



# Up to 24-Tb/s Capacity: Raman Amplification for Terabit Optical Networking Today and Tomorrow



## Introduction

Development of bandwidth-hungry applications, minimization of the cost per transported bit, optimization of the power and space efficiency, advent of IP routers with higher and higher line interface rates... These are some of the multiple challenges that the optical transport industry needs to address.

While the channel rate has experienced a continuous growth from 2.5 to 40 Gb/s between the mid-90s and the end of the 10s, together with development of more and more advanced modulation formats, the optical amplification, that is required for an efficient long-distance transport of all the channels, has been mostly limited to the use of Erbium-Doped Fiber Amplifiers (EDFAs). Although effectively enabling multi-channel amplification and transmission, the optical bandwidth of EDFAs is intrinsically limited to less than 40 nm,

offering room for less than 100 optical channels (a typical figure in today's conventional transport systems is 88 optical channels).

Furthermore the noise performance of EDFAs is not optimal, resulting in a significant noise accumulation along the optical path when multiple in-line amplifiers are inserted to periodically boost the signal power. This noise accumulation limits the [Capacity x Reach] performance of EDFA-based transmission systems.

Lastly the discrete nature of EDF amplification (i.e. the optical amplification happens at discrete "hot" spots along the optical path) is conducive to high nonlinear effects, which can impose an upper limit upon the [Optical reach x Channel count x Channel rate] metric.

Both optical noise and nonlinear effects produce more and more stringent restrictions for channel count and optical reach when the individual channel rate increases.

The net result for conventional EDFA-based transport systems is a capacity limited to 8.8 Tb/s per fiber pair (using state-of-the-art 100G coherent technology) with a reach not exceeding 2,000 km.

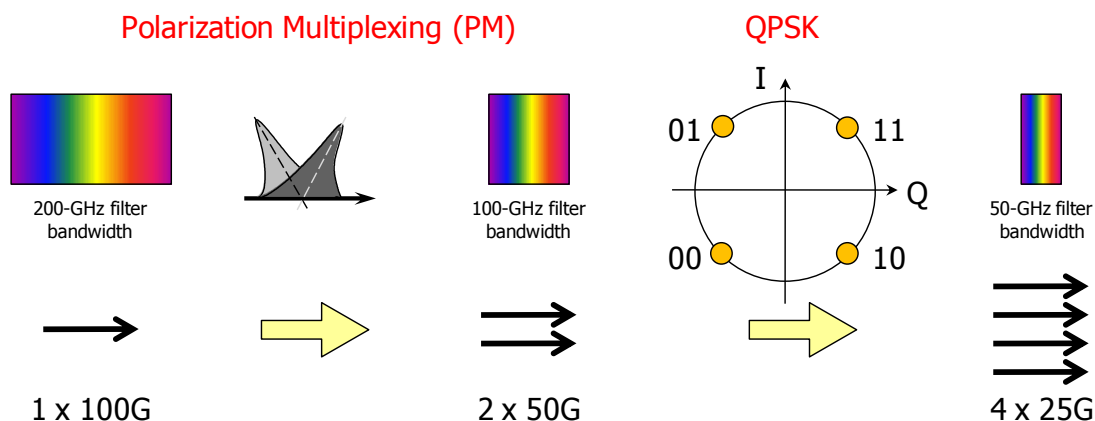
After a short description of today's 100G digital coherent technology, this White Paper illustrates the value and benefits of optical Raman amplification to go beyond these limits imposed by the physics of Erbium-doped fiber amplification, while using technology available today and already field-proven.

## 100G Digital Coherent Technology

Today (2011), the 100G digital coherent technology is getting more and more mature. There is a general consensus (e.g. from ITU-T and IEEE standardization bodies) around PM (or DP)-QPSK modulation format with coherent detection (PM: Polarization Multiplexing, DP: Dual Polarization, QPSK: Quadrature Phase Shift Keying). Almost all the equipment vendors, with the exception of a very few of them, are proposing this approach for enabling 100G channel rate.

On its side, the Optical Internetworking Forum (OIF) approved 100G coherent receiver Implementation Agreement (IA) in May 2010. The "*100G Ultra Long Haul DWDM Framework Document*" published by OIF provides a high-level description of PM-QPSK modulation format and associated 100G transmitter and digital coherent receiver design, as well as the rationale for this choice.

