INTRODUCING *Lc*WDM™ – THE NEXT WDM TECHNOLOGY FOR THE CABLE INDUSTRY

Oleh J. Sniezko, Sudhesh Mysore, Charles Barker
Aurora Networks, Inc.

Abstract

*This paper presents a WDM technology for downstream HFC communication. The technology, trademarked as Lc***WDM™***, is a dense wavelength division multiplexing (DWDM) technology based on an extension of the ITU-T Recommendation G694.1*[1] *to the optical O-Band (1260 to 1360 nm).*

*An order of magnitude decrease in wavelength spacing (as compared to CWDM) allows all Lc***WDM™** *wavelengths to be within ±20 nm window about the nominal zero dispersion wavelength (λ_0) of standard SMF-28 type fiber (ITU-T G.652). This greatly reduces chirp-induced CSO due to fiber dispersion and allows for longer fiber spans.*

*This paper describes the various fiber phenomena – both linear and nonlinear – that limit the fiber distance and the number of wavelengths that can be supported by the two technologies (CWDM and Lc***WDM™***). Descriptions of the detailed testing of fiber nonlinearities and how they affect system performance as well as architectural applications of the Lc***WDM™** *system is also presented.*

*The Lc***WDM™** *system has been carefully engineered to ensure that the fiber dispersion and nonlinearities of a typical (SMF-28) fiber, prevalent in HFC optical node links, do not degrade the link performance below the acceptable levels.*

INTRODUCTION

Quest for Bandwidth Never Stops

The demand for bandwidth among the customers of the telecommunications network operators increases continuously. On the other hand, the telecommunications network operators today are looking at adding services and programming to increase revenue potential and to match the demand for HDTV channels. This trend includes addition of bandwidth capacity on fiber to serve residential and commercial customers. HFC broadband network operators are also facing competition from satellite operators in video services and from Telcos in all services. Two of the most leading challengers from this side are Verizon (FiOS) and AT&T (U-Verse).

The continuous demand for increased bandwidth capacity per user is forcing segmentation of the node areas into smaller service groups. In parallel to this trend, the expansion of urban areas force HFC new builds with many nodes deployed every year to serve areas that were not served previously. Both of these trends (demand for higher bandwidth per user and demographical expansion of urban areas) lead to increased demand for fiber capacity through new construction or more efficient fiber capacity utilization. The first choice, new fiber construction, may prove costly in areas already equipped with fiber (at least to the existing serving area boundaries) but which lack dark fiber. Even at modest construction cost per mile and average population density, the cost per household (served or not served) will amount to $150 and more. For downtown areas, this cost can be much higher, even prohibitively so.

The second choice is preferred as it is an order of magnitude lower in cost than the cost of new fiber construction. There are several technologies that improve the efficiency of fiber utilization. These technologies can help to free up fiber on fully occupied optical cable routes for segmentation, serving area expansion and even new service addition (SMB packages).

The most effective and mature technology that has been deployed by many operators is C-Band DWDM (1530-1565 nm) and its distributed DWDM version. This technology allows for practically unlimited narrowcast bandwidth (upper octave in any system, e.g., upper 500 MHz of narrowcast signal in 1002 MHz systems) on 40-plus wavelengths over a single fiber, supplemented by an additional broadcast wavelength on the same fiber. In addition to its highly efficient fiber utilization, this technology allows for practically unlimited distance (100 plus km up to the DOCSIS latency limits).

DWDM technology, aided by TDM in digital reverse links, has been used for increasing the efficiency of fiber utilization for upstream communication in long-distance or on extremely fiber-starved routes.

At the other extreme of the fiber utilization efficiency spectrum are single-wavelength systems: either 1310 nm directly modulated DFB laser links in downstream and upstream transport, which have limited distance of 40 km if no passive loss is present, or 1550 nm eternally modulated laser links in downstream communication.

The most recent WDM technologies that are being introduced by vendors for downstream HFC communication are CWDM and *Lc***WDM™**. These technologies try to close the gap between the two extremes described above.

The coarse wavelength division multiplexing (CWDM) technology was introduced to increase efficiency of fiber utilization in shorter fiber runs and where the lower number of wavelengths per fiber was sufficient. CWDM wavelengths are specified in an ITU-T Recommendation G.694.2[2]. This document specifies up to 18 wavelengths between 1271 nm and 1611 nm with 20 nm wavelength spacing. In most applications on older fiber with higher water-peak loss, only 15 wavelengths can be used.

This technology has been successfully used in the upstream path, both analog (40km links) and digital (where it is not distance limited to 40 km) and for digital downstream, providing Ethernet links (data, T1 over IP and VoIP) for SMB services.

Downstream CWDM versus *Lc***WDM™** Distance/Capacity Limits

In downstream communication, where the optical transmitters are used for transporting SCM (sub-carrier multiplexed) analog video and QAM signals, two major challenges significantly limit the use of CWDM technology[3]. One of them is the high level of dispersion (see Figure 1) in SMF-28 fiber at CWDM wavelengths other than 1311 nm. This fiber type has been dominant in access plant deployment in HFC networks. The high dispersion, resulting from the large 20 nm CWDM wavelength spacing, combined with the chirp of directly modulated laser transmitters, results in high levels of CSO. The other technical hurdle is the high level of crosstalk between CWDM wavelengths on the same fiber due to SRS (see Figure 2) and XPM phenomena.

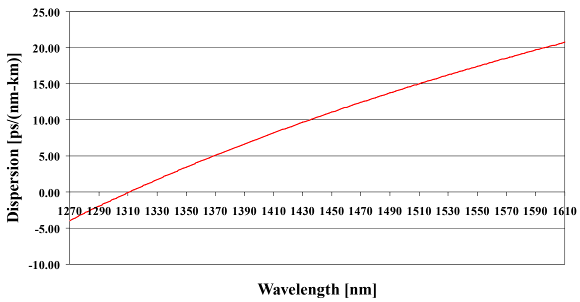
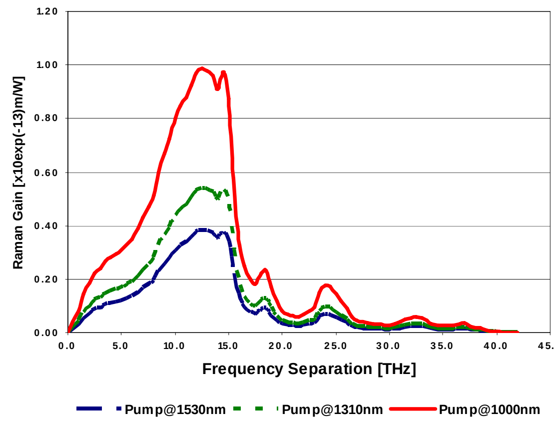


