Optical Transmitter Technology for Next Generation Access Networks

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Abstract

Initial Docsis 3.0 deployments increased during 2010 and are expected to accelerate rapidly over the next two to three years putting pressure on cable operators to allocate bandwidth in both the downstream and upstream paths. The number of added narrowcast QAM channels continues to steadily increase as a result of SDV deployments and the shift to HD content. The anticipated introduction of CMAP (Converged Multi-media Access Platform) equipment estimated for 2012 is also expected to dramatically amplify the need for even higher numbers of additional QAM channels and with it the requirements for a cost effective means to deliver these channels to smaller node serving areas and targeted customers. On top of this, new business services opportunities, cell tower backhaul, and WiFi access point deployments require a growing share of plant access network capacity.

The need for more bandwidth never sleeps which causes more than a few cable system operators to lie awake at night as they try to determine which of the numerous alternatives to meet this never ending challenge is the most cost effective and future proof. The consensus has gradually shifted away from the traditional path of expanding plant RF bandwidth and is now moving to take advantage of the broad WDM segmentation capacity of existing fiber. Facilitating this change is a wide range of fiber architectures and Headend optical transmitter technologies ranging from expanded capability QAM lasers to new 10 Gb devices that provide a bridge between today's analog / QAM transport requirements and the high speed IP delivery needs of the future.

This paper provides a comparison of these currently available laser transmitter technologies identifying the differentiating features and limitations of each design type along with link application examples. The impact of the all digital channel loading transition and converged services on the performance, reach, and network cost using these technologies will also be examined.

INTRODUCTION

The common complaint of most cable operators today regardless of size is that they are nearly out of downstream bandwidth. The growth of DOCSIS® services for small business and home office customers and the popularity of streaming video and downloading movies over the internet is stretching the available data capacity of existing nodes. At the same time the forecasted requirements for new Narrowcast (NC) channels is 2 to 3 times the number allocated in current systems.

The traditional path for expanding cable access bandwidth has always been to manipulate the available RF spectrum. Until recently this was accomplished through expensive wholesale upgrades of the access plant equipment extending the high frequency edge of the band to the current 750 MHz, 870 MHz and even 1 GHz networks that exist today. This approach was driven primarily by the broadcast analog video channel loading that is still considered by many MSO's to be a major positive differentiator between HFC cable and competitor systems.

The introduction of digital QAM channels provided more efficient use of the 6 MHz RF channel space allowing 10 to 15 standard definition digital video programs or 2 to 3 HD programs per downstream channel. Digital technology also opened the door to video on demand (VOD), high speed data (HSD), and other narrowcast services that could be targeted to specific subscribers or smaller serving areas within the MSO network. This actually caused a further increase in the number of possible channels and the pressure for more access plant bandwidth.

The cost and disruption of cable plant upgrades in order to increase bandwidth has created an adverse environment for the shares of publically traded cable companies. This has driven cable operators to implement a number of alternative, lower cost, incremental solutions including reclaiming analog channels, deploying Switched Digital Video (SDV) systems, and when necessary, selective node splits. These options have helped to extend the life of the current legacy HFC networks but the need for more bandwidth continues to accelerate. The potential cost / benefit gains from further RF bandwidth enhancements are limited. As a result, cable operators have shifted their focus and are now actively evaluating optical segmentation solutions that will provide increased BW per subscriber plus enable business services growth by reclaiming fiber for point to point applications such as cell tower backhaul. The technologies that offer these benefits are described in the following sections.

The Evolution of HFC Optics

Today's HFC optics are primarily dominated by point to point fiber links transporting the full downstream program channel load from hub to node over a single 1310 nm wavelength. Upstream traffic utilizes a second fiber in most common configurations. The selection of 1310 laser transmitters to transport a full spectrum of analog video and QAM signals is not a coincidence. The commonly deployed fiber in HFC networks is SMF28. This fiber type is a recognized standard with characteristics defined by ITU-T G.652 and numerous other standards organizations. An important property of SMF fiber is its zero dispersion value at 1310 nm. By operating in a zero dispersive media the detrimental effects of DFB laser chirp are completely mitigated improving the distortion performance of the link.

1310 DFB lasers are the workhorse of current HFC networks. The linearity of these devices has been optimized over many years such that the analog distortions are well controlled and with simple predistortion correction, meets and exceeds the requirements for end of line performance. 1310 DFB lasers are available in a wide range of output levels typically up to 15 dBm. This is sufficient for link reaches of at least 40 km based on the average 0.35 dB / km attenuation of SMF28 fiber. As long as additional fiber is available, segmenting traditional 1310 HFC networks is accomplished by adding new hub transmitters and node receivers connected using dedicated fibers as depicted in Figure 1 below.