The basic principle of PM-QPSK modulation format is to trade speed for parallelism at the expense of added complexity, as illustrated in the Figure below.



**Figure:** Principle of PM-QPSK modulation format.

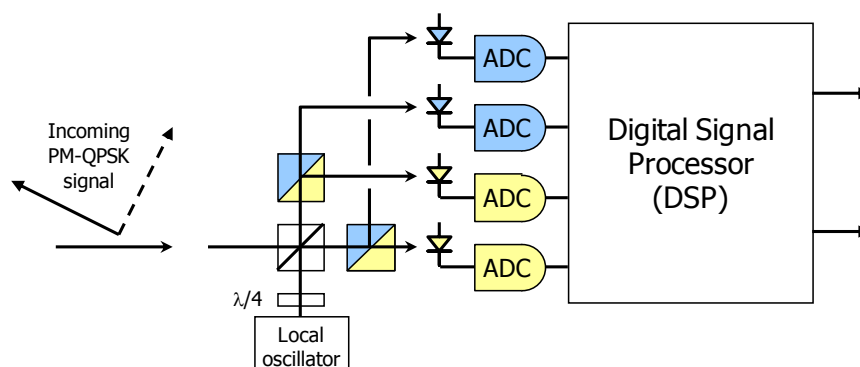
Instead of modulating a single optical carrier at 100G using 100-Gb/s binary modulation format, two independent orthogonal states of optical polarization, at the very same optical frequency (because delivered by the same single laser source), are modulated. The polarization multiplexing halves the data rate, halves the spectral width, but doubles the count of components.

The next parallelism step is to encode the data to be transported not into 2 states like in any binary modulation format, but into 4-phase states. Consequently a single phase symbol transports 2 bits of data. The quadrature phase shift keying halves the symbol rate compared to the binary phase shift keying. It also halves the spectral width but doubles the count of components.

The combination of dual polarization and QPSK reduces the required symbol rate by a factor of 4. To transport a 100-Gbit/s data stream, “only” 25 Giga of phase symbols (each encoded into 4-phase states) must be transmitted. We speak here of a symbol rate of 25 Gbaud/s for transporting a 100-Gbit/s data stream.

This approach allows the application of lower cost technologies when a lower symbol rate reduces the sensitivity of the signal to a number of optical propagation impairments.

At the output end, the received signal is mixed with a strong local oscillator (an optical laser source built in the 100G coherent receiver), generating mixing products at an intermediate frequency (i.e. the difference between the optical frequency of the received optical signal and the optical frequency of the local oscillator). The mixing products can be down converted and detected electronically. The analog components of the received signal are then digitized and fed to Digital Signal Processing (DSP) ASIC.



**Figure:** Synoptic of 100G digital coherent receiver for detection of PM-QPSK modulated signal.

The Analog to Digital Converters (ADCs) produce multi-level signal ideal for Soft-Decision Forward Error Correction (SD-FEC). The Digital Signal Processor (DSP) also compensates chromatic dispersion, Polarization Mode Dispersion (PMD) and frequency offset between the received signal and the local oscillator.

The main features of a digital coherent receiver are the higher OSNR tolerance and the full access to the electromagnetic field of the optical signal (i.e. amplitude and phase). On its side the standard receiver working with On/Off Amplitude Shift Keying (ASK) is able to recover only the power of the optical signal.

The full access to the electromagnetic field of the optical signal is key to allow digital equalization in the electrical domain of chromatic dispersion and Polarization Mode Dispersion (PMD). Accessing the amplitude and phase of the optical signal opens the path to multi-level amplitude and/or phase modulations (at the expense of added complexity compared to, e.g., quadrature phase shift keying), while the standard receiver working with On/Off Amplitude Shift Keying – ASK – could be implemented only with binary power modulation.

## Strategies to go Beyond 8.8 Tb/s Imposed by Traditional EDFA-Based WDM Transport Systems

The typical optical bandwidth available in traditional optical transport systems relying on EDF amplification ranges from 1534 to 1570 nm (i.e. an optical bandwidth of about 36 nm that can accommodate for 88 channels with 50-GHz channel spacing).

