100 Gb/s Transmission over TrueWave[®] Fiber

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This paper discusses the use of TrueWave® nonzero dispersion fiber (NZDF) in 100 Gb/s applications. We show that TrueWave fiber supports 100 Gb/s coherent systems to at least 1500 km. With its medium chromatic dispersion, extremely low PMD and optimized Raman amplification, TrueWave fiber is an excellent choice for current 10 Gb/s applications and future high speed / long haul networks.

Nonzero Dispersion Fiber (NZDF)

Nonzero dispersion fiber (NZDF) was developed to reduce the costs of dispersion compensation in 2.5 and 10 Gb/s systems. One of the first NZDFs was OFS' TrueWave RS fiber, which meets the ITU G.655.C and D standards. Later, OFS introduced TrueWave *REACH* fiber to fulfill the requirements of G.655.C and E as well as G.656. This fiber is optimized for Raman amplification.

Lower dispersion in these fibers means that fewer Dispersion Compensating Modules are required in the system, which in turn helps reduce system attenuation, Polarization Mode Dispersion (PMD) and cost. These benefits remain when selecting fiber for 10 Gb/s systems, which cover more than 90 percent of today's line card market and are expected to do so for years to come.

The development of 40 and 100 Gb/s systems make residual dispersion even more important - and more difficult to keep below a critical limit. The low residual dispersion required in these higher speed systems is made possible through deployment of Dispersion Compensating Modules.

TrueWave *REACH* fiber is specifically designed for use with Raman amplification. The fiber's ultra low Zero Dispersion Wavelength, its high Raman efficiency, and its Low Water Peak attenuation make it a perfect choice for systems using this method.

40 Gb/s and 100 Gb/s Non-Coherent Transmission Formats

Systems at 2.5 and 10 Gb/s are all non-coherent and most systems at 40 Gb/s are as well. At 100 Gb/s many - but not all - systems use coherent detection. While 2.5 and 10 Gb/s all are based on simple on-off keying, many different formats are used at 40 Gb/s. It is important to note this fact when looking at 100 Gb/s, a new bit rate where many new developments are still to be expected. Coherent detection systems have been developed and offered, but non-coherent 100 Gb/s systems are also becoming available. Non-coherent systems have the advantage of not using digital signal processing (DSP) and therefore use less energy, but they are limited in distance because of chromatic dispersion and PMD in the fiber. Also, non-coherent systems tend to be less costly than coherent systems.

Other systems use coherent detection and DSP and can provide full electronic dispersion compensation. The DSP can compensate for all dispersion, but to save energy and complexity there are limits to how much dispersion will be compensated. Some of the dispersion can be compensated or limited optically, by using medium dispersion fiber (NZDF) and/or Dispersion Compensating Modules. This will limit

the computational power and energy required by the DSP. Examples show that dispersion is a limiting factor in 100 Gb/s coherent detection systems (ref. 1). In cases where the more cost-efficient non-coherent detection is used, this will become even more important (ref. 2).

The 100 Gb/s Coherent Transmission Format

Lately, we have seen a number of initiatives to develop commercially available 100 Gb/s systems based on coherent transmission, which, by its nature, makes dispersion – both polarization and chromatic – less important, and optical non-linearities become the limiting factor. This applies also to 4x28 Gb/s systems. Some of these initiatives focus on larger effective area and/or lower attenuation to reduce non-linearities.

At first glance, one would tend to disqualify TrueWave fibers for these systems. However, a closer look shows that they are an excellent choice. Not only will they allow for optimized costs on today's 10 Gb/s systems, but they can also support 100 Gb/s coherent transmission much longer than one initially would imagine.

In this report, we discuss experimental trials that have proven that unrepeatered 100 Gb/s coherent transmission is possible on TrueWave RS fiber to at least 1000 km; on TrueWave *REACH* fiber the calculated reach comes to at least 1500 km. Ref. 3 discusses an experiment which demonstrates that a reach of 2650 km can be achieved by using a special coherent detection scheme.