Figure 1 – Typical 1310 Hub to Node Downstream Optics

For link distances longer than 40 km or areas that have limited available fiber, Broadcast / Narrowcast overlay networks have been deployed. In an overlay network all broadcast channels are carried by one transmitter on a dedicated fiber. A second fiber transports multiple DWDM wavelengths each carrying a unique set of narrowcast channels. The broadcast and demuxed narrowcast wavelength are combined at the node to reconstruct the full RF spectrum of channels. Figure 6 shows the connection details for the overlay architecture. The overlay design while complex is very fiber efficient. With relatively light narrowcast channel loads (up to ~30 channels) the DWDM overlay architecture can easily support 40 nodes on only 2 fibers. The overlay design also takes advantage of the lower (0.25 dB / km) fiber attenuation at 1550nm and the availability of EDFA's to further extend the reach compared to 1310 nm links.

As forecasted growth of VOD and internet traffic continues to accelerate, cable operators once again need to increase data capacity available per subscriber. Competition from FTTX suppliers also is driving many systems to enhance data capacity of their networks. To accomplish this, node serving areas have to be reduced. Additionally, many operators have begun to explore commercial services opportunities by addressing businesses that are within a few kilometers of an existing node. Each of these requirements potentially need additional allocated fiber. Unfortunately, a limiting factor in all HFC networks is the amount of available dark fiber. Meeting the network segmentation and business services needs without the major expense of pulling new fiber spurred the development of multi-wavelength optics.

Multi-wavelength Analog Optical Impairments

Optical Distortion

In order to understand the advantages and trade-offs of different multi-wavelength schemes it is important to recognize the various fiber distortions that can occur in these applications. The following is a brief explanation for the primary fiber induced distortions that affect WDM optical networks.

Stimulated Brillouin Scattering

Stimulated Brillouin Scattering (SBS) is a nonlinear interaction between laser light and the molecular structure of the fiber which generates acoustic waves causing a variation in the index of refraction corresponding to the intensity of the wave. This causes partial scattering of the light in the backward direction from the resultant index diffraction gratings. This can produce an avalanche effect if the intensity of the light is high enough, resulting in high attenuation and induced noise in the forward direction. This acts as a limiting factor as to how much power can be launched into fiber for single wavelength transport. Since the bandwidth in which this scattering process can take place is very narrow, the threshold power needed to initiate this effect can be raised significantly by widening the optical linewidth of the source. This can be accomplished through various methods of dithering the laser, either directly or indirectly, causing a spread in the optical spectrum beyond that of the Brillouin bandwidth (tens of MHz depending on the fiber characteristics). Since this linewidth spread can result in performance degradation when operating in the highly dispersive 1550 nm region of standard fiber, most externally modulated transmitters use some method of phase modulation using single or multiple high frequency tones to effectively breakup the optical signal into a number of separate carriers, each at a reduced level from the original spectra in which case the highest of these individual modes sets the SBS threshold.

Taking advantage of the mitigation techniques described above and with other more significant effects highly contingent on wavelength parameters, SBS would not be a major factor in determining optimal multi-wavelength schemes.

Raman Crosstalk

Stimulated Raman Scattering (SRS) is a nonlinear parametric interaction between laser photons and the molecular structure of the fiber which causes partial inelastic scattering of the light signal due to excitation. The scattered light is shifted downward in frequency (upward in wavelength), corresponding to the molecular vibration frequency, which results in energy transfer between the original wavelength and the generated scattered wavelengths. If additional wavelengths are within the range of the newly generated scattered photons, crosstalk will occur. The triangular shape of the Raman gain (excitation) profile peaks at a wavelength spacing of approx. 100 nm so while the magnitude of the Raman coefficient is much smaller than that of the Brillouin coefficient, it's bandwidth of influence is much wider. Since the ITU grid DWDM wavelengths are usually spaced 100 or 200 GHz apart (approximately 0.8 and 1.6 nm respectively at 1550 nm), it's a major source of crosstalk in a multi-wavelength system.

