ADVANCES IN OPTICAL FIBER TECHNOLOGY FOR ANALOG TRANSPORT-TECHNICAL ADVANTAGES AND RECENT DEPLOYMENT EXPERIENCE

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Abstract

Performance assessments in analog video transport and distribution will be compared and analyzed, based on existing commercial optical and electronic equipment used with a variety of standardized optical fiber types. Particular emphasis is placed on comparison of capabilities with standard single-mode fiber to improve SBS thresholds on the order of 2dB, with associated increases in CNR, as well as improvements in CSO on the order of 8-9dB.

Experimental and simulated results will be presented, in addition to recent field data collected from actual physical links deployed by a major MSO. This is the first known commercial deployment of an alternate optical fiber type (i.e., not standard single-mode) expressly for the purposes of improving analog video transport capability.

INTRODUCTION

Among the primary telecommunications network architectures in use today, modern CATV designs provide unrivaled capability and capacity afforded by the hybrid fiber-coax (HFC) architecture. The underlying foundation of HFC networks is the optical fiber deployed primarily in the trunk/transport and distribution portions of the plant. By eliminating RF trunk amplifiers, increasing transmission bandwidth, enabling two-way transmission, and eliminating interference ingress, optical fiber has allowed CATV networks to transform into the pipes which now carry the full spectrum of voice, video, and data services. Undeniably, standard single-mode fiber has been the workhorse, and arguably the key element, in HFC design. Improvements in transmission capabilities have, as a result, historically been designed within the constraints of standard single-mode fiber characteristics. Appreciating the historical evolution of optical transmission over HFC architectures provides a useful perspective on these constraints, and the issues which consequently remain in nearly all modern HFC optical transmission systems.

AN ALTERNATE PERSPECTIVE ON TRANSMISSION TECHNOLOGY DEVELOPMENT

In early stages of HFC deployment, the benefits of transitioning from copper to optical fiber for CATV transport purposes were clear, with some of those advantages stated above. Significant development (and acceptance) was required in the optical transmission arena, however, to realize the large and powerful HFC networks of today. Optical transmission at 1310nm was typically viewed as sufficient where copper trunks were replaced with fiber, and the technology was relatively mature and economically feasible. The economics of system clustering and regional interconnection drove the need to adopt 1550nm transmission technology, where fiber loss is significantly less than at 1310nm and signals can be optically amplified with erbium doped fiber amplifiers (EDFAs). Standard single-mode fiber’s chromatic dispersion at 1550nm is significantly higher than at 1310nm, however, which was a significant issue when the only sufficiently linear analog transmitters were high frequency chirp directly-modulated types[1]. The development of linearized externally modulated 1550nm transmitters addressed the issue of source chirp and interaction with fiber dispersion. However, fiber dispersion-induced self phase modulation (SPM) [2,3] was still an issue, in addition to exacerbation of the power-limiting impact of stimulated Brillouin scattering (SBS) (4,5) by the relatively narrow linewidth emitted by externally modulated sources. The severity of SBS was subsequently mitigated by integration of electrical pre-distortion and suppression techniques[6], although it is still a limiting factor in a number of system designs.

The transmission technology development summarized above can be viewed in the context of modification to optical fiber parameters, rather than working within the constraints of a fixed set of assumptions. While being an interesting academic exercise, it obviously does not address issues in the installed cable plant, where the fiber infrastructure is fixed. However, such an approach can indeed provide flexibility in designs for pending upgrades and rebuilds. Concerning the transition from 1310nm to 1550nm, significant reductions in attenuation at 1310nm would conceivably increase achievable transmission distances at the lower wavelength and enable wider application of lower cost transmitters, allowing enabling a broader application base for 1310nm. As illustrated in figure 1, however, Rayleigh scattering places a fundamental limitation on the minimum achievable loss at a given wavelength in current silica-based optical fiber, and current fibers closely approach that limit. While techniques exist to improve upon these limits through exotic materials and/or waveguide structures, they are not immediately adaptable into commercially viable fibers. The issue of high chromatic dispersion at 1550nm, on the other hand, has been addressed for some time in the long-distance telecommunications market with non-zero dispersion shifted fibers (NZDSF). NZDSF typically have dispersion on the order of 3 to 4 times smaller than that of standard single-mode fiber. Although designed primarily around the considerations of high capacity long distance networks, NZDSF can have direct benefit on CATV network designs by significantly reducing the impact of nonlinear and dispersion-related impairments such as SPM and composite second order distortion (CSO). Arguably the most significant limitation on analog transmission at 1550nm continues to be SBS, and the prevailing assumption has been that standard single-mode fiber best mitigates the effect. As SBS is directly dependent on the fiber's effective area (equation 1)[6], and standard single-mode fiber has a larger effective area (typically 80μm^2) than all NZDSF (typically 45-72μm^2)(7,8,9). However, it has been shown that some NZDSF are in fact superior to standard single-mode fiber in terms of SBS threshold, by as much as 2-3dB [10,11]. Fibers with this capability, coupled with optimally reduced chromatic dispersion, can show significant advantages over standard single-mode fiber to support real world analog transport network designs.