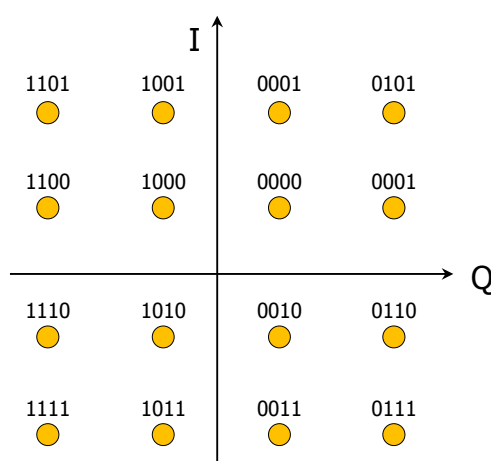
As the EDFA-based line equipment imposes an upper limit on the optical bandwidth, the next steps for line capacity increases must be achieved at the terminal/interface levels. New approaches need to be proposed in order to increase the number of bits carried by the

optical channels. This is typically contemplated via the development of more sophisticated, more complex modulation/detection schemes, and at the expense of extra cost.

## More Capacity per Individual Optical Wave

Examples of new modulation/detection schemes proposed by some equipment vendors are multi-level amplitude/phase modulations (the so-called Quadrature Amplitude Modulation – QAM). In QAM approach, two amplitude-modulated carriers in quadrature are added. Because of the 90° phase difference between both carriers (hence the term of *quadrature*), the sum of the two amplitude-modulated carriers results in a combination of amplitude and phase modulations.

For optical transmission, QAM approach can be envisaged with 16, 32 or 64 levels (16-QAM, 32-QAM, 64-QAM), still combined with polarization multiplexing (PM-16-QAM, PM-32-QAM, PM-64-QAM...).



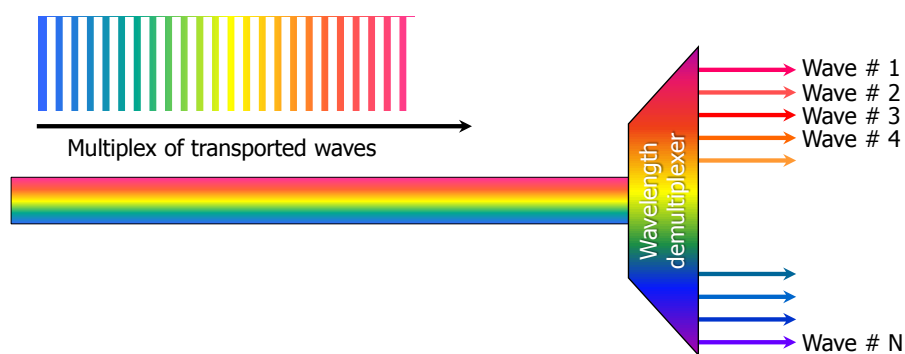
**Figure:** Constellation diagram for 16-QAM (where a single symbol transports 4 bits of data).

In addition to their higher complexity and cost compared to the current PM-QPSK option, these multi-level amplitude/phase modulation formats offer a reduced reach. The higher the QAM constellation size (i.e. the larger the number of amplitude/phase levels), the closer the different amplitude/phase levels (for a constant nominal output power). As any modulation format, high QAM constellation size eventually faces basic noise limitations due to the short distances between the different amplitude/phase levels.

Some equipment vendors propose line interface cards with programmable modulation format (with, e.g., PM-16-QAM format dedicated to the shortest transmission distance). However such an approach is likely to result in provisioning errors and complexity in meshed network with multiple restoration paths of different lengths.

Moving to numbers, tripling the current capacity of 8.8 Tb/s in order to get around 24 Tb/s would impose the development of line interface cards based on 64-QAM modulation scheme.