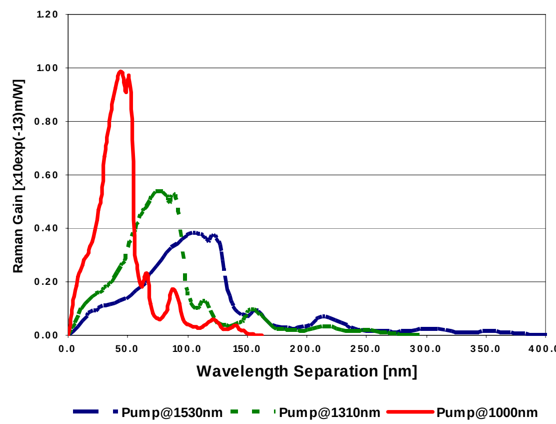
Figure 1: Dispersion Characteristics of SMF-28 Fiber

High dispersion limits the fiber span lengths to 15 km even for the two CWDM wavelengths closest to the nominal zero-dispersion wavelength. This limit can be increased only with sophisticated and complex dispersion compensation and/or mitigation technologies, which increase the cost of the transmitter. Use of very low chirp lasers, dispersion pre-distortion techniques (in distance intervals) and passive dispersion compensation techniques are a few examples. However, these are even more complex than techniques used in the DWDM systems described above as they have to be effective with analog channel load across the entire forward RF spectrum, which spans several frequency octaves. Moreover, some of the remedies increase sensitivity to other fiber induced impairments that require additional techniques to neutralize (e.g., low chirp lasers are subject to lower SBS threshold and higher IIN unless SBS suppression and IIN neutralization techniques are deployed).

SRS-induced crosstalk limits the total power allowed into the fiber for wavelength separations larger than 20 nm. Note that in a three-wavelength CWDM system, the separation between the two extreme wavelengths is 40 nm. Since SRS crosstalk increases in severity for larger wavelength separations (up to 13 THz frequency separation – equivalent to about 80 nm wavelength separation at 1310 nm and 110 nm wavelength separation at 1550 nm), this affects CWDM systems and further limits the allowed fiber distance (loss budget) in CWDM systems with more than two wavelengths.



a) Raman Gain vs. Wavelength Separation



b) Raman Gain vs. Frequency Separation

Based on G.P. Agrawal, *Nonlinear Fiber optics*, 3rd ed. (Wiley, New York, 2001), adapted from R.H. Stolen and E.P. Ippen, *Appl. Phys. Lett.*, 22, 276 (1973).

Figure 2: Raman Gain for Three Different Pump Wavelengths

An alternative technology, trademarked as *Lc***WDM™**, is based on extension of the ITU T.G694.1 standard to the optical O-Band (1260-1360nm). All wavelengths used in this system are within a ±20 nm window about the nominal zero dispersion wavelength (λ_0) of standard SMF-28 type fiber (ITU-T G.652). Each set of wavelengths is engineered for a total difference between the extreme wavelengths not to exceed 15 nm. This significantly lowers the rate of dispersion accumulation with distance and results in lower dispersion-induced CSO in longer fiber spans. Moreover, by placing all wavelengths closer together, SRS crosstalk is minimized even at low RF frequencies.

IMPAIREMNTS IN OPTICAL LINKS CAUSED BY LINEAR AND NONLINEAR FIBER PHENOMENA

Nonlinear and Linear Fiber Phenomena

Downstream HFC optical transport links involving analog video and digital video QAM SCM (subcarrier multiplexed) RF channels carry signals that are extremely sensitive to fiber effects that give rise to noise (CNR degradation) and nonlinear signal distortions – primarily second order, which results in CSO degradation. System degradation to varying degrees is observed due to the following linear and nonlinear effects:

1. Fiber Chromatic Dispersion (CD)
2. Interferometric Intensity Noise (IIN)
3. Fiber Nonlinearities
   a. Inelastic Scattering with Phonons
      i. SBS (Stimulated Brillouin Scattering)
      ii. SRS (Stimulated Raman Scattering)
   b. Nonlinear Refractive Index
      i. Cross-Phase Modulation (XPM)
      ii. Self-phase Modulation (SPM)
      iii. Four Wave Mixing (4WM)
      iv. Optical Kerr Effect and Polarization Dependent Loss (OKE/PDL)
4. Higher-order interactions of the above phenomena

The phenomena listed above are well described in the literature. This paper will focus on the impact they have on the performance of different optical link technologies and then concentrate on the *Lc***WDM™** technology based system performance in presence of those phenomena.

The dominant impairments caused by fiber in multiwavelength systems are crosstalk and second order RF distortions (CSO). The challenge in designing the multiwavelength system and its components (active and passive) is to minimize these two impairments while maintaining acceptable CNR, CTB and BER/MER performance of the transported signals. This is achieved by balancing the effects listed above.

Fiber Phenomena and Multiwavelength Optical Transport Systems

As mentioned above, the three major multiwavelength systems available (some of them widely deployed) for downstream links to optical nodes are:

1. 1550 nm broadcast with externally modulated lasers, together with 1550 DWDM narrowcast overlay on directly modulated lasers
2. CWDM directly modulated lasers
3. *Lc***WDM™** directly modulated lasers

Each of these systems is affected differently by fiber phenomena. Table 1 compares these impacts and lists some remedies implemented in these systems to limit or neutralize the contribution of the fiber phenomena to system performance degradation.

Table 1: Impact of Linear and Nonlinear Fiber Phenomena on Different Optical Transport Systems to Optical Nodes

Fiber Phenomenon	Its Impact on			
	1550 BC/1550 DWDM NC Overlay		CWDM	*Lc*WDM™
	1550 nm BC	1550 nm NC (40 wavelengths)		
Chromatic Dispersion	No real impact unless for very long distance (due to SBS suppression system)	Significant impact neutralized by frequency allocation and/or dispersion predistortion (cost impact). Other methods (e.g., selection of low chirp lasers) may require additional remedies.	Significant impact (no simple remedies, low chirp lasers may require SBS suppression circuitry and IIN suppression dithering)	No significant impact if laser chirp is optimized for both chromatic dispersion levels and fiber IIN
IIN	No impact (IIN is below the lower forward bandwidth frequency)	The same order of magnitude as for directly modulated 1310 nm DFB lasers	The same order of magnitude as for directly modulated 1310 nm DFB lasers unless low chirp lasers are selected to lower the impact of chromatic dispersion	The same order of magnitude as for directly modulated 1310 nm DFB lasers
SBS	Neutralized to the SBS threshold by SBS suppression methods	No impact for standard chirp lasers in the range of optical fiber launch powers	No impact for standard chirp lasers in the range of optical fiber launch powers	No impact for standard chirp lasers in the range of optical fiber launch powers
SRS	NA (other wavelengths have different RF frequencies)	No significant impact for QAM channels.	Significant impact for 3 and higher number of wavelengths per fiber	No significant impact on QAM channels and analog channels as long as analog channels are the same
XPM	NA (other wavelengths have different RF frequencies)	Not a dominant source of crosstalk	Not a dominant source of crosstalk	Contributes to crosstalk for lower separation wavelengths
4WM	No impact	No impact	Limited impact (under very unlikely scenario)	Measurable impact neutralized by the system design

MECHANICS OF DEGRADATION OF OPTICAL LINK PERFORMANCE

Chromatic Dispersion and Related Chirp Penalties

Chromatic dispersion refers to the variation in group velocity with wavelength. This characteristic is well-described by the Sellmeier equation, and a typical dispersion characteristic of SMF-28 fiber is shown in Figure 1.