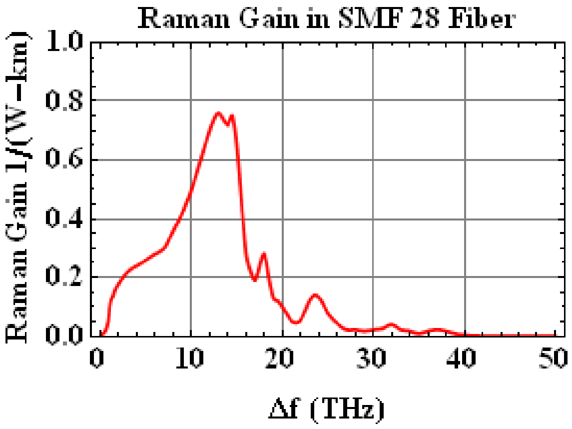


Figure 2 – Raman Gain Profile.
20 nm ≃ 3.4 THz

Chromatic Dispersion

Chromatic dispersion or group velocity dispersion is caused by a variation of the group velocity in fiber as a function of optical frequency. The chromatic dispersion of standard SMF-28 fiber at 1550 nm is approximately 17 ps/nm/km. When an intensity modulated transmitter with high laser chirp (change in optical frequency vs. modulation) is exposed to dispersive media, the incidental frequency modulation is converted to intensity modulation, which mixes with the original intensity modulation and leads to the generation of intermodulation distortion with 2nd order distortion being the most harmful. The impact of dispersion is greatly reduced if the transmitter has very low chirp. Additionally, the effects can be removed through the use of electronic delay circuit compensation or dispersion compensating fiber (DCF) with equivalent and opposite dispersion characteristics.

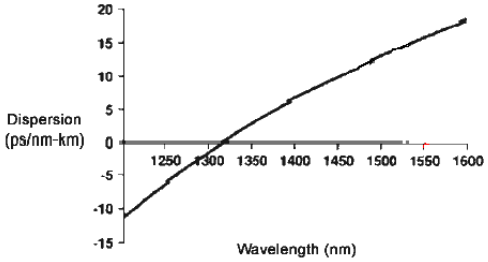


Figure 3 – Dispersion as a function of wavelength for single mode fiber

Crossphase Modulation

Cross-Phase modulation crosstalk is due to the non-linear index of refraction of fiber. The modulation power from one channel causes a small change in the index of refraction which results in a phase modulation of each channel traveling through the fiber. Chromatic dispersion due to the fiber then converts the phase modulation into an amplitude modulation. Cross-phase modulation tends to increase as the spacing between wavelengths decreases and the distance traveled increases.

Four Wave Mixing

Four-wave mixing (FWM) is a 3rd order non-linearity, comparable to the CTB intermodulation effect exhibited in electrical systems, due to the power sensitive refractive index of optical fiber. FWM occurs when multiple wavelengths interact and generate mixing products that fall at one or more of the existing channels, which in turn generates crosstalk at those channels. Four-wave mixing is most troublesome in systems that launch at high powers and utilize a large number of densely packed wavelengths in low dispersion environments.

Raman 2nd Order Distortion

Another potential limitation to using single transmitters for full spectrum BC and NC channels in a multi-wavelength transport has been the enhanced CSO distortions generated due to second order multiplicative effects of the parametric interactions between the various wavelengths due to Raman scattering.

Raman generated CSO is a function of the wavelength spacing, fiber distance and optical launch levels into fiber. The effect is typically strongest at the lowest frequency channels with higher frequencies having the mitigating benefit of dispersion induced walk-off effects.

Modeling shows that even with only two wavelengths, there is a need to carefully set the broadcast launch parameters in order to limit the induced CSO to tolerable levels. Assuming the native CSO distortion of the optical plant is typically around the -66 dBc level, the Raman induced CSO would need to be a maximum of -63 dBc in order to achieve a final CSO distortion contribution of -60 dBc due to the optical plant.

O-Band (1271 – 1371nm) WDM Technology

The first HFC analog full spectrum WDM solutions focused on familiar 1310 (O-Band) optics. The transmitter technology for these designs is identical to the standard point to point 1310 nm CATV transmitters that have been reliably deployed for many years.

There are a number of obstacles to analog multi-wavelength transport in the O-band. The usable bandwidth is bounded by water peak attenuation at 1383 nm on one side and increasing fiber attenuation below 1260 nm on the other side resulting from the loss profile of SMF28 fiber. Since the zero dispersion point of SMF fiber is centered near 1310 nm, dispersion effects are low and increase slowly up to the edges of the usable optical bandwidth. One anomaly in the O-band is that the polarity of dispersion reverses below 1310 nm further complicating multi-channel system designs. The primary distortion impacts are caused by either Raman effects or four wave mixing depending on the choice of wavelength spacing employed.

ITU standard grid wavelengths in the O-Band are only defined for CWDM channels spaced at 20 nm. CWDM optical passives are readily available and provide low ripple, flat passband response. However, systems with three or more 20 nm spaced wavelengths experience high Raman gain effects resulting in significant crosstalk degradation. Without applying unique correction techniques, the Raman impacted CNR and CSO performance severely limits the link reach of these systems.

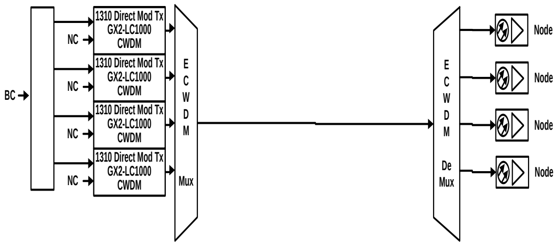


Figure 4 – Motorola ECWDM Multi-wavelength System

As shown in Figure 4 the broadcast channel signal is split to feed all transmitters launched into the same fiber. Most O-Band systems require the broadcast channel load to be identical for all transmitters in order to minimize crosstalk impairment on the analog channels.