100 Gb/s Coherent Transmission Trials

The experiments were performed outside of OFS by a specialist in coherent 100 Gb/s transmission. The results show that TrueWave fiber is well suited for

applications of future modulation formats, and that the fiber is a very good choice for existing and newly deployed networks.

In the experiment shown in Figure 1, a 1550 nm signal laser (SIG) was multiplexed with other signals at 50 GHz spacing. The signal was modulated at 100 Gb/s QPSK and launched into a fiber link - in this case 15 spans of 100 km fiber. The signal was detected in the coherent receiver (CRX). Input power was varied and optical signal-to-noise ratio (OSNR) was measured.
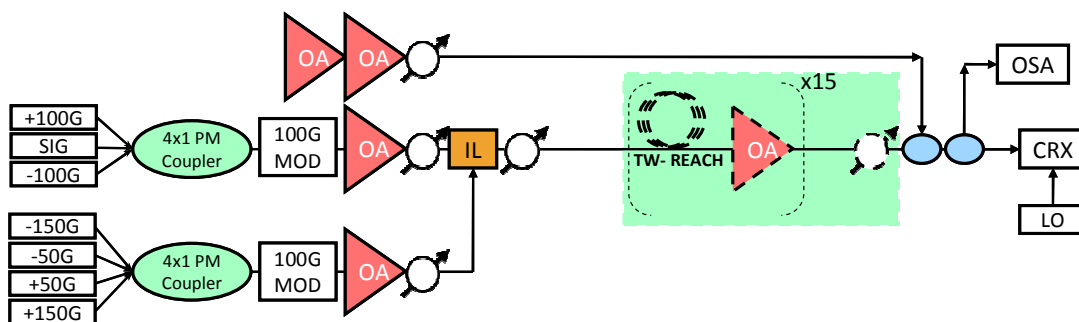

Figure 1. Experimental setup

This experiment was conducted with TrueWave RS fiber. The results for TrueWave *REACH* fiber, and - as a point of reference - with OFS' AllWave[®] Zero Water Peak G.652.D fiber, are based upon models. Actual tests with TrueWave REACH are planned.

TrueWave RS Fiber (G.655.C/D) Results

Results of the experiment with 1000 km of TrueWave RS fiber - 10 spans of 100 km - are shown in Figure 2. The OSNR penalty is shown at a bit error rate of 10^{-2}.

The OSNR link budget is calculated from

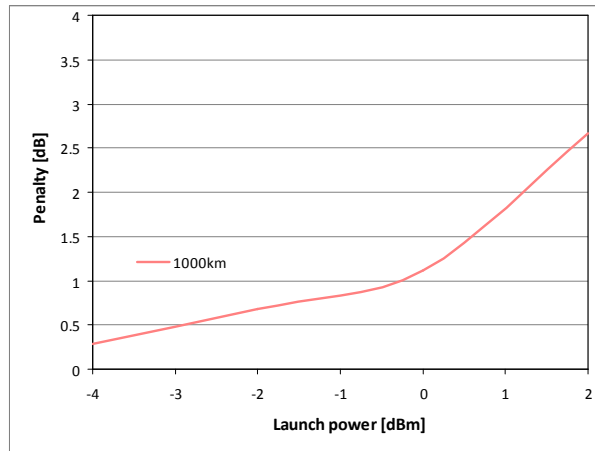$$OSNR = 58\ dB + P_{launch} - span\ loss - 10log_{10}(\#span) - NF_{EDFA} - OSNR_{penalty}$$

Figure 2. OSNR measurement for TrueWave RS fiber with no inline compensation

The experiment has been conducted for the three fiber types mentioned. The results of this trial indicate the OSNR link budget at a launch of 0.5 dBm:

OSNR = 58dB + 0.5dB – 22dB – 10log10(10) – 6dB – 1.5dB = 18db

Compare this to a typical specification of 14dB end of life.