Variations in group velocity with wavelength combined with periodic wavelength shifts due to laser chirp in a directly modulated transmitter results in CSO distortion of analog signals[4]. This dispersion/chirp-induced CSO increases very rapidly with dispersion, even for a 20km system, as shown in Figure 3. Several plots are shown for laser chirp (at 100% OMI modulation) ranging from 0.5 GHz to 10 GHz.

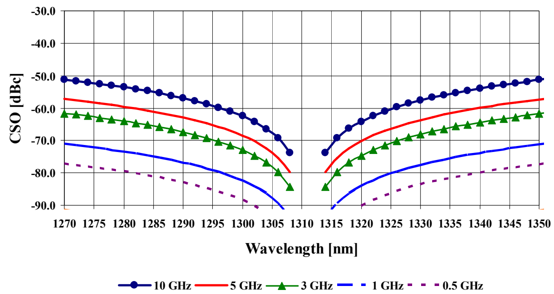


Figure 3: Chromatic Dispersion Accumulation with Wavelength (20 km of SMF-28 Fiber)

Note that even with CSO specifications relaxed to −60 dBc, CWDM systems are limited to three wavelengths (1291nm, 1311nm and 1331nm) due to dispersion/chirp-induced CSO for a typical 100% OMI laser chirp of 5 GHz for 8 dBm lasers. This is under the assumption that the average zero dispersion wavelength λ_0 in the link is equal to the nominal zero dispersion wavelength. The CSO will degrade further for one of the CWDM wavelengths if the λ_0 in the link is offset from the nominal value. Moreover, this CSO will cascade with optical link CSO generated by other mechanisms (including laser transmitter CSO).

Crosstalk Due to Stimulated Raman Scattering

SRS refers to optical gain experienced by one wavelength signal at the expense of another shorter-wavelength signal. Although the transfer of optical power is from the short-wavelength signal to the longer-wavelength signal, this transfer is modulated by the product of the optical power of both wavelengths, leading to leakage (crosstalk) of the RF signals in both directions at almost the same level. The coefficient of the product term is denoted by ***g***, the Raman gain coefficient. The Raman gain coefficient increases as the frequency difference between the two interacting signals increases, and reaches a peak at around 13 THz (see Figure 2a). Although the gain peak occurs at a fixed frequency difference of 13 THz when plotted against frequency shift, the position of the peaks vary for different pump wavelengths (i.e., the shorter of the two interacting wavelengths) when plotted against wavelength shift as in Figure 2b. The Raman gain increases for wavelength separation up to 80 nm for a pump near 1310 nm, and up to 110 nm for a pump near 1550 nm. Furthermore, the amplitude of the Raman gain decreases according to well-known scaling rules as the pump wavelength moves towards longer wavelengths as shown by the three curves in Figure 2b.

SRS-induced crosstalk can be extremely high at low RF frequencies as shown in Figure 4 for 55 MHz. For typical system parameters (+10 dBm/ch launch power, 1310 nm pump, 25 km fiber distance) the SRS-induced crosstalk can exceed −40 dBc for wavelength separations larger than 30 nm.

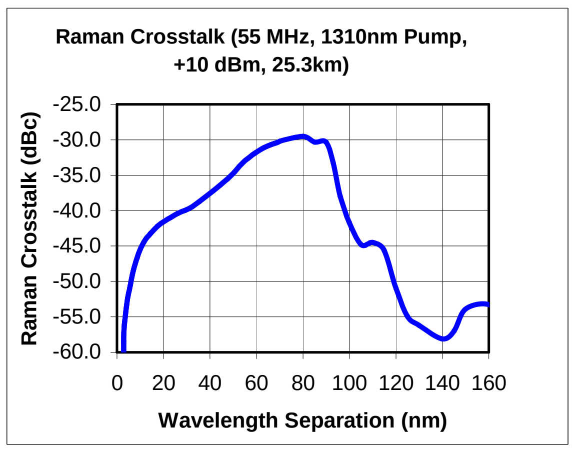


Figure 4: SRS-Induced Crosstalk

Cross-Phase Modulation (XPM)

At high RF frequencies (around 500 MHz) and small wavelength separation, the crosstalk does not vanish as predicted by Figure 4 due to the effect of another fiber nonlinearity, namely cross-phase modulation (XPM). This nonlinearity is caused by the nonlinear refractive index – modulation of the fiber refractive index – which causes modulation of one wavelength to induce phase changes in the other wavelengths. This induced phase modulation in conjunction with fiber dispersion results in crosstalk from one wavelength to another.

Fiber dispersion is therefore a necessary ingredient for XPM-induced crosstalk; XPM-induced crosstalk increases with increasing fiber dispersion and decreasing wavelength separations. Like other refractive index nonlinearities, XPM-induced crosstalk depends strongly on the group velocity mismatch (or "walkoff") between the affected wavelengths, which is approximated by the product of the fiber dispersion times the wavelength separation.

The actual crosstalk observed in a multiwavelength system depends on the relative magnitude and phase of the SRS-induced and XPM-induced crosstalk[5]. While optical crosstalk from other wavelengths appear at the same location (under each analog carrier) as CTB distortion (which arise from other RF carriers in the same optical wavelength), the CTB can be differentiated from the crosstalk as it is composed of a large number of discrete RF beat products that are slightly offset from each other.

At this high level of crosstalk (see SRS crosstalk in Figure 4 and XPM crosstalk addition), two major network design limitations must be observed:

1. All analog signals on multiple wavelengths on the same fiber must be the same (the same content at the same frequencies). This limitation allows for lowering the requirements for crosstalk levels.

2. Even for the same signals, multipath effect must be accounted for (from Figure 5, for −35 dBc of crosstalk, only 100 to 250 ns differential delay is allowed for signals traveling on different wavelengths on the same fiber – this translates to 80 to 200 feet of a typical RF cable in the headend combining network).

Four Wave Mixing (4WM)

Four-wave-mixing is another result of the fiber refractive index nonlinearity that results in three optical signals at distinct frequencies f_i, f_j, and f_k interacting as they propagate along a fiber to give rise to a fourth optical signal at frequency $f_{ijk} = f_i + f_j - f_k$ – similar to a third-order "beat product" in RF systems. The mixing product at frequency f_{ijk} is said to be non-degenerate if $i \neq j \neq k$ (i.e., the mixing product is generated by three distinct signals). It is possible for 4WM to occur with only two optical signals present (at frequencies f_i and f_j), giving rise to a so-called "partially-degenerate 4WM" (PD4WM) products at frequencies f_{iij} and f_{jji}.