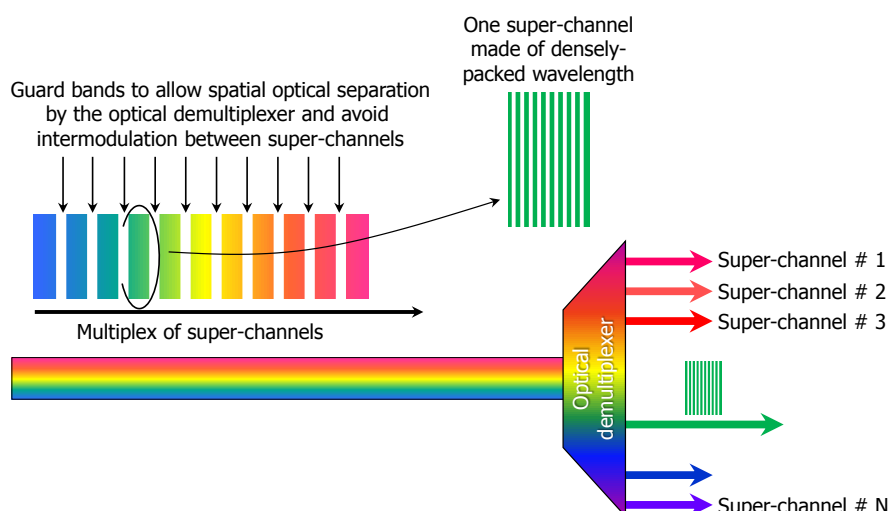
In this approach, optical carriers spaced 50 GHz apart are still assumed with spatial separation at the output end via a wavelength division multiplexer (functionally, this is a device with an input port connected to the output of the line fiber, and multiple output ports – typically 88 with EDFA amplifiers –, each delivering a single optical carrier). This capacity increase strategy is on a per channel basis, making it expensive when many channels are lit (up to 88 64-QAM interface cards).



**Figure:** Increase of the capacity carried by each wavelength in a spatial wavelength separation approach.

## More Densely-Packed Optical Waves

Another path is to try to pack more densely optical waves and to build what has been called by some equipment vendors super-channels or multi-carrier flex-channels (this technology is also sometimes referred as optical OFDM).

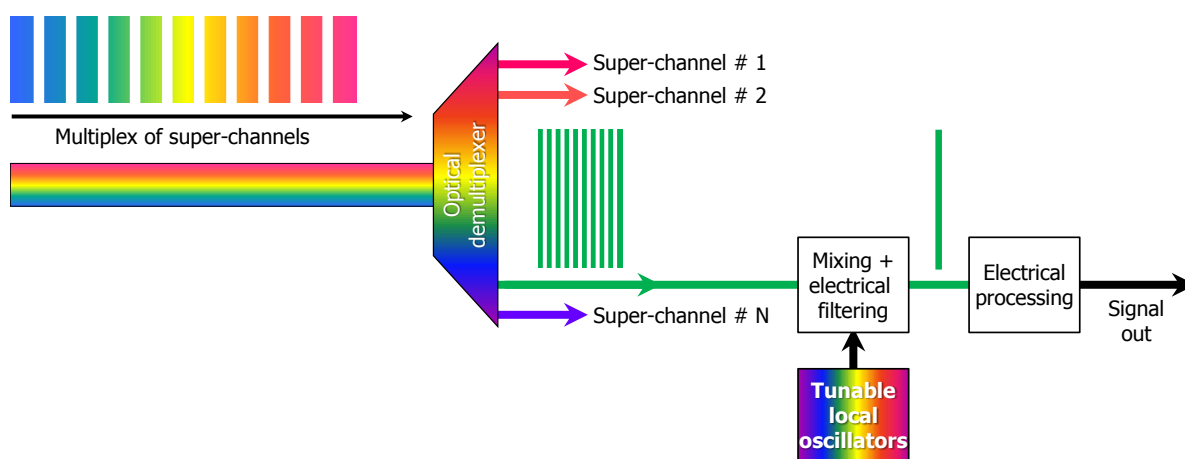


**Figure:** Increase of the line capacity carried by packing more densely the optical carriers.

Instead of optical carriers uniformly spaced (e.g. 50 GHz apart), the optical carriers are packed by groups of, e.g., ten. There is an optical guard band between two adjacent 10-carrier groups in order to make it possible the spatial optical separation by an optical demultiplexing device and avoid intermodulation between super-channels.

Within each 10-carrier group, the inter-carrier spacing is significantly smaller than 50 GHz. With such an inter-carrier spacing, there is no sufficient optical guard band and traditional optical demultiplexing strategy does not allow the proper separation/extraction of individual carrier before feeding the receiver.