ASSESSMENT OF TECHNICAL ADVANTAGE

Details of technical capability

In simple terms, stimulated Brillouin scattering occurs in optical fiber due to a generation of acoustic waves in the optical waveguide, which create periodic variations in the fiber's refractive index. This periodic variation effectively reflects part of the original transmitted optical power thus diminishing the power seen at a receiver. The effect worsens with increasing launch power, so the signal reduction at the receiver cannot be overcome simply by increasing the transmitter output. The power threshold at which SBS begins to quickly deteriorate a signal is given by:

$$(1)\quad P_{th} \cong \frac{21A_{eff}}{L_{eff}\, g_B}$$

where P_{th} is the SBS-dictated optical power threshold (in dBm), A_{eff} is the fiber effective area, L_{eff} is the nonlinear interaction length, and g_B is the peak Brillouin gain of the fiber. As stated previously, standard single-mode fiber A_{eff} is larger than that of typical NZDF, but significant variability in threshold among different fiber types due to variation in Brillouin gain characteristics has been empirically explored. Regardless, this phenomenon is commonly overlooked and effective area dependence is typically the only consideration made. With the appropriate combination of reasonable effective area ($>70\mu m^2$) and Brillouin gain, some NZDSF can support higher SBS thresholds than standard single-mode fiber.

Figure 2 shows an SBS threshold comparison between several commercially available optical fiber types. Considering standard single-mode fiber as the presumed standard for SBS threshold, the most commonly deployed NZDSF varieties were evaluated in comparison. The three NZDSF variants considered were: large area NZDSF, characterized by a relatively high effective area (approximately $72\mu m^2$)[7] in comparison to other NZDSF; high dispersion NZDSF, with relatively high chromatic dispersion at 1550nm (~8ps/nm*km)[8]; and reduced slope NZDSF, characterized by relatively low chromatic dispersion slope and very small effective area at 1550nm ($0.045 ps/nm^2*km$ and $\sim 55\mu m^2$, respectively)[9]. All fibers under test were at a nominal length of 50km, and tested in the configuration illustrated in figure 3, with backscattered signals detected through a self-heterodyne configuration. As indicated in the figures, large area NZDSF has a significantly higher SBS threshold than standard single-mode fiber, in spite of the fact that it has a lower effective area ($72\mu m^2$ and $80\mu m^2$, respectively). A relevant point to consider is that the relative differences in SBS thresholds are nominally constant regardless of electronic-based SBS suppression techniques. In other words, a transmitter with maximum SBS-limited power of 16dBm on standard single-mode fiber could support approximately 18dBm over large area NZDSF, while a 17dBm standard single-mode fiber rated transmitter could accommodate a similar 2dB increase (to 19dBm) over large area NZDSF. Also significant is the fact that other NZDSF varieties can not support the SBS threshold allowed on standard single-mode fiber.