The mixing efficiency of the 4WM process is maximized when the phase-mismatch parameter is zero. The relative 4WM power P_{ijk}/P_{out} generated by three polarization-aligned signals with the same fiber launch power P_{in} and fiber output power P_{out} can be easily calculated from a simple equation[6]. The same slightly modified equation can be used for the case of PD4WM mixing products.

The equations for the mixing products are valid only so long as they are small enough that the "pump power" in the original signals is not depleted. Even so, they predict that very large mixing products can be generated at power levels of +10 dBm/ch if the fiber dispersion is low since the corresponding phase-mismatch parameter is then also small.

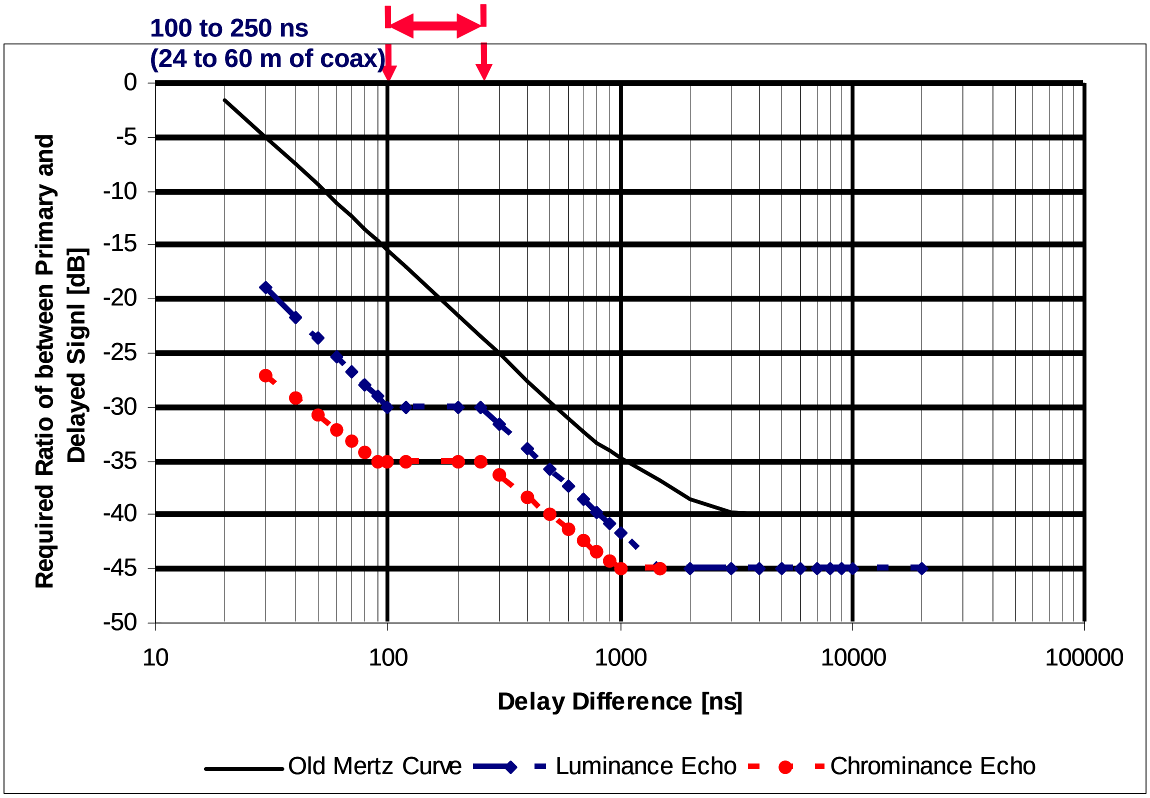


Figure 5: Echo Tolerance Curves for Color TV Programming Displayed on Large Screen (Based on Rogers Published Test Results – Gary Chan and Nick Hamilton-Pierce and in Line with Dan Pike's[7] Published Test Results)

Figure 6 shows the calculated power levels of 4WM and PD4WM mixing products as a function of the phase-mismatch parameter for +10 dBm/ch launch power and 20 km fiber distance.

Note that relative mixing products as high as –20 dBc can be generated if the system is not designed properly. Figures 7a and 7b show the input and output spectra, respectively, of an actual 5-wavelength system, demonstrating that such high levels of 4WM and PD4WM can indeed be obtained in not optimized systems.

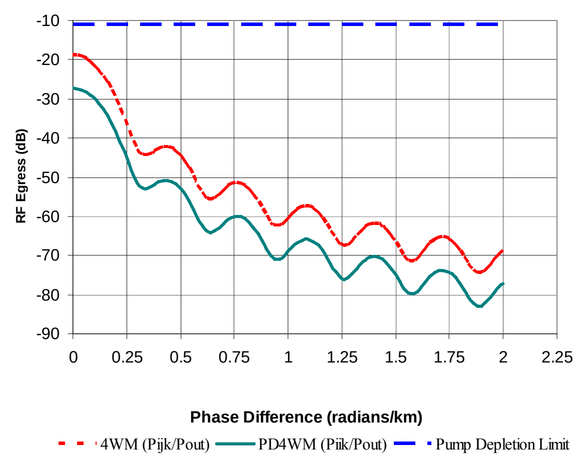
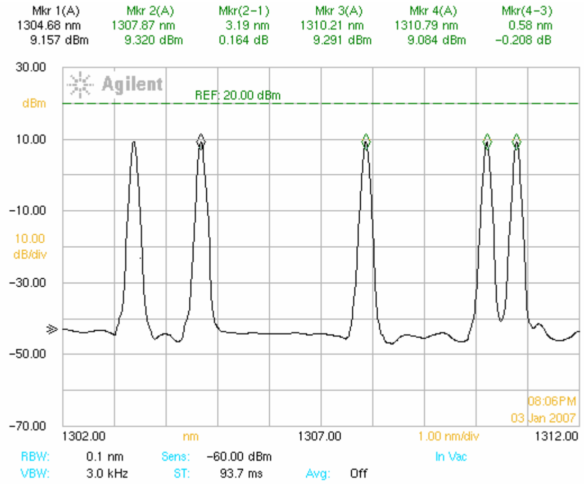
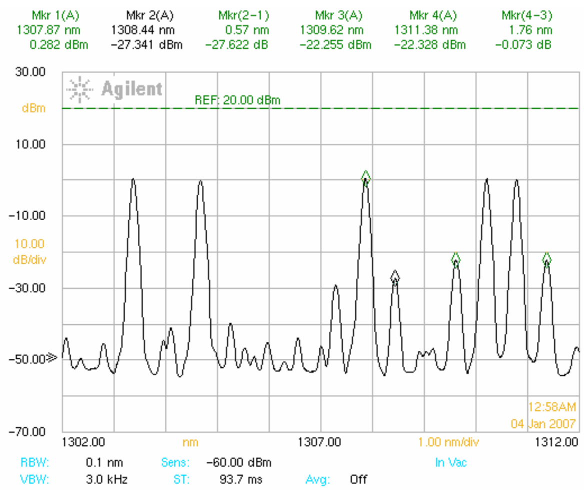