Another benefit of coherent receivers is then used to access each carrier within this densely-packed group of 10 carriers: the higher spectral selectivity offered by coherent technology compared to optical demultiplexing technology. Inside a coherent receiver, the incoming wave (carrying the signal) is mixed with a strong signal, the so-called local oscillator; the resulting signal is centered on the intermediate frequency (beat frequency, or difference of the frequencies of the incoming wave and the local oscillator). The intermediate frequency is small enough to enable filtering in the electrical domain before processing by high-frequency electronics. As electrical filtering is more elective than optical filtering, the coherent receiver is able to separate/extract each of the carriers within the densely-packed group of 10 carriers.



**Figure:** Combination of optical and electrical demultiplexing in the super-channels or multi-carrier flex-channels approach.

The super-channels or multi-carrier flex-channels require quite complex coherent receiver (with, in the example above, 10 local oscillators within each coherent receiver in charge of handling one 10-carrier group).

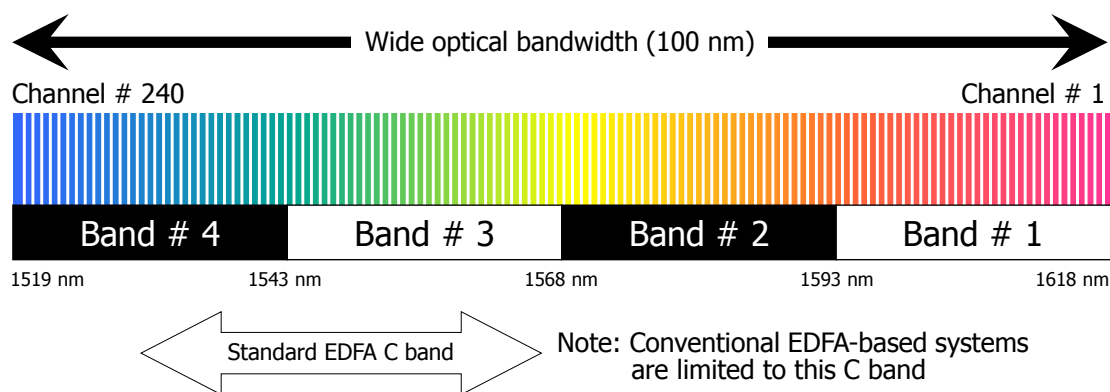
## More Capacity per Individual Optical Wave AND More Densely-Packed Optical Waves

The two strategies exposed above can be combined in an attempt to maximize the line capacity that can be transported with line equipment based on EDFAs. For instance, using the today's PM-QPSK modulation format combined with super-channels or multi-carrier flex-channels approach could offer a line capacity of about 12 Tb/s (i.e. larger than the one proposed today – 8.8 Tb/s). Moving to more complex modulation format (i.e. larger QAM constellation size) at the expense of significant development efforts, higher line capacity could be offered (e.g. 25 Tb/s with 16-QAM modulation scheme and super-channels or multi-carrier flex-channels approach).

## A Different Approach to go Beyond 8.8 Tb/: (Simply) Expanding the Optical Bandwidth!

Xtera's philosophy for optical transport is simple: to make the best usage of optical amplification. Optical amplification is the key technology to design subsystems able to simultaneously amplify multiple channels (for a cost shared by all the channels) instead of developing sophisticated per channel strategy (e.g. more complex modulation format). This per channel strategy results in extra cost for high-capacity networks because of the high count of channels found in such networks.

This is one of the reasons why Xtera originally developed all-Raman optical amplification with ultra-wide optical bandwidth.



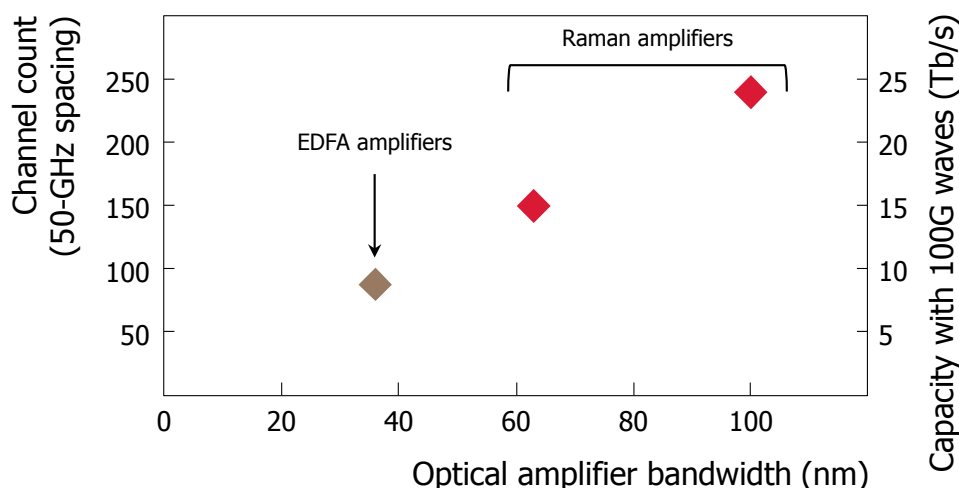
**Figure:** 100-nm optical bandwidth offered by all-Raman optical amplification.