Some equipment manufacturers took a completely different approach to reducing crosstalk impairments by designing O-Band WDM systems with closely spaced wavelengths which minimize Raman gain interactions. Unfortunately, given that one of the primary properties of SMF fiber is zero dispersion at ~ 1310 nm, a different fiber distortion (FWM) is strongly enabled by the use of dense, equally spaced wavelengths. Dispersion helps to de-correlate signals, preventing coherent signal beats. FWM is especially severe in fiber with low dispersion. To avoid

FWM degradation unique uneven wavelength spacing plans are required along with a shift away from the zero dispersion point of the plant fiber.

DWDM equivalent wavelength spacing in the 1310 band is not defined by ITU or other standards organizations therefore custom optical passives are required. Another challenge that had to be addressed is the passband flatness response of these custom passives. DWDM optical filters have narrow pass bands which can result in higher wavelength tilt response. DFB laser chirp creates an optical frequency modulation which can interact with the ripple tilt response of the Mux and Demux filters. The optical FM to intensity modulation conversion caused by this interaction can cause relatively high additive second order distortion depending on the amount of tilt encountered through all of the optical passive elements in the system. Specifying low passband tilt passives introduces another layer of customization to these filter devices.

Figure 5 shows the measured tilt response of a 1310 band CWDM and DWDM mux filter. The broad low tilt ripple of the CWDM filter dramatically reduces any laser chirp generated second order effects. Filter slope tilt greater than +/-0.1 dB per nm is usually not acceptable unless laser chirp is extremely low.

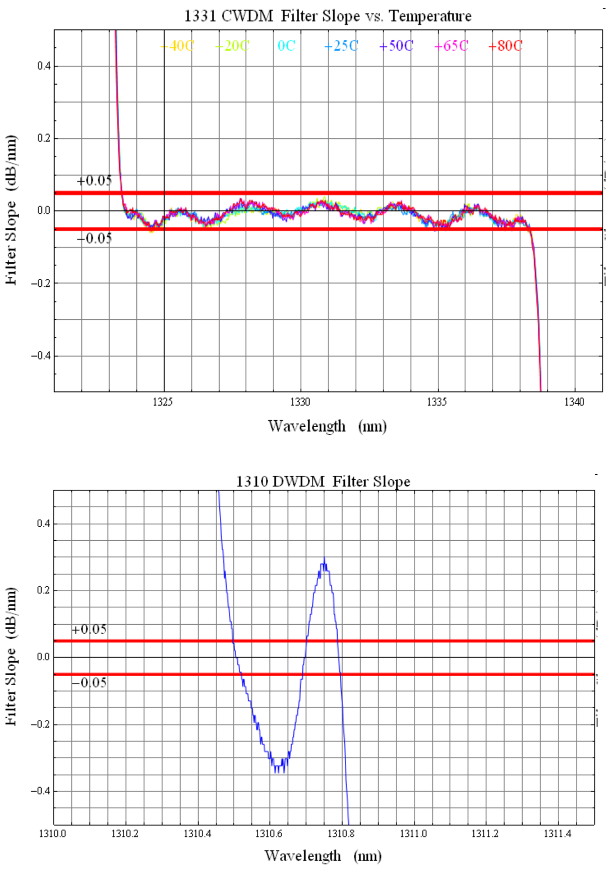


Figure 5 – CWDM and DWDM Slope Tilt Comparison

Due to the significant fiber induced distortions encountered in designing a multi-wavelength system at O-Band, each HE equipment vendor solved the problem in a unique way creating a different, proprietary solution.

Higher fiber attenuation in the 1310 nm band along with crosstalk and FWM analog distortions restrict the link reach of a four wavelength WDM system to roughly 25 km. This limited reach is adequate for approximately 65% of the total links served by the major MSO’s.

C-Band (1530–1565nm) Broadcast – Narrowcast Overlay Technology

Fiber attenuation at 1550 nm is 30% lower than 1310 nm. Erbium Doped Fiber Amplifiers (EDFA) make optical amplification possible and practical in the C-Band. These advantages along with ITU grid DWDM wavelength channel standards make the C-Band the logical choice for long reach and limited fiber serving areas.

Along with the fiber distortion impairments described previously in 1310 WDM systems, fiber dispersion at C-Band wavelengths must now be considered. The high chirp of DFB lasers makes full spectrum (55 MHz – 1 GHz) loading impractical for long link networks. Dispersive 2nd order distortion generated by the interaction of the fiber dispersion and laser chirp would dramatically limit the distortion performance of the system.