Figure 6: Dependence of 4WM and PD4WM products on phase-mismatch parameter.



a) Input Signals



b) Output Signal Spectrum

Figure 7: Spectra of 5-Wavelength System with High Levels of 4WM and PD4WM Products

With N=5 wavelengths, there are a total of N2(N-1)/2 = 50 mixing products generated. Even though it is possible to design the system so that none of the mixing products fall on any transmission wavelength and hence there is no crosstalk caused by ingress of 4WM power into any wavelength, there will still be egress of power out of each wavelength.

In fact, each wavelength is supplying power into a total of (N-1)∗(3N-2)/2 = 26 mixing products. Since this egress power is proportional to $P_iP_jP_k$, where each of the P term is composed of 79 analog channels, egress of power out of a wavelength generates a multitude of second and third order intermodulation distortion products and degrades the CSO (and to a lesser extent, the CTB) performance of the wavelength.

*Lc*WDM™ SYSTEM TEST RESULTS

Test Setup

*Lc*WDM™ systems with two to eight wavelengths were tested in a setup similar to that presented in Figure 8. Each transmitter is loaded with 79 channels of CW carriers from 54 to 552 MHz and 75 channels of 256-QAM signals from 552 1002 MHz. Matrix 1 is used to drive the wavelength under test while Matrix 2 drives the other transmitters with other wavelengths (all wavelengths are tested for performance). This is necessary to measure crosstalk from the other optical wavelengths due to SRS, 4WM and XPM. If it is desired to test only the CTB for the particular wavelength, then the same signal source can be connected to all transmitters.

A polarization controller is attached to each transmitter and the worst-case settings are found prior to each measurement. Testing was performed on several dozen spools of fiber covering a wide range of fiber parameters.

Initial testing started with just two wavelengths in order to test the basic theory. With just two wavelengths present, it is quite easy to model the performance of each wavelength. This allows calculating the strength of each mixing products, in which the particular wavelength is involved and hence the CSO and CTB degradation contribution of each of them. The baseline performance of each single wavelength without fiber is used as a reference.

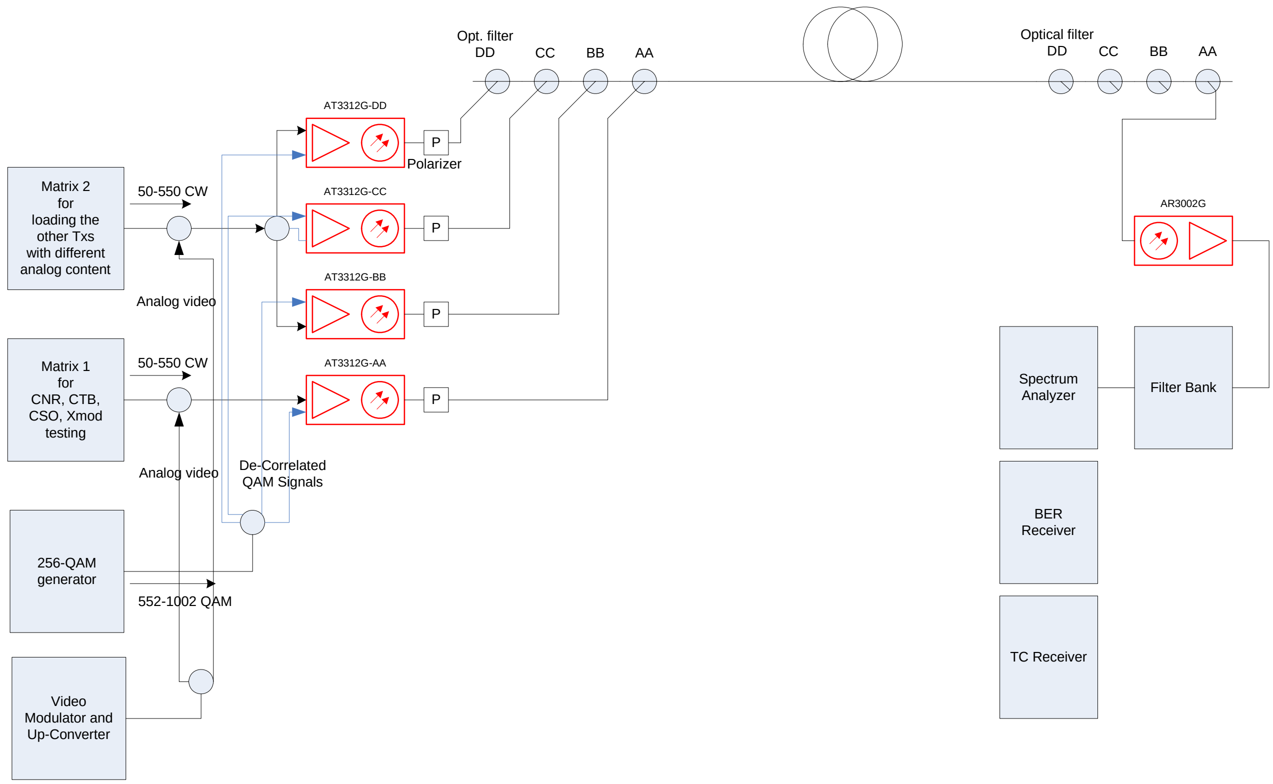


Figure 8: Test Setup for Multi-Wavelength *Lc*WDM™ System

Figure 9 shows a 3-D surface that describes the strength of the PD4WM products for a system where one channel is fixed at λ_2=1308 nm. The x-axis is the zero-dispersion-wavelength λ_0 and the y-axis is the wavelength λ_1 of the second channel. The fiber distance has been assumed to be 25 km and the power level to be +10 dBm/ch.

Note that as the phase-mismatch approaches zero, PD4WM product power rises sharply. Also, when wavelength separation is small, the PD4WM power remains high over a much larger range.