Aside from variation in SBS suppression capabilities among standard single-mode fiber and the NZDSF variants, an approximation can be made to assess the introduction of second order distortion in different fiber types. Second harmonic distortion for a chirp-free externally modulated source, as determined by fiber dispersion and nonlinear refractive index, can be expressed as:

$$(2)\qquad \frac{1}{4}m\ddot{\beta}^2 z^2\Omega - \frac{1}{2}m\ddot{\beta}^2 z^2\Omega^2 P\left(\frac{2\pi N_2}{\lambda A_{eff}}\right),[1]$$

where m is the modulation index, z is the fiber length, Ω is the modulation frequency, P is launched optical power, N_2 is the Kerr nonlinear-index coefficient, λ is the transmitter center wavelength, and A_{eff} is the fiber effective area. Also, note that

$$\ddot{\beta} = -(\lambda^2 / 2\pi c)D$$

is the second-order fiber dispersion coefficient , where D is the fiber dispersion coefficient. For standard single-mode fiber, large area NZDSF, reduced slope NZDSF, and high dispersion NZDSF, we can consider the chromatic dispersion at 1550nm (17, 4, 5.2, 8ps/nm*km, respectively) and effective area

(80, 72, 55, 63 μm^2, respectively. Assuming all other terms in (2) are constant, we can make a qualitative assessment of the relative magnitude of CSO impairment in each fiber by scaling the ratio of fiber dispersion to effective area, D/A_{eff}. As is evident from the table, all NZDSF should have a significantly reduced CSO distortion relative to standard single mode fiber.

Fiber Type	D/A_{eff} ratio ($ps/nm*km*\mu m^2$)
Standard single-mode	0.212
Large area NZDSF	0.056
Reduced slope NZDSF	0.094
High dispersion NZDSF	0.127

If only performance parity with standard single-mode fiber is desired, the comparative assessment of SBS thresholds carries significant implications in the choice of fiber type to deploy. While large area NZDSF can support any given single wavelength 1550nm transmission scenario designed around standard single-mode fiber constraints, a system design would otherwise require careful consideration and possible power budget de-rating to avoid significant signal degradation if deployed over other types of NZDSF (i.e., high dispersion NZDSF and reduced slope NZDSF). The true justification for a choice of fiber other than standard single-mode fiber would obviously come from a desire to achieve performance benefits, as opposed to simple parity with the effective standard (standard single-mode fiber). Therefore, the gains derived from exploiting an increased SBS threshold, as well as the merits of reduced chromatic dispersion and other optimal parameters, warrant exploration.

Taking Advantage of the Technical Benefits

A number of potential performance advantages can be identified considering the combined impact of increased SBS suppression and optimized chromatic dispersion. The most readily apparent benefit gained from an increase in SBS threshold on large area NZDSF is the capability to support higher optical launch powers, and consequently extend the distance over which in-line optical amplifiers (EDFAs) would otherwise be required. Assuming equivalent loss characteristics on large area NZDSF and standard single-mode fiber, and considering only SBS, a 2dBm increase in SBS threshold would translate to approximately 8km increased distance with equivalent end-of-line received power. Coupled with a reduced chromatic dispersion and optimal effective area, however, large area NZDSF can further increase capability by both supporting higher powers and mitigating distortions. Indeed, previous studies have demonstrated 100km transmission over large area NZDSF with no repeaters or in-line EDFAs[10], and at shorter distances (50km) with high launch power demonstrated significant CSO and CNR advantage with large area NZDSF (CSO<-65dBc, CNR>50dB), compared to standard single-mode (CSO<-52dBc, CNR>44dB) and reduced slope NZDSF (CSO<-37dBc, CNR>24dB). By extension, this capability could extend to supporting longer reaches or superior signal integrity over a fixed distance with large area NZDSF while remaining within the constraints of existing design rules (e.g., maximum allowable number of cascaded in-line EDFAs). Link engineering rules can also potentially be extended since the input power to cascaded in-line EDFAs can increase due to higher launch powers, thus improving EDFA output CNR.

Given the broadcast nature of analog video transport, another beneficial application of increased launch power capability with large area NZDSF would be the potential to increase the number of remote locations supported with a single transmitter. Particularly for those locations not immediately targeted for advanced services, the economics of basic service distribution from a single transmitter become appealing. As an example, as illustrated in figure 4, an additional 2dBm maximum launched power could scale from a 1x8 passive splitter (loss=9dB/output) to accommodate the additional 2dB loss encountered on each arm of a 1x12 split (loss=11dB/output).