Externally modulated laser transmitters eliminate the laser chirp issue. ExMod transmitters combine a high power DWDM DFB CW laser source with a Lithium Niobate ($LiNbO_3$) Mach Zehnder (MZ) modulator. The MZ modulator produces zero chirp. To avoid SBS impairment and allow amplified high optical output level for extended reach the CW laser is dithered with one or more high frequency tones. MZ modulators are not inherently linear so a number of correction circuits and multiple feedback loops must be used to optimize 2nd and 3rd order distortion. The $LiNbO_3$ modulator also has a relatively high optical through loss of 3 to 5 dB. A higher power CW laser is usually selected to compensate for this loss although at a higher cost. The $LiNbO_3$ modulator which is designed for CATV linear applications is also a high cost component. All of these elements that make up a typical HFC ExMod transmitter cause this design to be extremely complex and expensive. As a result muxing multiple ExMod transmitters as a full spectrum multi-wavelength system would be cost prohibitive.

The alternative architecture which has been deployed for several years combines a single ExMod transmitter with multiple directly modulated DWDM DFB QAM laser transmitters in an overlay configuration. This architecture allows the high cost of the ExMod transmitter to be spread across a large number of nodes and subscribers. The ExMod transmitter carries the entire broadcast analog and broadcast QAM channel load. The lower cost digital QAM transmitters carry unique channel loads of narrowcast content targeted for specific node serving areas. The content of each QAM transmitter is also carried on a separate DWDM wavelength and muxed together at the hub. The optical launch level of the narrowcast wavelengths must be adjusted based on the OMI per RF channel to assure that a – 6 dB derate between analog and QAM channels is maintained at the node receiver.

The ExMod and muxed QAM laser outputs can be transported on separate fibers or combined onto a single fiber. EDFA’s are used to extend the reach up to 100 km or more. At a remote hub or splice housing the narrowcast QAM wavelengths are demuxed for transport to the individual node serving areas. The broadcast wavelength is split and combined with each narrowcast stream either at the demux point or in the node.

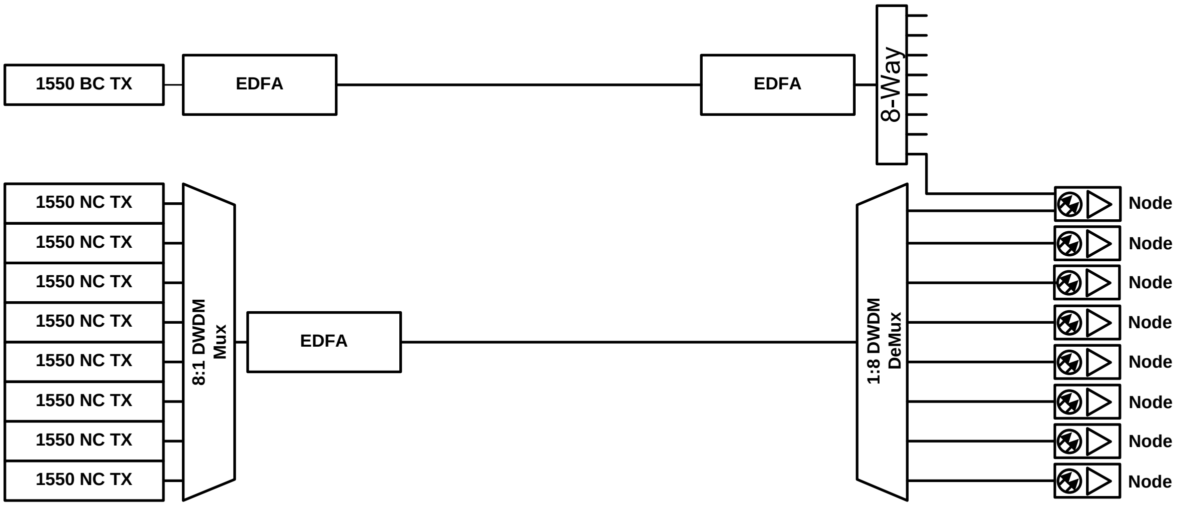


Figure 6 – Broadcast – Narrowcast Overlay Representative Design

Although complex, the BC–NC overlay configuration is very fiber efficient. Up to 40 nodes can be served using only 2 fibers. Until recently most cable networks used very few narrowcast channels. This minimized the level of crosstalk and second order distortion generated by the DFB QAM laser chirp. The low number of NC channels also meant that the OMI per channel was high which also improved distortion performance and subsequently caused the optical launch level of the NC wavelengths to be set ~ 7 dB lower than the BC wavelength in order to maintain the proper RF derate at the node receiver. In many systems a single node receiver detects the incoming BC-NC optical stream.

