram showing one example of a wideband Raman amplifier operable to provide compensation for failing pump signals by altering the power of other already active driving pumps in the same amplification stage. In this particular example, the wideband amplifier comprises a multiple stage Raman amplifier using a distributed Raman amplifier in a first stage and a discrete Raman amplifier in a second stage. The DRA includes a gain medium comprising approximately eighty kilometers of SMF-28 fiber, while the discrete Raman stage includes a gain medium comprising approximately 13 km of DK-30 fiber.

Both stages of amplification have a plurality of pump wavelengths for pumping. For example, during normal operation, pump signals may provide the following power at the following wavelengths to the first stage:

Pump wavelength:	Pump power:
1396 nm	560 mW
1416 nm	560 mW
1427 nm	560 mW
1455 nm	250 mW
1472 nm	100 mW
1505 nm	85 mW

The pump powers to the second stage may be as follows:

Pump wavelength:	Pump power:
1405 nm	470 mW
1418 nm	530 mW
1445 nm	310 mW
1476 nm	85 mW
1509.5 nm	25 mW

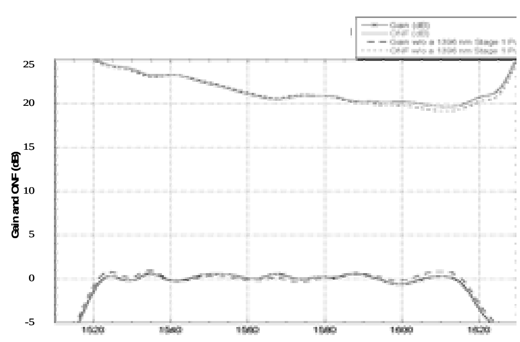

Fig.3.6.2. Gain and optical noise figure (ONF) of the multiple pump wavelength Raman amplifier of Fig. 4.6.1 (solid curves). The dashed curves show the gain and ONF of the amplifier when the 1396 nm pump in the first stage is removed.

To illustrate the reliability benefits obtained by pump-to-pump interactions, Fig. 3.6.2 through 3.6.7 show the gain and noise figure in the DRA stage calculated when one of each pump wavelength in the first stage is turned off and the other wavelengths' power are adjusted to compensate. For instance, Fig.3.6.2 has the 1396 nm pump turned off in the first stage, Fig. 3.6.3 has the 1416 nm pump turned off in the first stage, etc. The top curve shows the noise figure including the loss of the transmission fiber, while the bottom curve (close to zero) shows the net gain as a function of wavelength. The solid curves correspond to the undisturbed cases for the pump powers described above, while the dotted or dashed curves are with at least one pump turned off.

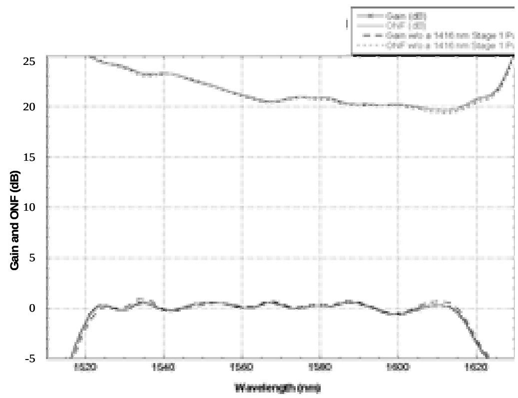

Fig. 3.6.3. Gain and noise figure of the multiple pump wavelength Raman amplifier with the 1416 nm pump in the first stage removed (dashed curves).

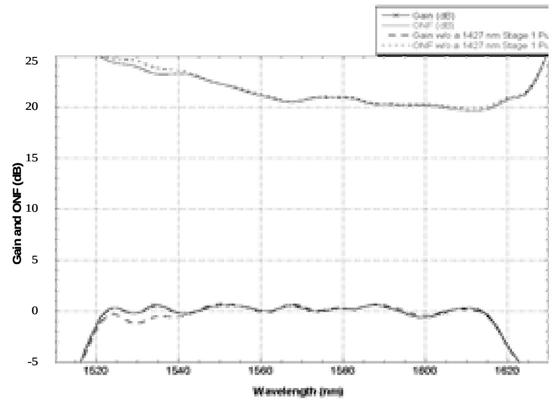

Fig. 3.6.4. Gain and noise figure of the multiple pump wavelength Raman amplifier with the 1427 nm pump in the first stage removed (dashed curves).