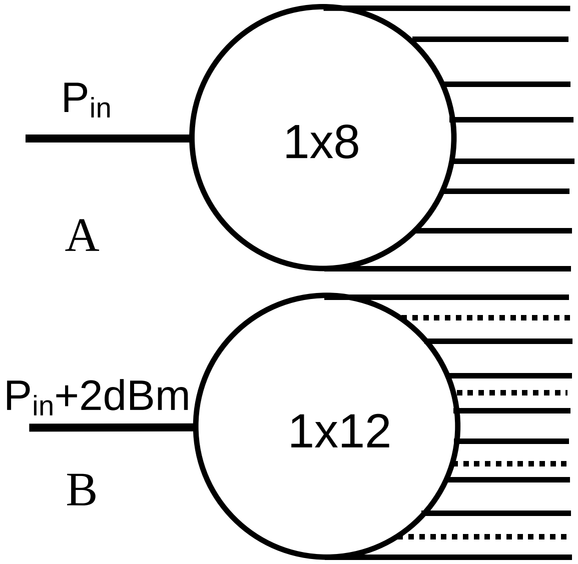

Figure 4: Splitter configurations: A-with standard single-mode fiber, B-with large area NZDSF

A promising possibility, again born from the coupled advantages of reduced chromatic dispersion and increased SBS threshold in large area NZDSF, is the ability to significantly increase the usable range of directly modulated 1550nm PEG transmitters. Typically characterized by significant frequency chirp and thus severely limited by dispersion-induced CSO, the introduction of large area NZDSF with reduced dispersion could potentially allow for PEG transmitter displacement of more costly externally-modulated sources to address trunking applications as opposed to simple signal insertion. The inherent SBS suppression resulting from modulation-induced spectral broadening, coupled with the improved power characteristics due to the lack of an attenuating modulator section, aids in drawing a significant comparison with conventional long reach externally modulated sources. This scenario is currently being experimentally evaluated at Corning.

FIELD DATA FROM DEPLOYED CABLE

Available commercial transmission equipment operating over a contiguous link of standard single-mode fiber was not capable of supporting internal CSO requirements of 68dB in the system link depicted in figure 5. As suggested previously, a reduction in total link chromatic dispersion could potentially mitigate CSO brought about by direct interaction between fiber dispersion and residual transmitter chirp, as well as CSO introduced by SPM-induced signal chirp (which also has some dependence on fiber effective area). Indeed, concatenating a 56.4km length of large area NZDSF to the previously installed 53.2km of standard single-mode fiber enabled a significant improvement in CSO. With an initial transmitter CSO of 76.9dB, the contiguous link of all standard single-mode fiber received 61.6dB and 59.4dB at channels 36 and 67, respectively. By introducing large area NZDSF into the latter portion of the total link, thereby reducing the overall accumulated chromatic dispersion, received CSO values with identical system parameters were 70.9dB and 71.4dB at the respective channels. For the two monitored channels, 9.3dB and 12dB improvements in CSO were realized over the total link, reducing the impairment such that it was well within the internal requirement. Note in addition the increased magnitude of improvement at the higher modulation frequency. Marginal improvements in CTB were also realized with the heterogeneous standard single-mode/large area NZDSF link, with 0.3dB and 1.1dB improvements at the respective monitored channels when compared with the homogeneous standard single-mode fiber link. Note again the slight increase in the performance delta at the higher modulation frequency.

CONCLUSION

Looking at the evolution of CATV networks and systems free from the technical constraints of the majority installed base of standard single-mode fiber allows for consideration of system solutions that can meet challenging performance requirements, extend the capabilities of existing transmission equipment, and provide opportunities to deliver significant savings in network flexibility and equipment cost. The capabilities of non-zero dispersion shifted fibers to significantly mitigate signal distortions are beginning to be explored in actual installations. Moreover, the large effective area subset of NZDSF allows for the broadest range of performance capability improvements among alternate fiber types, and in comparison to standard single-mode fiber.