Narrowcast content is steadily increasing and is expected to triple or quadruple over the next several years. There are a number of consequences to the overlay configuration as a result of this increased NC loading.

As the number of NC channels significantly increases, the OMI per channel correspondingly decreases. This requires a re-balancing of the optical launch levels between the BC and NC transmitters. In a system with 64 NC QAM channels the optical power delta between the BC and NC wavelengths at the node receiver would decrease to only 3 dB raising the detector noise level in single receiver systems as well as the low frequency RF CIN cumulative noise contribution. The higher number of NC channels also means that the chirp performance of the DFB QAM laser becomes critically important. Additional dispersion compensation may be required to reduce crosstalk impairments to acceptable levels. CIN distortion due to the higher NC channel load will increase impacting the lower frequency BC channels. This increased level may challenge the acceptable CCN performance requirement in single receiver systems. Adding a second receiver to separate the BC and NC detection plus filtering the NC RF output will appreciably improve the low frequency noise performance.

C-Band DWDM Full Spectrum Technology

The reach limitations in addition to proprietary issues with 1310 WDM and the higher complexity of BC-NC overlay networks has caused system operators to seek a low complexity, more flexible system that can be expanded where needed on a pay as you grow basis. Development of low cost analog capable full spectrum transmitters for C-Band DWDM has proceeded rapidly. As always, each manufacturer has approached the problem from a slightly different angle and came up with a distinctive solution. The following is a description of the technologies employed in these designs.

Analog DFB Lasers

A directly modulated DFB laser design is always the lowest cost transmitter solution. However, there are significant issues in using a DFB that ultimately limit the useful reach and distortion performance. Laser manufacturers continue to make improvements in the analog distortion performance of high power DFB lasers. The problem at 1550 wavelengths is the fiber induced distortion generated by the interaction with directly modulated DFB laser chirp. The use of pre-distortion correction and tightly controlled electronic dispersion compensation can provide usable performance even with multi-wavelength configurations. Trade-offs between optical launch power, link length, and distortion, particularly CSO, considerably limit WDM reach compared to other available technologies. Since precise dispersion compensation is required to correct for laser chirp the compensation must match the link distance within 5 km to achieve good analog distortion performance.

ExMod Technology Solutions

Long reach external Mach Zehnder modulator transmitters were described earlier for BC-NC overlay applications. The high cost component driver in this design is the $LiNbO_3$ MZ modulator itself. In shorter reach configurations it may be possible to reduce the cost of the modulator and supporting circuitry with some tradeoffs in distortion performance. However, even with the achievable cost reductions the price of a MZ based ExMod transmitter will typically be 2X to 3X the cost of a reference 1310 DFB laser transmitter.

An alternative design uses a $LiNbO_3$ Phase Modulator to cancel the chirp produced by a directly modulated analog DFB laser. The phase modulator pass through loss is also 3 to 5 dB requiring a higher output analog capable DFB laser to compensate. The chirp level of the DFB is somewhat sensitive to the channel loading. The phase modulator and supporting loop circuitry must be optimized to cancel the worst case chirp generated by the laser.

As with other ExMod designs, the $LiNbO_3$ phase modulator component is the highest cost element. One novel approach to mitigate the modulator cost penalty is to share a single phase modulator with multiple analog DFB laser sources. This approach distributes the modulator and supporting circuitry cost across typically four wavelengths, lowering the cost per stream of the full spectrum WDM system. A caveat in this design is that the phase modulator can only be aligned for a single operating condition. Therefore all of the shared lasers must be identically matched to the same operating point (phase, chirp, OMI, etc) to achieve optimum system distortion performance. This approach lowers the cost per stream of the WDM system but requires the operator to absorb the full cost of the multi-wavelength system on day one even if the designed segmentation deployment is planned over several years.

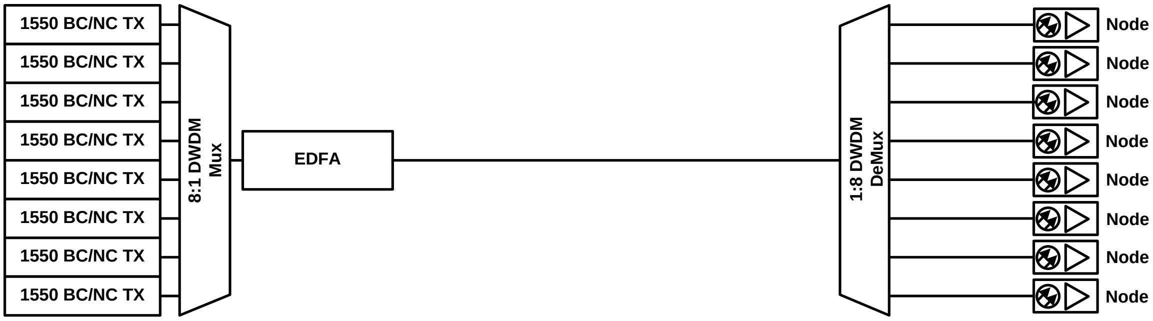
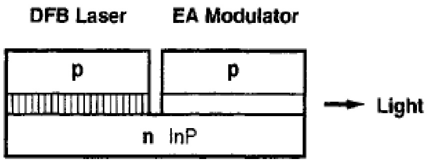