In the first WDM optical transport equipment deployed by Xtera in 2004, a 100-nm optical bandwidth was offered in a contiguous way (no gap in the optical spectrum). The four optical bands shown in the Figure above resulted from the multiplexing architecture of the terminal equipment: there is no optical guard band and this 100-nm optical bandwidth can house 240 optical channels spaced 50 GHz apart.

## Benefit # 1 from Raman Amplification: Capacity

Raman optical amplification avoids the spectral bottleneck imposed by Erbium ions. With its first-generation optical amplifiers (deployed in the field since 2004), Xtera offers a 100-nm optical bandwidth. With our more recent optical amplifier implementation (as found in Nu-Wave Optima platform), we offer a 63-nm optical bandwidth with a modular design which allows scalable optical bandwidth.

Using standard 50-GHz channels spacing, these optical bandwidths turn into 240 optical channels for our first-generation optical amplifiers and 150 optical channels for our last-generation Nu-Wave Optima optical amplifiers.



**Figure:** Optical bandwidth and line capacity (assuming 100G waves spaced 50 GHz apart) for different types of optical amplifiers.

Using today's 100G coherent technology, these channel counts lead to 24 Tb/s per fiber pair for Xtera's first-generation optical amplifiers and 15 Tb/s per fiber pair for Xtera's last-generation Nu-Wave Optima optical amplifiers.

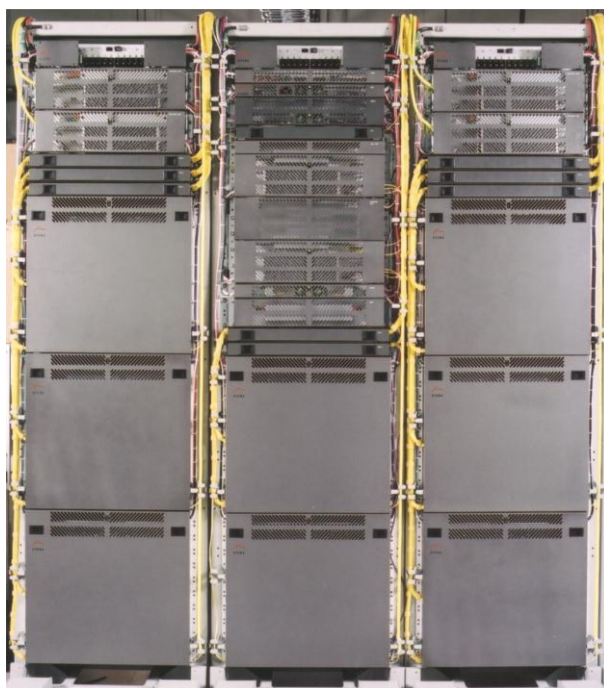
## Benefit # 2 from Raman Amplification: Equipment Density

The high performance (in terms of, e.g., optical bandwidth and OSNR) of the common equipment based on Raman optical amplification relaxes the requirements and specifications of the interface cards.

In conventional EDFA-based transport systems where the common line equipment brings many limitations (narrow optical bandwidth, poor noise performance, generation of high

nonlinear effects within the line fiber), advanced (and expensive) technologies must be developed and implemented at the interface card level in order to make the most of the common equipment. Before the advent of 100G technology, these advanced options included channel spacing narrower than 50 GHz, sophisticated modulation formats (RZ, duobinary...)... With the advent of 100G technology, these advanced options include today multi-level QAM modulation formats, super-channels (or multi-carrier flex-channels)...