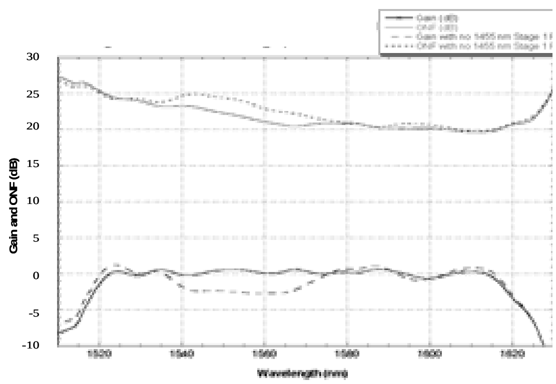

Fig. 3.6.5. Gain and noise figure of the multiple pump wavelength Raman amplifier with the 1455 nm pump in the first stage removed (dashed curves).

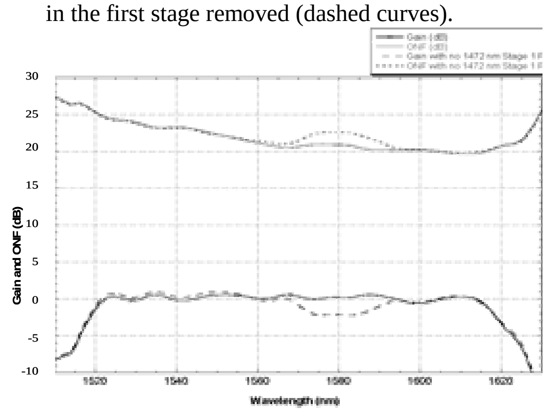

Fig. 3.6.6. Gain and noise figure of the multiple pump wavelength Raman amplifier with the 1472 nm pump in the first stage removed (dashed curves).

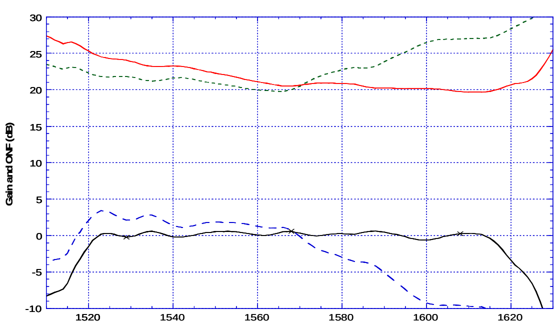

Fig. 3.6.7. Gain and noise figure of the multiple pump wavelength Raman amplifier with the 1505 nm pump in the first stage removed (dashed curves).

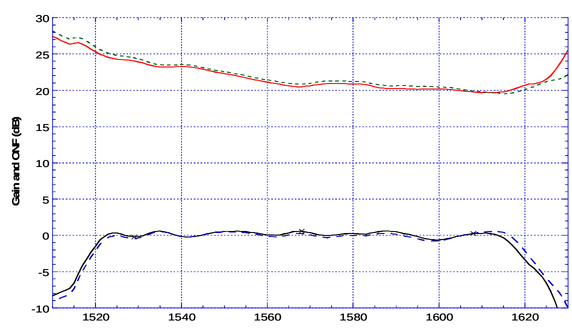

Fig. 3.6.8. Gain and noise figure of the multiple pump wavelength Raman amplifier with the 1505 nm pump in the first stage removed and the 1509 nm pump in the second stage adjusted to compensate (dashed curves).

The ability to compensate for missing pumps depends on the location of the pump wavelength. Because of the strong interaction between pumps and because the shortest pump wavelengths are rapidly depleted by the longer pump wavelengths, turning off either of the first two pump wavelengths 1396 nm (Fig. 3.6.2) or 1416 nm (Fig. 3.6.3) can be almost completely compensated by increasing the power of subsequent pumps. The removal of one of the middle pump wavelengths–e.g., 1427 nm (Fig. 3.6.4), 1455 nm (Fig. 3.6.5) or 1472 nm (Fig. 3.6.6)–leads to a depression in the gain near the peak of the gain for that particular wavelength, but the other pumps do a reasonably good job of keeping the rest of the gain curve uninterrupted. Since all of the pump power rolls down hill to the longest wavelength pump, the strongest effect occurs when the longest pump wavelength is missing, as illustrated by Fig. 3.6.7. The absence of the last pump wavelength causes a gain tilt and a lower gain and increased noise figure toward the long wavelength side of the band. Two things should be noted, however. First, the power in the last pump wavelength is quite small (e.g., 85 mW at 1505 nm as compared with 560 mW at 1396 nm), so the failure of this pump is least likely. Also, if a slight amount of power from the longest pump wavelength in the discrete stage is added (1509.5 nm), then the absence of the pump can be almost completely compensated (Fig. 3.6.8).

3.7 Other Enhancements

Although many techniques have been described for wideband Raman amplifiers that give them unique properties in the above sections, this treatment is by no means exhaustive. Also, as research and development continues on wideband Raman amplification, more and more feature sets are expected to arise. The latest developments in all-Raman amplification that have not been treated in detail here include: forward pumping, higher-order pumping and time-multiplexed or frequency-swept pumping.