Figure 7 – Full Spectrum WDM System Design

EML Technology Solution

A completely different approach to full spectrum C-Band laser transmitter design utilizes devices that are widely deployed in 10 Gbps telecom optical transport networks. Electro absorption modulated lasers (EML's) are semiconductor devices that combine an E-A Modulator with a CW DFB laser integrated on a single chip. The E-A modulator is processed as a waveguide structure that uses an electric field to control (modulate) the intensity of light passing through it. E-A modulators require low control voltages and are capable of operating at very high speeds making them ideal for digital communications over optical fiber. EML's produce near zero chirp giving them the same immunity to dispersion as MZ based transmitter designs.



Integrated laser and electroabsorption modulator

Figure 8 – EML chip design

While the intended application for EML devices is high speed baseband digital over fiber, many of these devices have very linear response characteristics making them capable of transporting analog video and QAM signals with excellent distortion performance. Digital links do not require high optical power levels so the range of available EML device output levels is from -1 dBm to +6 dBm. Higher output levels are possible by using a higher level DFB laser source but this would result in the creation of a custom version with relatively low volume potential compared to the commercially available devices.

The design of an EML based full spectrum analog transmitter is very similar to a typical 1310 DFB laser transmitter. One notable unique difference is that the EML has an impedance controlled GPO / SMP RF connector built into the standard butterfly laser package to facilitate 10 Gbps input signals. During the 2011 CableLabs Winter Conference held in Atlanta, GA a dual mode (HFC analog / 10 Gbps digital) modular laser transmitter was demonstrated to the attending MSO's. The basic 10 Gbps performance characteristics of the EML are unaltered by use in analog HFC applications, making these devices a candidate for eventual migration to 10 Gb optical transport in the access fiber plant.

Figure 9 – 10 Gb EML Device Example

Since EML's are wafer scale devices the cost is dramatically lower than competing lithium niobate modulators. The use of EML's also leverages the much larger volumes of the telecom market putting these devices on the favorable side of the cost curve.

Full Spectrum WDM Link Performance

Full spectrum distortion performance and usable link reach for DWDM multi-wavelength systems is largely determined by the inherent optical fiber distortion impacts rather than the base transmitter performance. For directly modulated DFB laser transmitters, dispersion is the primary distortion performance limiter. In the case of ExMod and EML transmitter designs Raman crosstalk and parametric 2nd order distortion dominate.

Four wave mixing has previously been regarded as a less serious impairment issue for C-Band WDM systems. In HFC BC – NC overlay architectures the DWDM NC transmitter modulation consists of a limited number of channels each loaded with unique un - correlated content streams. High dispersion in SMF fiber provides another strong de-correlation mechanism that has been supported by a number of white paper studies and system analyses. Also, the number of FWM beats falling on any particular channel is usually low considering the limited number of wavelengths deployed in typical applications. Empirical testing however has shown that full spectrum DWDM transmitter configurations do confirm slight but measurable improvement when FWM distortion is avoided. Shifts in wavelength and phase offset of the FWM beats can reduce the observable distortion impact. Therefore aligning all transmitters exactly on ITU consecutive channel centers would represent the worst case impairment condition.

Unique, non-consecutive, or shifted wavelength plans have been proposed to avoid even the chance of FWM distortion. While these solutions are feasible when the number of combined wavelengths is small, they become increasingly difficult to manage in larger scale multi-wavelength networks. The cost / benefit of these solutions are also uncertain since components needed to implement these strategies make volume pricing and repair sparing logistics more difficult.

Full Spectrum multi-wavelength link reach capability varies depending on several factors such as the number of deployed wavelengths, the wavelength spacing, and the channel loading. Ultimately, the link reach limit is determined primarily by the fiber induced distortions that these factors generate.

Figure 10 below provides a guide to the achievable link reaches for different wavelength configurations and two channel load examples.

λ's	79 Analog 75 QAM	30 Analog 124 QAM
2	50 km	60 km
4	40 km	50 km
8	30 km	40 km
16	15 km	25 km

Figure 10 – Full Spectrum Link Reach

All Digital Migration

Analog video distortion performance is always the most stringent. As analog gradually gives way to digital QAM the performance of the remaining channels will significantly improve, particularly CSO and CTB due to the lower number of 2nd and 3rd order beat counts. The robust tolerance of QAM to noise and beat interferers allows transport systems with only QAM channel loads to achieve better end of line performance and in most cases longer link reach than systems with analog video loading.