Because of its large optical bandwidth, low noise level and the minimization of the impact of the nonlinear effects it offers, Raman optical amplification can be combined with simple interface card technology to provide high very large capacity with high equipment density. This was clearly illustrated with Xtera's first product offering 2.4 Tb/s in 3 racks by 2004 with simple 10G NRZ technology applied to 240 channels in a 100-nm optical bandwidth. This 2.4-Tb/s capacity could be transported on 3,000 km with only in-line amplifiers, without any need for regeneration. Moving back to equipment density, photonic integrated circuit approach, with 10G waves, did not bring any density advantage at this time.



**Figure:** 2.4 Tb/s in 3 racks by 2004 with simple 10G NRZ technology applied to 240 channels in a 100-nm optical bandwidth.

Today, with Nu-Wave Optima platform, Xtera offers to the industry what we believe to be the highest equipment density: 2.5 Tb/s per rack with 100G interface cards. No real comparison can be made with photonic integrated circuit approach because 100G waves are not yet (in 2011) commercially available.

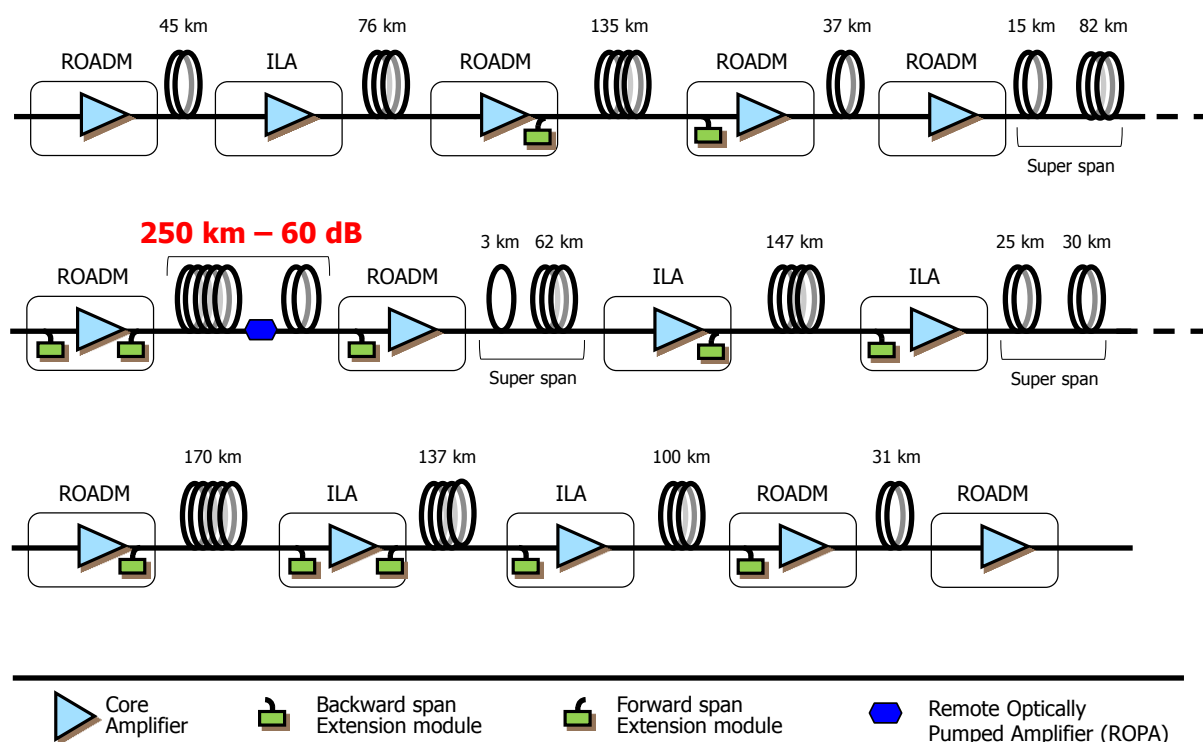
No need to say that lower power consumption comes along with higher equipment density.