Most Raman amplifiers use counter-propagating pump configuration to avoid coupling of pump fluctuations to the signal. In addition, by using the counter-propagating geometry, other effects such as pump mediated cross-talk and four-wave-mixing between pumps are also reduced. However, forward pumping improves noise figure and enables implementation of Raman amplified bi-directional systems. Forward pumping improves noise figure because the signal is amplified at the signal input end of the fiber before it is significantly attenuated, thereby maintaining a high signal-to-noise ratio throughout the fiber. Forward pumping requires the use of low-RIN pump lasers such as Fabry-Perot laser diodes.

One way to obtain some of the benefits of forward pumping without the direct coupling of the pump fluctuations to the signal is to use so-called higher-order pumping. In higher-order pumping, a co-propagating pump is used to pump a counter-propagating pump, thereby increasing the counter-propagating pump at the beginning of the fiber. Thus, the signal gain is increased at the beginning of the fiber. In general, the co-propagating pump is of shorter wavelength than the counter-propagating pump, and the counter-propagating pump is primarily responsible for the gain to the signal wavelengths. This approach has several limitations, however. First, the process tends to be somewhat inefficient, since one pump amplifies the other pump before it supplies energy to the signal. Also, the pumps are at the two ends of the fiber, and are therefore maximally attenuated by the propagation loss. Second, the co-propagating pump can still provide gain to the signal directly through the features on the gain spectrum, which means that the pump fluctuations can still couple to the signal.

Finally, time-multiplexed-pumping or frequency-swept pumping can be used to solve a number of problems in wideband Raman amplifiers. In time-multiplexed pumping different pump wavelengths are modulated in time and made to either overlap or not overlap in the fiber. Time-multiplexed pumping can be used to reduce the pump-pump interactions or to avoid four-wave-mixing between different pump wavelengths. The idea of frequency-swept pumping is to use a tunable wavelength pump laser and to time adjust the frequency of the laser. This may have several benefits including: (a) suppression of four-wave-mixing between pumps; (b) suppression of Raman interaction between pumps; and (c) very precise control of the gain profile.

4. WIDEBAND ALL RAMAN AMPLIFIED SYSYTEMS

Numerous high-performance experiments that use all-Raman amplification have been reported. In one example, Gnauck *et al.* [Gnauck02] report transmission of 2.5 Tb/s (64 channels at 42.7 Gb/s per channel) aggregate capacity over 4000 km (40 x 100 km spans) of non-zero dispersion shifted fiber in a loop-back experiment. This performance is achieved in a single 53 nm extended L band using return-to-zero differential-phase-shift keyed modulation, balanced detection, distributed Raman amplification, and forward error correction. In the return-to-zero differential-phase-shift keyed format, an optical pulse appears in each time slot, with the binary data encoded as either a 0 or π phase shift between adjacent bits. In principle, this coding scheme can reduce the SNR required to achieve a given BER by 3 dB, thereby increasing the system margin. The amplifier is a DRA followed by a discrete Raman amplifier implemented in a dispersion-compensating module. After forward error correction (FEC), an uncorrected BER of 2.4 x 10^{-4} corresponds to a corrected BER of less than 10^{-12}.

In another experiment, Sugahara *et al.* [Sugahara02] demonstrate transmission of 32 x 42.7 Gb/s DWDM signals over a distance of 6050 km using a Raman-amplified quadruple-hybrid span configuration. Transmission of the DWDM signals, which are spaced by 100 GHz, is accomplished through suppression of fiber non-linearity effects by distributed all-Raman amplification in dispersion managed fiber. The dispersion map consists of lengths of low-loss, pure silica core fibers (PSCFs) interleaved with DCF. The Q-values are all above 11.7 dB, corresponding to a BER below 3 x 10^{-17} with the use of FEC.

As another example, a 1.6 Tb/s system (40 x 42.7 Gb/s) transmission over 3600 km of dispersion managed fiber is accomplished using all-Raman amplification in 100 km terrestrial spans using a loop-back configuration [Liu02]. The long transmission distance and high capacity are enabled by a carrier-suppressed return-to-zero (CS-RZ) modulation format, distributed Raman amplification and new fiber types. Unlike many 40 Gb/s systems that use optical time-division-multiplexing, these results are obtained using electronic time-division-multiplexed (ETDM) transmitter and ETDM receiver. Even without using polarization interleaving, a high spectral density (40 Gb/s on 100 GHz channel spacing) is achieved because of this combination of techniques. The loop-back experimental configuration is 100 km spans consist of 35.5 km of large area fiber in series with 29 km of perfectly slope matched dispersion compensating fiber and an additional 35.5 km of large area fiber. Each link is also bi-directionally pumped, yielding a forward gain of ~7.5 dB and a backward gain of ~18.5 dB. In addition, fixed gain-flattening filters are used after each amplifier and a dynamic gain-flattening filter is used in one location of the loop. Using FEC, a bit error rate that is lower than 10^{-11} is achieved for each channel.