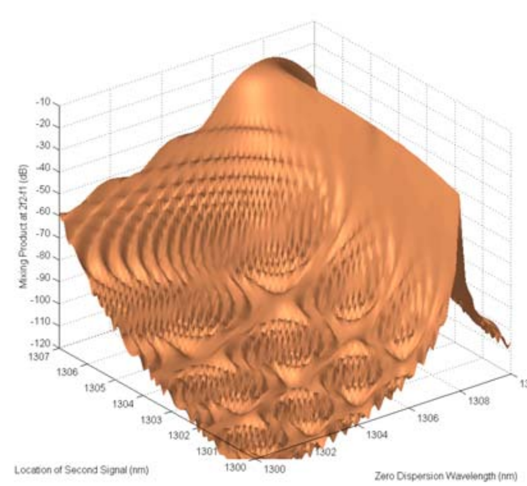


Figure 9: Modeling PD4WM Power

Figure 10 shows the results of testing with a fixed wavelength at λ_2=1311.5 nm. The x-axis is the wavelength λ_1 of the second channel, which is varied from 1307 nm to 1314 nm. Good correlation is seen between the observed PD4WM power and the calculated values.

Figure 11 shows the same system but over a different fiber. Measurements are made as λ_1 is varied from 1307 nm to 1314 nm. Again, there is very good correlation between theory and measurements. Note also that the PD4WM power level remains high over a much wider range of λ_1 values.

Tests on 3-, 4-, 5- and 6-channel systems also showed very good agreement with theoretical models. The tests will be also expanded to 8 wavelengths.