### **Benefit # 3 from Raman Amplification: Reach**

Not only Raman amplification brings today to network operators high capacity but it also offers unparalleled reach capabilities. Compared to EDFA-based transport systems, this reach superiority comes from two main factors:

- Better noise performance
- Lower peak-to-peak power excursion for the individual channels along the optical path (due to the distributed nature of Raman amplification occurring inside the line fiber)

As a result innovative link designs can be proposed and implemented with Raman amplification while they were simply not possible with EDFA technology. An example is provided by the Figure below where an all-optical path exceeding 1,300 km is made of spans of different lengths and attenuations, one of them being 250-km long with a 60-dB optical attenuation.



**Figure:** Example of all-optical path exceeding 1,300 km including one 250-km, 60-dB span, enabled by Raman amplification.

With the common EDFA approach, the channels would have to be terminated at either end of this 250-km, 60-dB span, imposing costly regeneration sites. The Raman amplification sub-systems depicted in the Figure above are implemented using the Nu-Wave Optima platform. This platform is highly modular and allows the customization of the amplifier configuration (forward and/or backward Raman pumping, with or without Remote Optically Pumped Amplifier – ROPA) in order to efficiently cope with actual spans attenuations encountered along an all-optical path.

Similarly Raman amplification is the best amplification technology for unrepeated applications (no active elements between the two end points), whatever terrestrial or submarine.

## Conclusion

Following Xtera's activities, Raman amplification is in commercial services in backbone networks since 2004 with 100-nm optical bandwidth. Since then Raman-based optical transport systems have been flawlessly deployed in multiple environments for various applications (backbone networks, backhaul, regional networks, unrepeated links...) with high operation simplicity.

Based on this experience, the value offered by this innovative and fully field-proven amplification technology can be summarized as follows:

- Capacity:
  - A scalable optical bandwidth is enabled by modular Raman amplification implementation as found in the Nu-Wave Optima platform while the largest optical bandwidth (100 nm) was offered by Xtera's first-generation product.
  - 150 or 240 channels, depending on the physical implementation of Raman amplification technology, are available with 50-GHz channel spacing, resulting in a line capacity of 24 Tb/s with current 100G technology.
  - 10, 40 and 100G channels can be mixed and matched on the 50-GHz grid with no need for optical guard band.
- Reach:
  - As Raman-amplified links avoid the "hot spots" made of EDFA amplifiers, per channel optical power is better controlled along the link with a smaller breathing (smaller peak-to-peak power excursion).
  - This specific longitudinal per channel optical profile results in smaller nonlinear effects that lead in turn to longer reach and/or higher channel count.
  - This longer reach performance can be used in different ways:
    - Either skipping some intermediate sites (when required because of lack of building or power);
    - Or long regenerated sections in terrestrial networks (e.g. 150 x 100G on 3,000 km).

In addition to the capacity and reach benefits summarized above, it is important to stress again on the fact that Raman amplification has been deployed by Xtera since 2004 and that this high-bandwidth approach allows to maximize the line capacity up to 24 Tb/s while using available interface card technology (100G PM-QPSK modulation format with digital coherent detection and soft-decision FEC).

## Glossary

| Acronym | Meaning                                    | Unit<br>(If applicable) |
|---------|--|-------------------------|
| ADC     | Analog to Digital Converter                |                         |
| ASK     | Amplitude Shift Keying                     |                         |
| DP      | Dual Polarization                          |                         |
| DSP     | Digital Signal Processing                  |                         |
| IA      | Implementation Agreement                   |                         |
| QPSK    | Quadrature Phase Shift Keying              |                         |
| EDF     | Erbium Doped Fiber                         |                         |
| EDFA    | Erbium Doped Fiber Amplifier               |                         |
| FEC     | Forward Error Correction                   |                         |
| NRZ     | Non Return to Zero                         |                         |
| OFDM    | Orthogonal Frequency Division Multiplexing |                         |
| OIF     | Optical Internetworking Forum              |                         |
| OSNR    | Optical Signal-to-Noise Ratio              | dB / 0.1 nm             |
| PM      | Polarization Multiplexing                  |                         |
| PMD     | Polarization Mode Dispersion               |                         |
| QAM     | Quadrature Amplitude Modulation            |                         |
| RZ      | Return to Zero                             |                         |
| SD-FEC  | Soft-Decision Forward Error Correction     |                         |
| WDM     | Wavelength Division Multiplexing           |                         |



## **Maximizing Network Capacity, Reach and Value** *Over land, under sea, worldwide*

Edition Date: August 2011

Version: 1.0