A similar experiment was performed by Zhu *et al.* [Zhu02], where transmission of 3.2 Tb/s (80 x 42.7 Gb/s) over 20 x 100 km of non-zero dispersion shifted fiber was accomplished in a re-circulating loop. All-Raman amplified spans, dispersion-slope-matched DCF modules covering a 75 nm band, CS-RZ modulation format, and FEC were employed. The low dispersion slope of the transmission fiber enables C+L-band dispersion and dispersion slope compensation of each span in a single DCF module. Also, the location of the zero-dispersion wavelength of the transmission fiber at <1400 nm enables co- and counter-pumping of the fiber spans for flat Raman gain and noise figure across the entire C+L bands by eliminating pump-pump four-wave mixing and pump-signal four-wave mixing. The all-Raman amplifier is a DRA in the 100 km transmission spans that is bi-directionally pumped and a discrete Raman amplifier in the DCF that is only counter-pumped. In general, the SNRs at short wavelengths are lower than at long wavelengths since the shorter wavelength pumps amplify the longer wavelength pumps through the Raman effect. Therefore, the use of higher co-pumped Raman gain at short wavelengths and the complementary slope for the counter-pumped Raman gain provides both flat noise figure and gain. The Raman on-off gain in the DCF is only used to compensate for losses in the DCF module and other components. With FEC, the worse case BER corresponds to a corrected BER below 10^{-13} at the receiver. This experiment illustrates the importance of both dispersion and dispersion slope matching, as well as proper use of complementary gain slopes to make the gain and noise figure more uniform.

Lowered Cost of Single Wideband Raman Amplifier

Telecommunications operators are shifting from demand for "capacity at any price" to demand for "capacity at the lowest price". Thus, the focus now is to achieve large throughputs over long distances before regeneration on a single optical fiber with the lowest cost. The effective metric for long-haul and ultra-long-haul WDM transmission systems moves from just the product of total throughput and maximum un-regenerated distance (measured in units of Gbps km), to the cost per unit transmitted bandwidth and per unit distance ($/(Gbps km)). Raman technology not only provides the basis for low-noise amplification of a very large continuous bandwidth, but also contributes to a substantial reduction in transmission cost by enabling high-capacity WDM system design utilizing low-cost terminal components.

A single, large transmission band is desirable since it minimizes amplifier cost by lowering the total number of passive components and pump sources, reduces the complexity of amplifier configurations, simplifies amplifier management, and minimizes the overall terminal cost by simplifying the multiplexer/demultiplexer structure. The challenge then is to achieve an amplifier structure capable of providing gain over a single ~100 nm wide band, with performance and total transmission cost comparable to those of traditional C-band (~35 nm) EDFAs with DRA and dispersion compensation, i.e., almost a 3-fold reduction of the $/(Gbps km) metric. By allowing gain in any wavelength window with a simple tailoring of the gain bandwidth, Raman amplification presents a reliable and low-cost solution to extend the bandwidth to well beyond that of the EDFA.

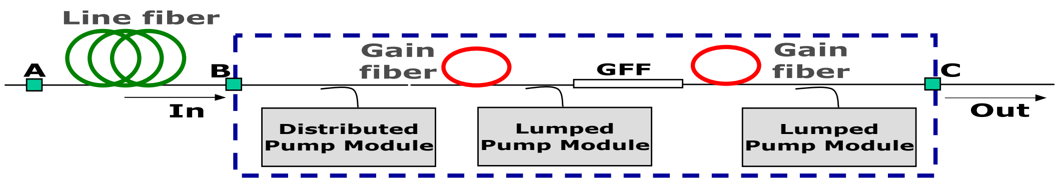

Fig. 4.1. Schematic diagram of all-Raman line amplifier comprising distributed and lumped Raman amplifiers. Dispersion and dispersion slope compensation are provided by discrete amplifier gain fibers.

A Raman amplifier structure combining both lumped Raman amplification (LRA) and DRA can give significant advantages of reach and capacity while dramatically lowering the overall cost of the system. Such a design has been implemented and the feasibility of transmitting 240 OC-192 channels over 1565 km standard single-mode fiber has been demonstrated. In this all-Raman experiment, a wideband 100 nm Raman amplifier is used both for the booster amplifier and the in-line amplifier (ILA). The booster amplifier is placed after the transmitter and consists of an LRA. The ILAs use a hybrid distributed/lumped Raman amplifier in a three-stage configuration (Fig. 4.1). Dispersion and dispersion slope compensation is provided by the DCF in the LRAs, and a static gain-flattening filter is used to obtain a substantially flat gain spectrum over 100 nm. The LRA is broken into two stages separated by isolators to reduce double Rayleigh scattering, so that the resulting amplifier has a low MPI level.