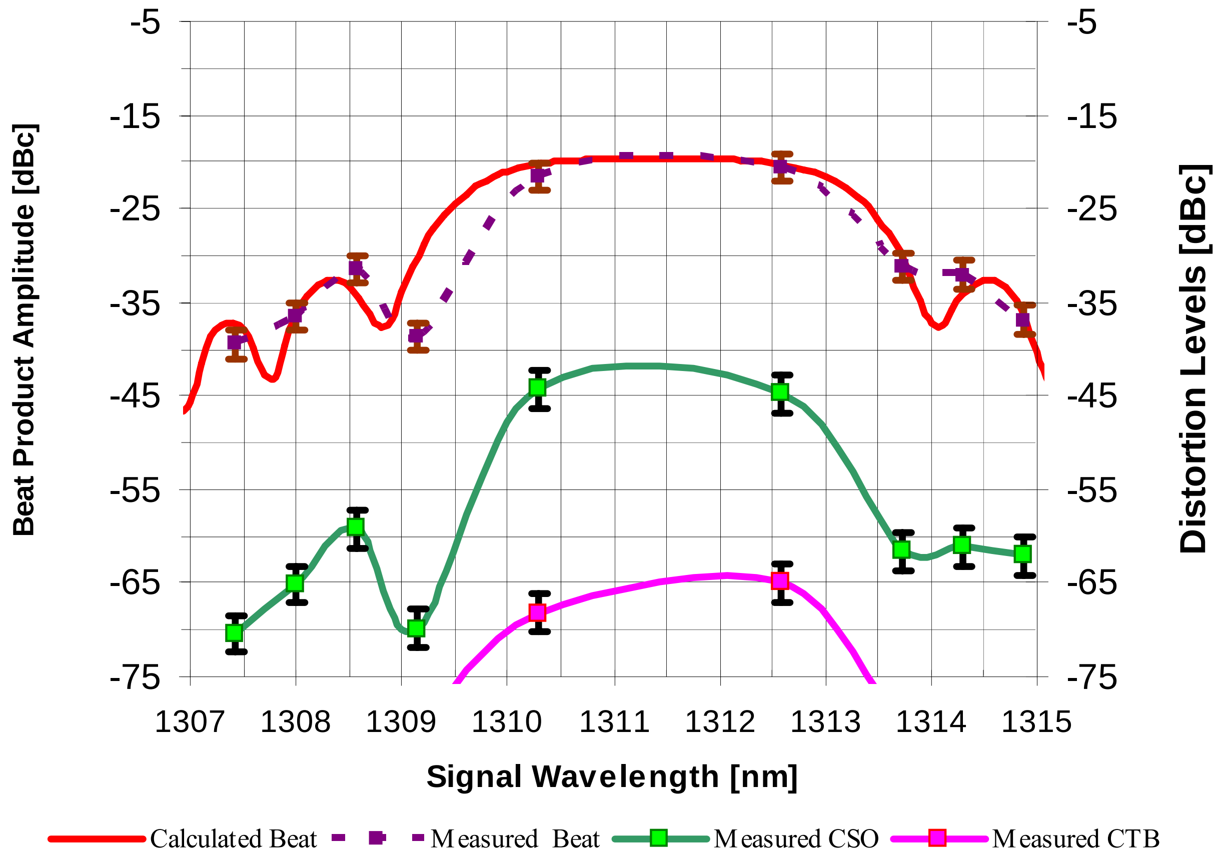


Figure 10: PD4WM Power versus Wavelength Separation on Fiber with Distant λ_0

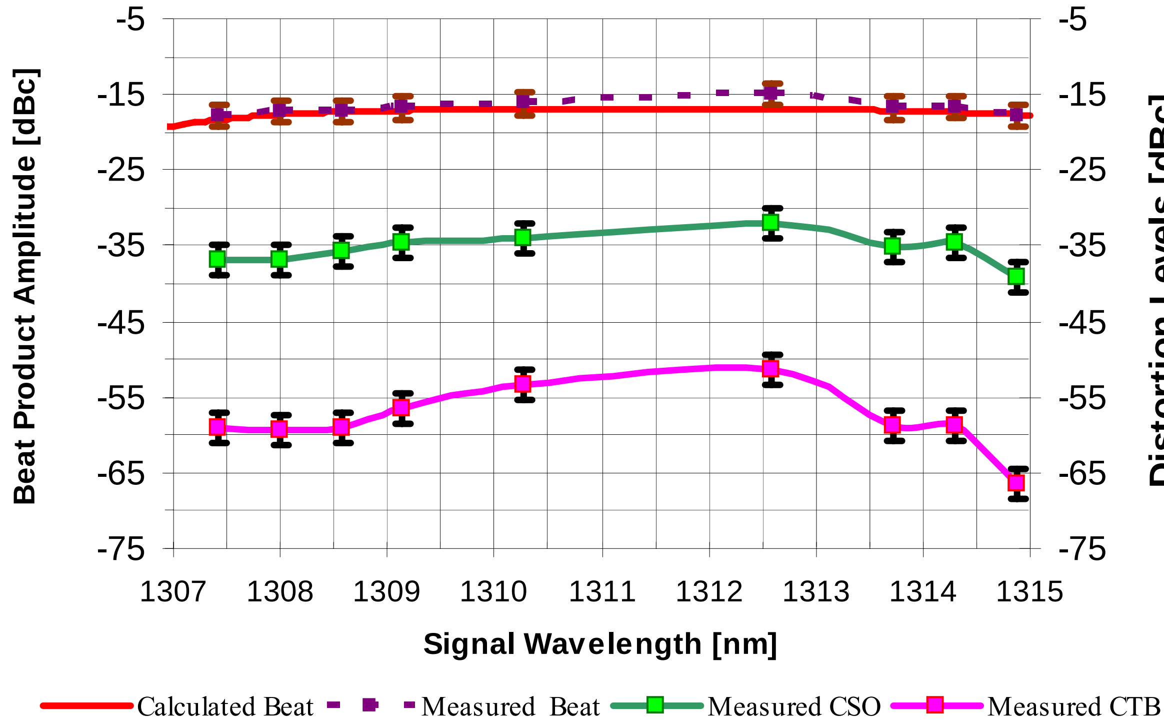


Figure 11: PD4WM Power versus Wavelength Separation on Fiber with Close λ_0

*Lc*WDM™ SYSTEM DESIGN CHALLENGES

The *Lc*WDM™ design took into account the theoretical modeling results and extensive testing results of the nonlinear and linear fiber phenomena and their effect on analog and digital QAM signal performance transmitted on multiple wavelengths. Two major parameters that posed the design challenges were crosstalk and second order (CSO) distortions. The *Lc*WDM™ system was optimized to meet the requirements for these two parameters while securing acceptable performance for CNR, CTB and MER/BER. Achieving this goal required balancing the fiber effects described previously[8].

Crosstalk

Three major fiber phenomena cause inter-wavelength crosstalk:

1. SRS
2. XPM
3. 4WM ingress

The optimization of the first two is difficult as the requirements to minimize SRS crosstalk most of the time conflict with the requirements to minimize XPM crosstalk. Fortunately, SRS crosstalk is highest at lower RF frequencies and XPM crosstalk is highest at highest RF frequencies. Moreover, *Lc*WDM™ system has a significant advantage as the separation between wavelengths are relatively small (in comparison to CWDM system) and hence SRS crosstalk is low while XPM crosstalk affects mostly QAM channels. As long as the two assumptions:

1. All analog signals on multiple wavelengths on the same fiber are the same, and
2. Multipath effect is accounted for;

(as explained above) are met, these two effects do not limit the application of the system. Moreover, the third effect is completely eliminated by *Lc***WDM™** system design. Additional contributors to crosstalk (e.g., OKE-PDL interaction) are being controlled by system component selection and specification.

Second Order Distortions (CSO)

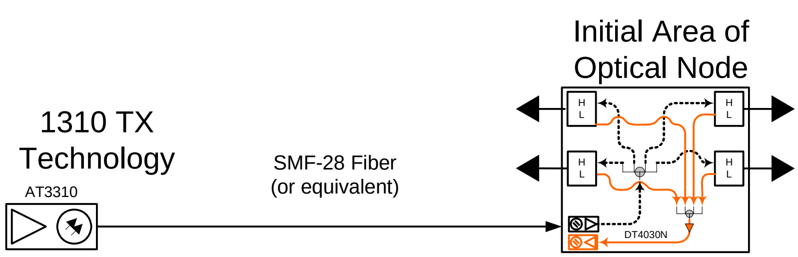
Two major phenomena contribute to degradation of the CSO in analog multiwavelength links:

1. Linear effect of chromatic dispersion resulting in chirp-related penalty, and
2. 4WM egress.

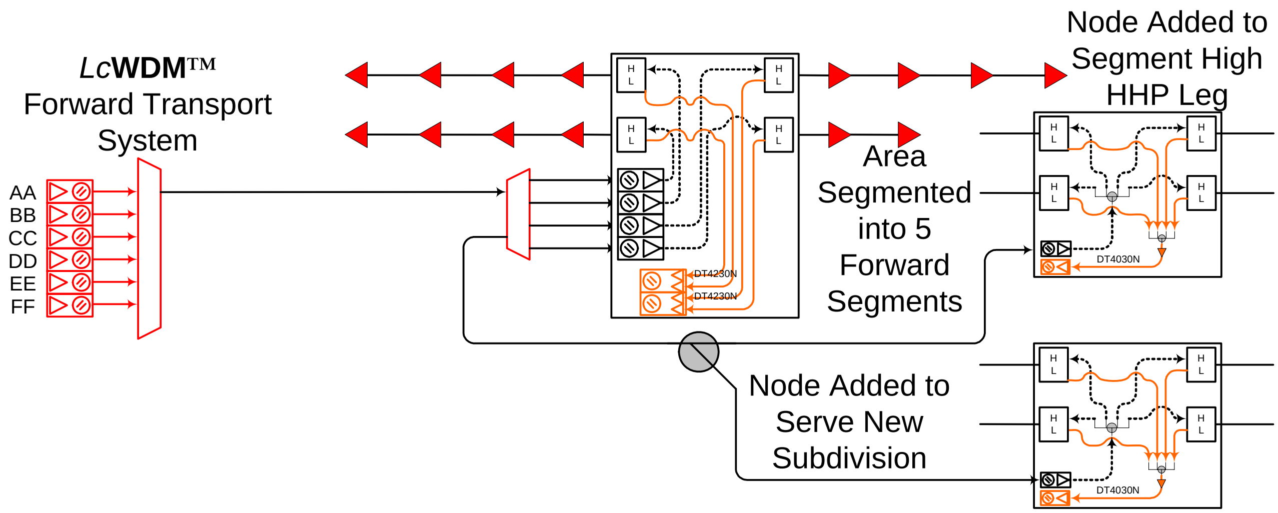
The first effect is minimized in *Lc***WDM™** system by the proximity of the wavelengths to the zero-dispersion-wavelength λ_0 of SMF-28 fiber that is predominant in optical links to the nodes. Moreover, the laser chirp is managed to optimize both CSO and IIN contribution. The second effect is minimized by the system design. The 4WM egress in extreme cases causes CTB degradation but if the CSO degradation is under control, CTB degradation is negligent (see Figures 10 and 11).

APPLICATION OF *Lc***WDM™** SYSTEM FOR NODE SEGMENTATION AND SERVICE AREA GROWTH

Figures 12 illustrates the use of *Lc***WDM™** technology for downstream transport in conjunction with CWDM technology and digital technology for upstream transport to segment an initial node into 5 forward and reverse segments using only two fibers. Additional node is added to split a node leg that served a high number of households. Sixth node is added (in future) for the new growth area. The upstream fiber is not shown here but at the discretion of the operator, the same fiber that is used for downstream transport can be used for upstream transport (see Figure 13). Alternatively, the second fiber can be used for upstream transport (this will yield longer reach as combining and de-combining filter loss is eliminated from the downstream path).



a) Initial Node Service Area



b) Node Service Area Segmented into Fiver Areas with 6^{th} Node Added to Serve New Subdivision

Figure 12: *Lc*WDM™ System Applied for Area Segmentation and Service Area Expansion