This shows that TrueWave RS fiber easily supports 100 Gb/s over 1000 km. Before we discuss the results for TrueWave *REACH* fiber, let's take a look at AllWave standard single-mode fiber.

AllWave ZWP Fiber (G.652.D) Results

The results of the same experiment using 15 spans of 100 km AllWave fiber are shown in Figure 3.
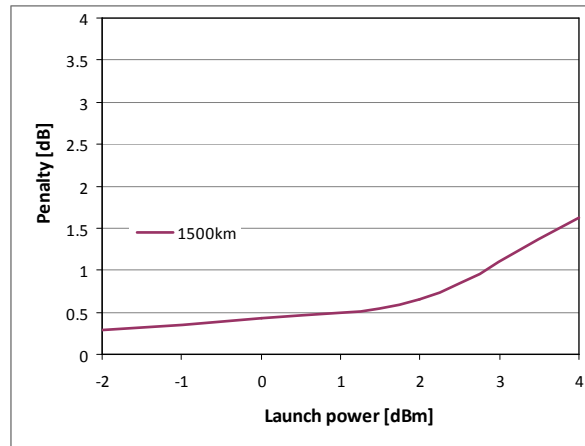
Figure 3. OSNR measurement for AllWave fiber

We took the OSNR calculation for two different cases. The optimal launch power is 4 dBm. "Optimal launch power" is the power at which the increase in launch power equals the improvement in OSNR:

$$OSNR = 58dB + 4.0dB - 22dB - 10log_{10}(15) - 6dB - 1.5dB = 20.5db$$

Typically, launch power is limited to around 0 dBm due to the design of optical amplifiers; in most cases, it is most sensible to do a comparison of different system settings by setting the power to around 0 dBm. For TrueWave RS fiber, the optimal power is close to this value; for 1500 km of AllWave fiber, the OSNR link budget at this launch power is given by:

$$OSNR = 58dB + 0dB - 22dB - 10log_{10}(15) - 6dB - 0.6dB = 17.4db$$

This is almost equal to the value we arrived at for 1000 km TrueWave RS fiber.

TrueWave *REACH* Fiber (G.655.C/E and G.656) Results

Now we'll look at the results of the same experiment using 1500 km of TrueWave *REACH* fiber (see Figure 4). The link budget for TrueWave *REACH* fiber at an optimal launch of 2 dBm:

$$OSNR = 58dB + 2.0dB - 22dB - 10log_{10}(15) - 6dB - 2.3dB = 17.7db$$

At 0 dBm:

$$OSNR = 58dB + 0dB - 22dB - 10log_{10}(15) - 6dB - 0.8dB = 17.2db$$

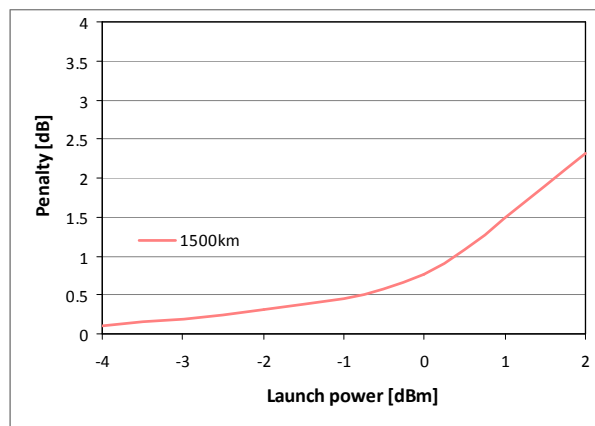TrueWave *REACH* fiber has a link budget very similar to standard single-mode fiber.

Figure 4. OSNR measurement for TrueWave REACH fiber

Collective Experimental Results

Based on this simple comparison, we conclude that 100 Gb/s coherent systems perform equally well using all three fiber types at a launch power at 0 dBm, which is a typical value.