The experimental set-up for the ultra-long-haul transmission experiment is shown in Fig. 4.2. For this example, the transmission of 67 x 10.7 Gb/s channels spanning > 97 nm (from 1519.9 nm to 1617.0 nm) was achieved over 19 spans of average loss 19.7 dB. The total distance is 1565 km, and the average span length is 82.4 km. Using tunable sources, each measured channel was set at the center of a group of five 50 GHz-spaced channels, all NRZ-modulated with 2^{31}-1 pseudo-random bit sequence. The overall system performance was measured using a bit-error-rate tester (BERT).

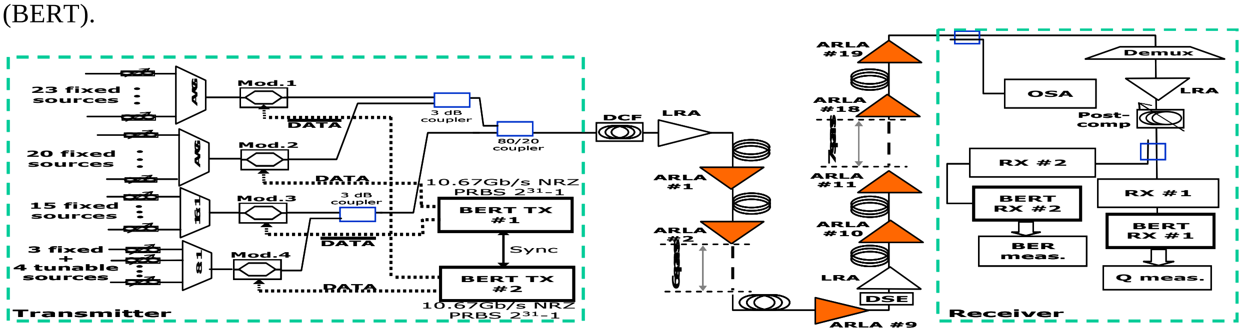

Fig. 4.2. Experimental setup for ultra long-haul transmission of 67 x 10.7 Gb/s channels over 1505 km of standard single-mode fiber.

The dispersion map for the experiment is illustrated in Fig. 4.3. For all of the channels there is a common pre-compensation of –1000 ps/nm, which is provided by the DCF after the transmitter block and before the booster amplifier in Fig. 4.2. Because the dispersion slope match is not perfect, the continuous band is divided into four sub-bands at the end, each of which receives a different level of post-compensation. In particular, for frequency bands 1, 2, 3, and 4, the post-compensation is 0, -300, -300, 0 ps/nm. Better slope matching of the DCF to the transmission fiber would reduce the need for post-compensation.

The spectrum at the input and output of the transmission system are illustrated in Fig. 4.4. The spectrum is measured with a resolution of 0.1 nm on an optical spectrum analyzer. Whereas the input spectrum is more or less flat, the output shows some accumulation of ripple after the 19 amplifier spans. The amplifier output power per channel is 0 dBm (1mW), and the minimum optical SNR is 18 dB (measured from ASE floor to the peak of the signal). On the right side of the figure, an expanded view is shown of several channels at the short-wavelength, mid-range, and long-wavelength side of the band.

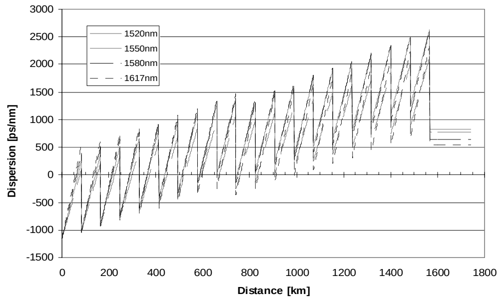

Fig. 4.3. Dispersion map for transmission experiment utilizing 100 nm bandwidth all-Raman line amplifiers. A common pre-compensation of ~-1000 ps/nm is provided across the full bandwidth. Banded post-compensation of 0, -300, -300, and 0 ps/nm is provided in four sub-bands.

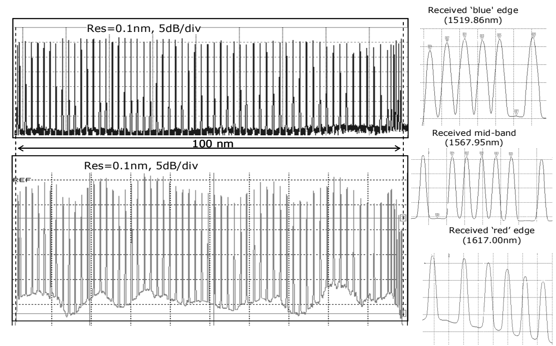

Fig. 4.4. Input (top left) and output (bottom left) signal spectra in the 100 nm bandwidth all-Raman amplified transmission experiment. The insets on the right show output spectra near the short wavelength (top), central (middle), and the long wavelength portions of the signal band.