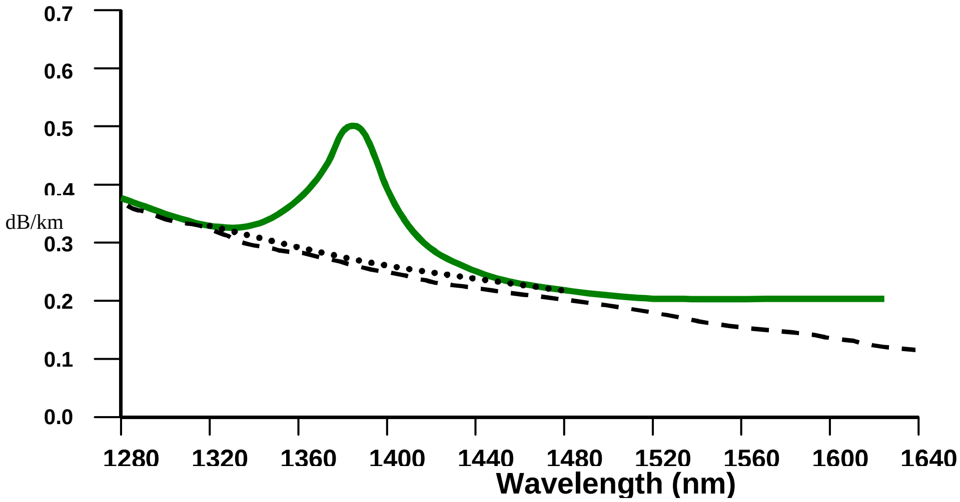

Figure 1: Typical attenuation curves for standard single-mode fiber (solid curve) and low water peak standard single-mode fiber (dotted curve), and fundamental Rayleigh scattering limit (dashed line)

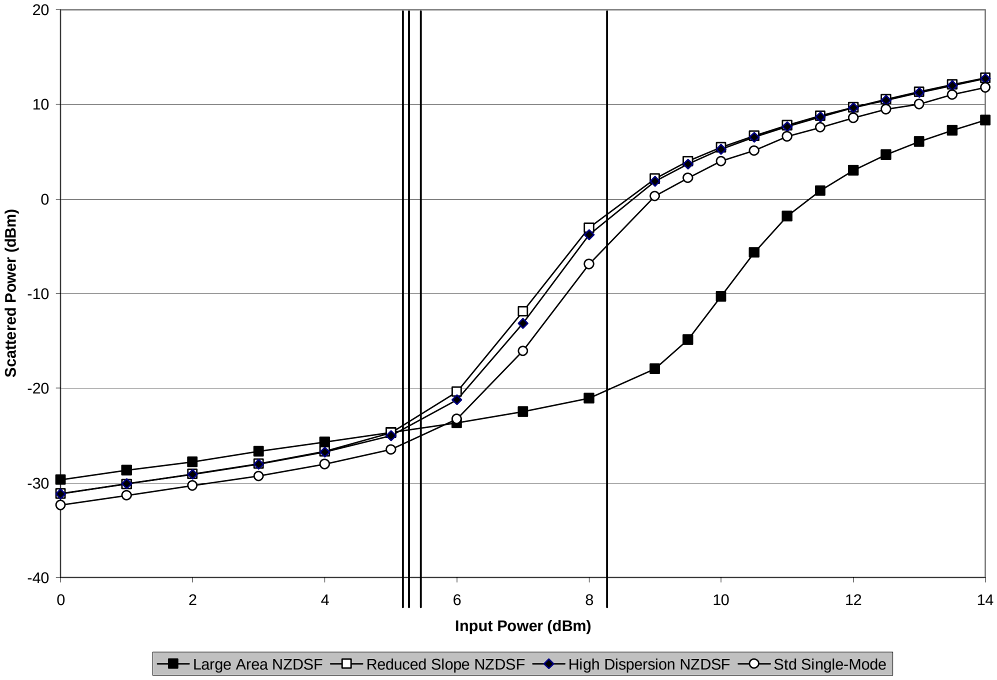

Figure 2: Comparison of input optical power and scattered optical power. Elbow of curve indicates approximate location of nonlinear onset of Brillouin scattering, values indicated by vertical markers for reduced slope NZDSF, high dispersion NZDSF, standard single-mode, and large area NZDSF, respectively.