TrueWave *REACH* fiber will still have benefits over G.652 fiber due to its lower chromatic dispersion and low PMD, enabling 10, 40 and even 100 Gb/s non-coherent system to perform optimally. What's more, the ultra low PMD and reduced

chromatic dispersion of TrueWave fiber enables lower OPEX in coherent higher speed systems, since less power is needed in the receiver to process the bit stream.

Note that Raman amplification has not been included in this study. The high Raman efficient gain in TrueWave *REACH* fiber can significantly improve performance in terms of OSNR and system reach.

Conclusion

We have shown that TrueWave *REACH* and TrueWave RS fibers with medium dispersion in many cases are excellent fiber choices for terrestrial transmission systems at 500-2000 km. 100 Gb/s systems will be available at different cost and complexity levels but in all cases low chromatic dispersion and low PMD are of value.

What does this mean for fiber selection? All fibers have certain "sweet spots" under which they perform optimally. Combined with the inherent uncertainty about the timing, pricing and availability of future transmission systems to be used on fiber deployed today, this fact point towards the selection of composite cables. For greenfield applications, OFS recommends a mixture of AllWave ZWP fiber and TrueWave REACH fiber.

In Figure 5, we provide a simple overview of the advantages of TrueWave fibers in various systems.

References:

(1) SURFnet deploys 100 Gb/s over 1650 km between Amsterdam and Geneva: The SURFnet link between NetherLight in Amsterdam and CERN in Geneva is an all-optical 100 Gb/s ULH link that extends over 1650 kilometers, with 23 fiber spans comprising a mixture of optical fiber types, i.e. 800 km of TrueWave RS fiber, 835 km of TrueWave *REACH* fiber and 20 km of AllWave fiber. No Dispersion Compensating Fibers were deployed in the link. The VTL fiber link was selected from

a number of links between Amsterdam and Geneva using a metric to optimize system OSNR performance. No RAMAN amplification is employed on the link. The Ciena 6500 Packet-Optical Platform was used in Amsterdam and Geneva using Dual Carrier 100 Gb/s DP-QPSK technology which occupies a single 50GHz channel window, creating high spectral efficiency.

(2) Non-coherent, direct detection 100 Gb/s system:
ADVA explains, "The 100Gbps metro card has half the cost of a 100 Gigabit coherent design while requiring half the power and space"
(http://www.gazettabyte.com/home/2011/9/8/100-gigabit-for-the-metro.html).

(3) ECOC 2011 paper: ***Colorless Coherent Receiver Using 3x3 Coupler Hybrids and Single-Ended Detection by Chongjin Xie1, Peter J. Winzer1, Gregory Raybon1, Alan H. Gnauck1, B. Zhu2, T. Geisler3, and B. Edvold3,*** *1. Bell Labs, Alcatel-Lucent, 791 Holmdel-Keyport Road, Holmdel, NJ 07733, USA, 2. OFS Labs, Somerset, NJ, 08873, USA; 3. OFS, Broendby, Denmark*. It is demonstrated that a single-ended colorless coherent receiver using symmetric 3x3 coupler hybrids works well in transmission over 2560 km TrueWave *REACH* fiber.

- **10 Gb/s transmission**

    Lowest systems cost opportunities
    Highest RAMAN gain

- **40 Gb/s transmission**

    Lowest systems cost opportunities
    Highest RAMAN gain
    Lowest systems PMD
    TrueWave has excellent performance
    TrueWave has high RAMAN gain

- **100 Gb/s non-coherent transmission**

    Very low residual dispersion
    Excellent unrepeated transmission length
    Highest RAMAN gain
    Lowest systems PMD

- **100 Gb/s coherent transmission**

    TrueWave can transmit more than 1500 km
    Most systems transmit at 0 dBm; only a marginal advantage from larger areas
    TrueWave with ultra low PMD offers energy savings opportunities
    TrueWave with low or medium dispersion offers energy savings opportunities
    TrueWave is designed for RAMAN amplification

- **Low Latency systems**

    TrueWave has proven value in low latency systems

Figure 5. Advantages of TrueWave fiber in various systems.