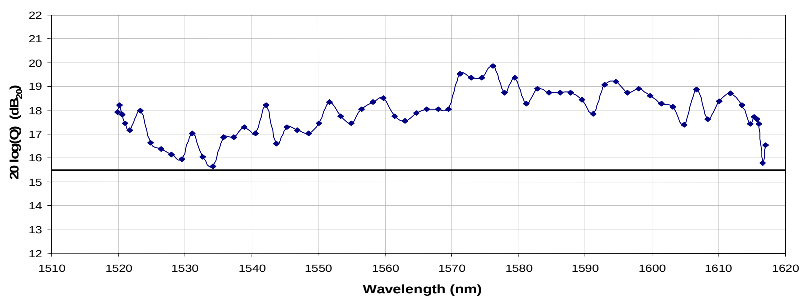

Fig. 4.5. Experimental Q value spectrum in the 100 nm bandwidth all-Raman amplified transmission experiment. The solid horizontal line indicates the target end-of-life Q.

The transmission performance measured with the BERT is shown in Fig. 4.5. The end-of-life BER target is 10^{-15}, which corresponds to a quality factor Q of 12.5 dB_{20} . (Note that it is traditional to measure Q in 20 log (Q), which is referred to as dB_{20}.) However, an additional 3 dB of end-of-life margin needs to be allocated for loss and other impairments. Hence, the target end-of-life Q is 15.5 dB_{20}. Figure 4.5 shows the measured Q across the ~100 nm band by using the tunable lasers to obtain five consecutive 50 GHz-spaced channels for each measurement. All channels showed a performance exceeding the end-of-life target of 10^{-15} BER, given a 5.5 dB coding gain from FEC (RS 255/239).

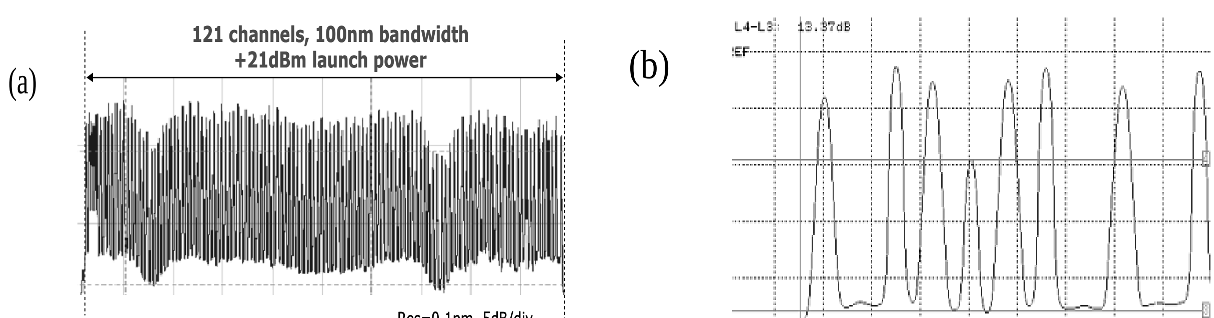

Fig. 4.6. (a) Signal spectrum after transmission of 121 channels over 1505 km of standard single-mode fiber. (b) Detail of signal spectrum showing system margin for 50 GHz channel spacing at 0 dBm/channel. The composite launch power is 21 dBm.

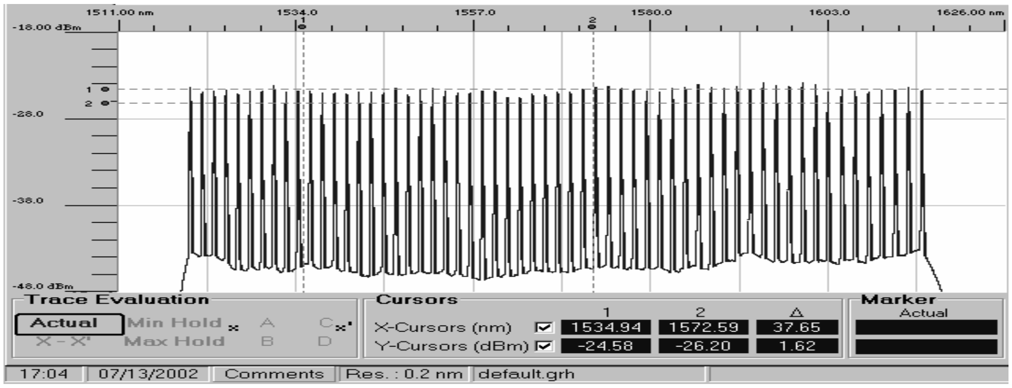

Fig. 4.7. Output spectrum for 240 channels after transmission over 650 km (eight spans) of standard single-mode fiber [Puc01].