Each of the full spectrum analog transmitter technologies described in the preceding sections of this paper are also capable of operation with an all QAM channel load. One possible application that may benefit is the traditional BC – NC overlay. If the current directly modulated DFB NC QAM transmitters used today were replaced with full spectrum transmitters much of the dispersion related distortion impacts would be eliminated. This could potentially improve the CCN performance of the low frequency broadcast channels which are the most vulnerable to dispersive CIN distortion particularly with older legacy equipment that are not capable of increased NC loading. Full spectrum transmitters are higher cost than DM QAM transmitters but the performance gains that could be achieved without the expense or disruption of added node receivers and filters or external dispersion compensation may justify the cost differential.

Link reach for fully loaded all QAM WDM systems can increase but not dramatically when compared to systems with a small tier of analog channels. CIN distortion due to the increased channel load along with fiber induced Raman distortion effects still dominate the final system performance. This result implies that the BC – NC overlay network is still an essential solution for long reach networks.

System Cost Comparison

To compare the relative cost of each multi-wavelength architecture the bill of material for a 40 km, 8 wavelength downstream aerial fiber link was prepared. Three designs were analyzed; 1310 home run, 1550 BC–NC Overlay, and 1550 Full Spectrum multi-wavelength corresponding to Figures 1, 6, and 7 as illustrated in this paper. The O-Band multi-wavelength design shown in Figure 4 was excluded because it is not capable of supporting a 40 km links.

The following component costs were included in each design:

- Hub Transmitters (8) plus a BC Tx in the case of the overlay design
- Node cost plus optical receivers
- Mux and Demux passives where required
- EDFA's where required
- Optical Splitters where required
- Aerial 12 count fiber construction (40 km) at $3000 per kilometer

The chart in Figure 11 summarizes the relative cost difference of each architecture in a Greenfield application. As expected the BC–NC overlay is the most expensive due to the high ExMod laser cost and multiple EDFA's used to overcome optical splitting losses. The other result is the comparable cost of 1550 Full Spectrum to traditional 1310 system designs while providing an 8:1 improvement in fiber utilization preserving additional dark fiber for other revenue generating applications. The slightly higher premium for the full spectrum solution is due to the additional optical passives and EDFA required to combine wavelengths onto a single fiber.

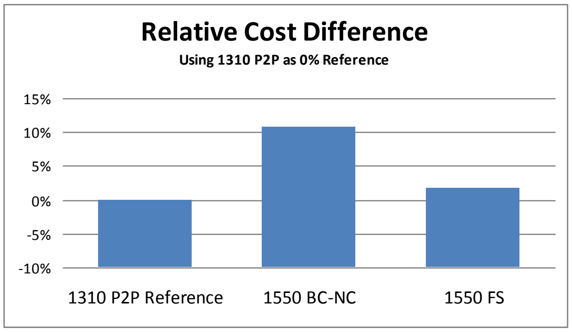


Figure 11 – Multi-wavelength system cost comparison

Summary

The continuing expansion of new narrowcast HD, VOD, and HSD channels is putting pressure on available downstream bandwidth. To meet this demand cable operators need a solution that does not require expensive fiber deployments or the need to touch every active in the network. Virtual segmentations and node splits are part of the answer but to make these viable solutions a fiber efficient WDM design is needed that offers the flexibility to adapt to the increasing channel load while providing the link reach capability required to cover 95% or more of the network footprint.

Broadcast – Narrowcast overlay designs are still the most fiber efficient architectures for long haul access networks and systems with very limited available fiber. But the overlay scheme is complex, requiring optical level rebalancing as the ratio of narrowcast channel loading changes. Overlays are also expensive, especially if only a small numbers of nodes are connected.

Attempts to leverage 1310 laser technology for WDM segmentation has had limited success. The high chirp levels generated by directly modulated 1310 DFB lasers in conjunction with the particular fiber distortion mechanisms present in the 1290 to 1370 nm wavelength region limit the link reach capability to 25 km with four wavelengths. While this is certainly valuable for most near term applications the link reach constraint means that multiple solutions will be needed to cover the full network footprint area.

The advances made with 1550 DWDM analog + QAM Full Spectrum laser transmitter designs has opened the door to a number of realizable near term solutions and potential future migration possibilities. The Full Spectrum designs available today eliminate laser chip and take advantage of lower fiber attenuation losses and EDFA amplification to address link reach coverage that is compatible with existing 1310 deployments. This allows operators to harvest fiber from existing nodes for use by commercial services customers or for new node serving area reduction targets.

The introduction of Electro Absorption modulated laser technology for HFC analog transport provides a new lower cost solution that can ultimately support digital data rates up to 10 Gbps for future generation system applications.

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