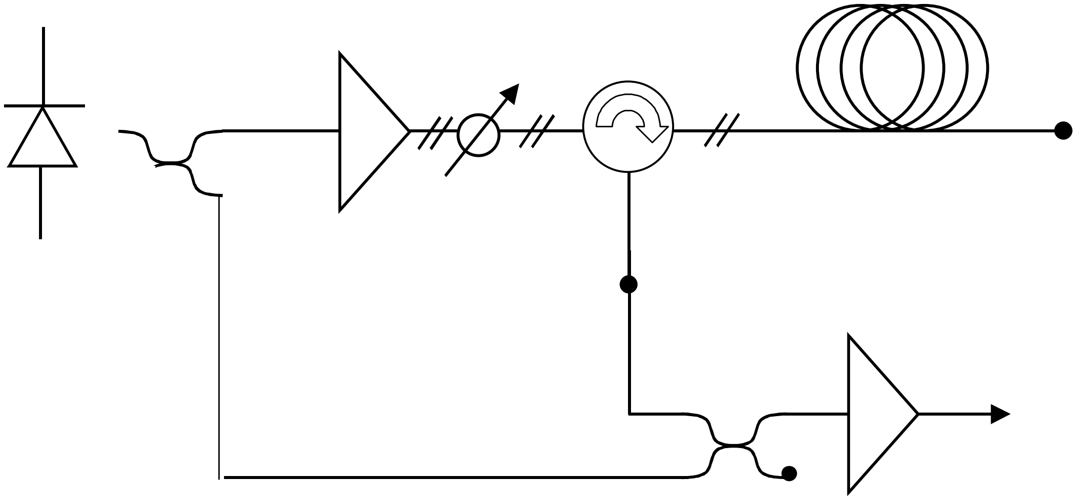

Figure 3: Experimental configuration for evaluating SBS threshold

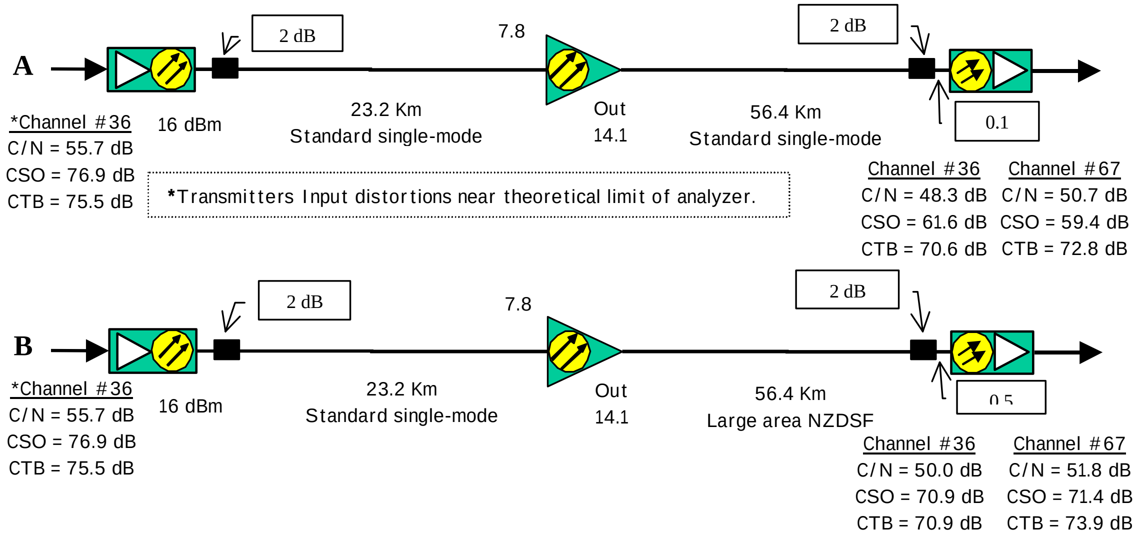

Figure 4: Configuration of installed links for comparison. A-Contiguous standard single-mode fiber link, B-Standard single-mode fiber extended with large area NZDSF.

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