Although this exemplary experiment uses only 67 channels, newer results do show the performance of the system up to the full load of 240 channels. For example, Fig. 4.6 shows the output spectrum after 1565 km for transmission of 121 channels over a 100 nm bandwidth with a composite launch power of +21 dBm. As the lower curve shows, the system margin is tested by using the tunable lasers to create five channels at 50 GHz channel spacing with the output from each amplifier set at 0 dBm per channel. All channels are decoded error-free with FEC (RS 255/239). Margin measurements on all channels from 6.3 to 7.5 dB were obtained by input channel de-emphasis from the nominal amplifier output channel power (0 dBm). Figure 4.7 shows the output spectrum for 240 channels after eight spans (~650 km total length) for a substantially flat input spectrum. Each ILA now has an output power of +24 dBm, corresponding to 0 dBm per channel for the 240 channels. With the use of dynamic gain equalizers placed periodically in the span (i.e., one or two in the entire 19-span link), transmission of all 240 channels over a distance above 1500 km can be achieved.

5. SUMMARY AND CONCLUSIONS

In summary, the design and implementation of wideband Raman amplifiers have been described in this paper. All-Raman amplification enables the lowest cost and smallest footprint system for a number of reasons. First, an all-Raman amplifier requires fewer components than the alternative split-band approach. Second, the broadband gain (100 nm or more) allows for the highest bandwidth, allowing use of less dense channel spacing (e.g., 10 Gb/s on 50GHz channel spacing) and standard non-return-to-zero modulation, thereby lowering transponder cost. Third, although most long-haul and ultra-long-haul amplified systems are limited by SNR or non-linearity, the use of distributed Raman amplification offers significant improvement in noise figure and mitigation of non-linearity compared with discrete amplification as offered by EDFAs.

To realize wideband systems, a number of key enabling technologies are required. First, of course, is the wideband amplifier itself. A number of alternative approaches for constructing wideband amplifiers include: EDFAs in various glass compositions, other rare-earth dopings, split-band S/C/L amplifiers, hybrid Raman/EDFA amplifiers and all-Raman amplifiers, which is the primary focus of this paper. Second, broadband components are required, such as multiplexers and demultiplexers. Third, wideband systems require gain equalizers and gain-flattening filters, which may be static or dynamic. Finally, for operation at 10 Gb/s dispersion compensation as well as dispersion slope compensation is required periodically in the system.

Raman amplification provides a simple, single platform for long-haul and ultra-long-haul fiber-optic transmission systems. The DRA alone or in combination with lumped Raman amplification has an improved noise figure and nonlinear penalty performance. Also, the gain in Raman amplification is obtainable in practically any wavelength band and can be wideband, determined primarily by the pump power distribution. In addition, lumped Raman amplification can integrate dispersion compensation by using the highly efficient Raman gain in DCF. Other advantages of Raman amplification include higher system reliability, simpler equalization, simple adjustment of gain flatness and large power dynamic range for flat gain operation. Despite this significant list of advantages, a number of challenges exist for Raman amplification, including: pump-to-pump interactions, inter-band and intra-band Raman gain tilt, noise arising from thermally-induced phonons near the pump wavelengths, MPI from double Rayleigh scattering, coupling of pump fluctuations to the signal and pump mediated signal cross-talk.

Fortunately, design techniques exist for overcoming all of these physical limitations, thus allowing for the relatively simple implementation of 100 nm Raman amplifiers. Section 3 of this paper on design of wideband Raman amplifiers provides in detail the engineering design rules used to determine the architecture of wideband Raman amplifiers. Because of MPI penalties from DRS, the wideband Raman amplifier is typically made into a multi-stage amplifier, where each stage is separated by an isolator. Also, the easiest way to deal with the short upper-state lifetime of the Raman effect is to introduce an effective lifetime equal to the transit time by making the pump and signal counter-propagating.

For wideband Raman amplifiers, several physical effects become particularly important. The Raman effect in the fiber leads to power exchange between the pumps and between the signals (inter-band and intra-band). To overcome the pump-to-pump interactions, the basic idea is to increase the pump spectral density at shorter wavelengths. Moreover, thermal noise is a significant limitation for any Raman amplifier with about 70 nm or more of bandwidth. To mitigate the effect of thermal noise at room temperature, one strategy is to amplify the vulnerable signals first. For example, in a hybrid amplifier comprising a DRA followed by a lumped Raman amplifier, this technique leads to gain slopes that are complementary in the two stages with the DRA gain increasing with frequency.