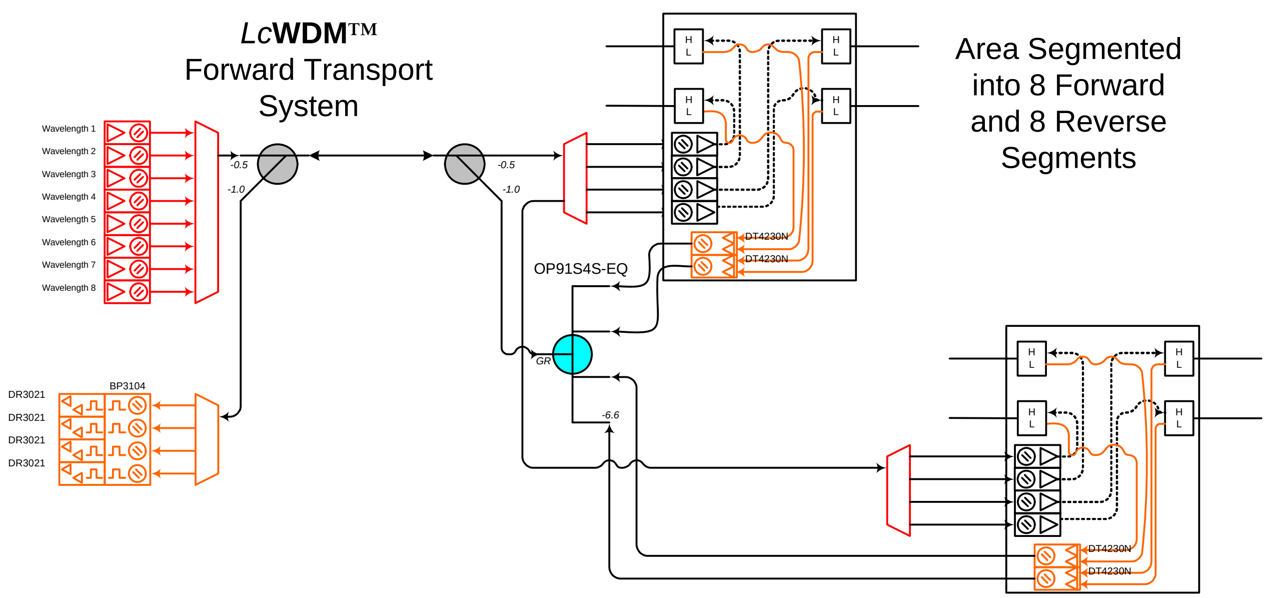


Figure 13: *Lc*WDM™ Downstream System in Combination with CWDM/Digital Upstream System to Serve 8 Forward and 8 Reverse Segments on Single Fiber

CONCLUSIONS

*Lc*WDM™ systems close the performance and cost gap between single wavelength optical links based on 1310 nm directly modulated DFB laser technology and DWDM 1550 nm systems based on externally modulated technology for broadcast links and directly modulated DFB technology for narrowcast overlay. They are much more immune to both SRS-induced crosstalk and dispersion-induced CSO than CWDM systems. This allows for extending their reach and increasing the number of wavelengths per fiber. The fiber length dispersion limits are doubled. The *Lc*WDM™ systems allow for cost-efficient node area segmentation on a single fiber. In combination with CWDM (15 wavelengths after exclusion of water peak and 12 wavelengths after exclusion of CWDM windows occupied by *Lc***WDM™** wavelengths traveling on the same fiber) and digital TDM technology in upstream, *Lc***WDM™** systems can support 6 to 8 forward segments and 24 upstream segments on a single fiber. This allows not only for segmentation of the area but also for node addition in the growth areas without the need for fiber construction on the existing fiber routes. In fact, it allows for fiber recovery to support commercial and other services and generate incremental revenue.

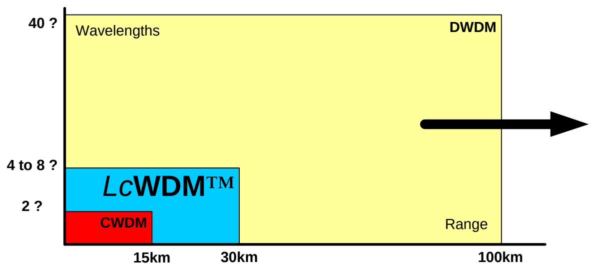


Figure 14: Capacity/Distance Limits of Various WDM Technologies for Downstream HFC Optical Transport

A critical advantage of the technology described in this paper is its simplicity. The transmitters carry entire forward load from 54 to 1002 MHz on the same wavelength and in this sense are equivalent in operation to 1310 nm directly modulated DFB transmitters. The *Lc***WDM™** system design follows the same rules as the design of a system with 1310 nm DFB lasers, taking into account the required input level to the node and power budget of the link (including fiber and passive component losses). After accounting for these design rules, the 30 km fiber length limit is rarely reached if more than two wavelengths are used for downstream transport.

ACKNOWLEDGMENTS

The authors wish to express deep gratitude to Shamino Wang, Samuel Chang and Ricardo Villa of Aurora Networks, who spent hundreds of hours testing all aspects and components of the *Lc***WDM™** systems. Without their dedication, the systems would have taken much longer to develop since its conception in May of 2006. The authors also appreciate the support of the Aurora operations team in building countless iterations of the system components. Extreme gratitude also goes to Wim Mostert who first coined the idea in casual conversation on the way between the Aurora headquarters and the company rental apartment. After peeling the layers and analyzing all possible pitfalls, we realized we have a jewel on our hands, technology that benefits the entire industry.

---

[1] ITU-T G.694.1 (2002), *Spectral Grids for WDM Applications: DWDM Frequency Grid*
[2] ITU-T G.694.2 (2002), *Spectral Grids for WDM Applications: CWDM Wavelength Grid*
[3] T. Werner and O. J. Sniezko, *Exploiting HFC Bandwidth Capacity To Compete With FTTH*, 2006 NCTA Technical Papers
[4] M. R. Phillips, T. E. Darcie, D. Marcuse, G. E. Bodeep, and N. J. Frigo, *Nonlinear Distortion Generated by Dispersive Transmission of Chirped Intensity –Modulated Signals*, IEEE Photonics Technology Letters, Vol. 3, No. 5, May 1991
[5] M. R. Phillips and D. M. Ott, *Crosstalk Due to Optical Fiber Nonlinearities*, Journal of Lightwave Technology, Vol. 17, No. 10, October 1999
in WDM CATV Lightwave Systems
[6] R. W. Tkach, A. R. Chraplyvy, Fabrizio Forghieri, A. H. Gnauck, and R. M. Derosier, *Four-Photon Mixing and High-speed WDM Systems*, Journal of Lightwave Technology, Vol. 13, No. 5, May 1995
[7] D. Pike, *The Effects of Reflections*, 1989 NCTA Technical Papers
[8] H. A. Blauvelt, P. C. Chen, N. Kwong, I. Ury, *Optimum Laser Chirp Range for AM Video Transmission*, 1992 NCTA Technical Papers