Several unique features of Raman amplification also lead to simplified system implementations. For example, in a Raman amplifier the gain shape and noise figure shape as a function of frequency can be controlled by varying the pump powers. This leads to a simple system where the signal input and output spectra can be monitored and used to control the pump powers applied to the Raman amplifier. In addition, in a wideband Raman amplifier with multiple wavelength pumps, the interaction between the various pump wavelengths can be used to advantage to make a high-reliability amplifier. Thus, a Raman amplifier provides a significant advantage over a conventional EDFA system in providing a mechanism for ensuring amplifier reliability without requiring one hundred percent redundancy for all driving pumps.

Finally, Section 4 describes successful application of wideband Raman amplification in high-performance transmission systems. For example, a hybrid Raman amplifier structure, combining both LRA and DRA, can give significant advantages of reach and capacity while dramatically lowering the overall cost of the system. Such a design has been implemented and the transmission feasibility of 240 OC-192 channels over 1565 km standard single-mode fiber has been demonstrated. The BER target is 10^{-15} and a 3 dB of end-of-life margin for loss and other impairments leads to a target Q of 15.5 dB_{20}. In the systems experiment all channels showed a performance exceeding the end-of-life target, given a 5.5 dB coding gain from FEC (RS 255/239).

Although the history of Raman amplification in fibers dates back to the 1970's, only in recent years has the technology matured to the point that practical systems based on wideband Raman amplification can be built and commercialized. Engineering design rules have been developed to address almost all physical limitations of Raman amplification, and advances in pump lasers, fiber quality, and passive components have made Raman amplifiers economical.

Raman amplification is the key enabling technology for other system cost reductions. Although amplifiers account for about 20% of the total loaded system cost in fiber-optic transmission systems, wideband Raman amplifiers lead to other system cost reductions. For example, due to the lower noise figure and reduced nonlinear penalty with DRAs, the system reach can be 1500 km or more, thus reducing the cost associated with channel-by-channel regeneration. Because of the broad bandwidth enabled by Raman amplification, several terabit-per-second capacities can be achieved on a single strand of fiber without exceeding a spectral density of ~0.2bit/s/Hz and using standard NRZ format. Hence, the transponder cost can be lower for wideband Raman systems. Moreover, since a single wideband amplifier can be used instead of three amplifiers in a split-band configuration for a 100 nm bandwidth, the amplifier cost is reduced by eliminating band couplers and consolidating dispersion compensation modules and monitoring and control circuits. With the fewer parts, the footprint for all-Raman amplification can be lowered, thereby also reducing the operating expense to carriers. For all of these reasons, Raman amplification can be expected to be dominant in new long-haul and ultra-long-haul systems in the near future.

REFERENCES

[Bromage02] J. Bromage *et al.*, in OSA *Trends in Optics and Photonics (TOPS) Vol. 77, Optical Amplifiers and Their Applications*, OSA Technical Digest, Post Conference Edition (Optical Society of America, Washington DC, 2002), p. OWA5-1.

[Fludger02] C. R. S. Fludger *et al.*, in *OSA Trends in Optics and Photonics (TOPS) Vol. 70, Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002), p. 183.

[Foursa02] D. G. Foursa *et al.*, in *OSA Trends in Optics and Photonics (TOPS) Vol. 70, Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002), p. FC3-1.

[Frignac02] Y. Frignac *et al.*, in *OSA Trends in Optics and Photonics (TOPS) Vol. 70, Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002), p. FC5-1.

[Gnauck02] A. H. Gnauck *et al.*, in *OSA Trends in Optics and Photonics (TOPS) Vol. 70, Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002), p. FC2-1.

[Kidorf99] H. Kidorf *et al.*, IEEE Photon. Technol. Lett. **11**, 530 (1999).

[Liu02] F. Liu *et al.*, in *OSA Trends in Optics and Photonics (TOPS) Vol. 70, Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002), p. FC7-1.

[Puc01] A. B. Puc, M. W. Chbat, J. D. Henrie, N. A. Weaver, H. Kim, A. Kaminski, A. Rahman and H. A. Fevrier, "Long-haul WDM NRZ transmission at 10.7Gb/s in S-band using cascade of lumped Raman amplifiers," *Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2001) Post-deadline paper 39.

[Sugahara02] H. Sugahara *et al.*, in *OSA Trends in Optics and Photonics (TOPS) Vol. 70, Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002) p. FC6-1.

[Zhu02] B. Zhu *et al*, in *OSA Trends in Optics and Photonics (TOPS) Vol. 70, Optical Fiber Communication Conference*, Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2002) p. FC8-1.