MANAGEMENT OF STIMULATED RAMAN SCATTERING IN CATV WDM REVERSE PATH SYSTEMS

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Abstract

Fiber nonlinearities can significantly limit the performance of WDM optical systems. Crosstalk due to Stimulated Raman Scattering (SRS) can potentially reduce carrier-to-interference ratios to unacceptable levels. The effects of SRS include crosstalk that may produce interference at levels up to 30dB below desired carriers. The reverse path is particularly susceptible to this impairment.

This paper presents theoretical models for SRS. Empirical and simulation data is presented showing impairments from SRS in fiber links. Management of the factors that contribute to SRS is a critical part of system design. Specific techniques are described that will ensure that acceptable levels of system performance are obtained.

INTRODUCTION

New services requiring two-way traffic on HFC networks (such as cable telephony, VoIP, cable modem and two-way set-top proliferation, IPPV, etc.) have created additional demands on reverse path transmission capability. System architecture considerations, focused on the management of this additional traffic, must take into account frequency allocation, homes passed per node, and segmentation in the reverse path. Until recently, the generally accepted standard fiber optic reverse plant design was built upon the FP (Fabry-Perot) or DFB (distributed feedback) laser at 1310nm or a DFB at 1550 nm with a dedicated return fiber. The emergence of CWDM laser technology allows for a low cost strategy to expand the capacity of the reverse path plant by allowing multiple (typically up to eight) return path transmitters to share a single return fiber. This approach serves to "future proof" the network by allowing additional transmitters to re-use the same fiber as well as facilitate a fiber-deeper architecture in which the node supports a smaller number of subscribers, thereby boosting customer performance as transmitter bandwidth is shared with fewer end-users. CWDM offers these benefits at a much lower cost, size, and power consumption than an equivalent DWDM solution.

A WDM solution is not without its drawbacks, however. Optical losses from the combining and splitting of wavelengths at the HFC network endpoints, as well as degrading signal distortions due to channel-to-channel interactions caused by nonlinearities in the fiber itself must be understood and accounted for to achieve acceptable network performance.

It is convenient to assume that each wavelength on a multi-channel WDM optical system will behave and perform as if it was on its own dedicated fiber. A system designer that uses this viewpoint would calculate loss budgets, compute SNR, etc. for each service, and would expect service performances accordingly. The well-known performance-limiting degradations suffered by a telecom system's high-powered, tightly spaced, amplified DWDM systems seemingly would not apply to CWDM in an HFC reverse path application. Given a typical reverse path CWDM system's modest launch power into a shorter fiber span, with wide channel spacing and narrower modulation bandwidths, one would expect each of the wavelengths to behave as an independent link. Unfortunately, the reality is that even these systems can have wavelength interaction affecting system capability.

Interactions between optical signal carriers propagating along a fiber can cause a multitude of potentially degrading effects and much work has been done to understand their behavior and impact [1]-[4]. Long haul digital DWDM transmission system designers, whose challenge is to extract maximum link performance under extreme optical budgets, are well aware of the pitfalls and consequences of improper management of fiber effects.

Any fiber optic system must deal with the possibility of one or more of the following nonlinear fiber impairments.

- Four Wave Mixing (FWM, is similar to CTB with optical carriers)
- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (XPM)
- Stimulated Brillouin Scattering (SBS)
- Stimulated Raman Scattering (SRS)

Each of these nonlinearities is dependent upon system parameters that govern how much of an effect it will have on system performance. Individual transmitter launch power, number of wavelengths, total power in the fiber, transmission distance, modulation type and bandwidth, laser wavelengths and spacing all have an influence on which nonlinear mechanism will have significance on the system. These parameters, as they apply to reverse plant systems using CWDM, play into making one type of fiber non-linearity dominate the others and have a significant influence on system performance. Our studies show that reverse path CWDM systems are most susceptible to stimulated Raman scattering, or SRS.

STIMULATED RAMAN SCATTERING

Stimulated Raman scattering is a fiber nonlinear effect which results in the transfer of optical power from one wavelength to another. This is characterized as a broadband scattering effect [6] and it influences all other wavelengths on a fiber within approximately 125 nm due to an intrinsic property of fused silica glass. SRS occurs when the laser signal is scattered by natural molecular vibrations in the fiber (phonons). Interaction between the laser signal and the vibrating glass molecules scatters light from the signal in all directions. Nearby molecules absorb the scattered light and re-emit a photon with energy roughly equal to the original photon. SRS-induced crosstalk (Raman crosstalk) occurs when another signal at a different wavelength is co-propagating on the fiber and causes the molecule stimulated by the first wavelength to emit a photon at the second. As photons of shorter wavelength light (higher frequency) contain higher energy, the transfer of energy due to Raman scattering causes energy to transfer from shorter to longer wavelengths. In terms of measured crosstalk, the effect is equal in both directions, meaning the shorter wavelengths experience crosstalk by power reduction, the longer wavelengths by power addition.

For Raman crosstalk to occur, optical power must be simultaneously present between interfering signals. This implies that on digital systems, crosstalk will only

$$Crosstalk(SRS) \approx 10\log\left\{\left(\frac{\rho_{srs} g_{12} P_{\text{int}}}{A_{eff}} \cdot \frac{m_{\text{int}}}{m_{CATV}}\right)^2 \frac{1+e^{-2\alpha L} - 2e^{-\alpha L}\cos(\omega d_{12} L)}{\alpha^2 + (\omega d_{12})^2}\right\} \quad (1)$$

$$\Theta_{SRS} = \tan^{-1}\left(\frac{-\omega d_{12}}{-\alpha}\right) + \tan^{-1}\left(\frac{e^{-\alpha L}\sin(\omega d_{12} L)}{e^{-\alpha L}\cos(\omega d_{12} L) - 1}\right) (2)$$

where,

$Aeff$	effective area of fiber
ρ_{srs}	effective polarization overlap factor
g_{12}	Raman gain coefficient
P_{int}	optical power of the interfering signal
m_{CATV}	optical modulation index (OMI) of signal
m_{int}	OMI of the interfering signal
α	attenuation coefficient of the fiber
d_{12}	group velocity ($\approx$ D (λ_1- λ_2))
D	dispersion coefficient
L	fiber length
ω	RF angular frequency

occur when both wavelengths are transmitting a '1'. No crosstalk occurs when either path is transmitting a '0'. In analog modulated systems, where the optical carrier is always present, Raman crosstalk can be present continuously.

SRS Equations

Phillips and Ott studied the governing mathematics of channel-to-channel interference caused by Raman crosstalk on WDM CATV systems, and derived equations for magnitude (in dB) and phase (in radians) of crosstalk between two wavelengths [5].

The Raman gain coefficient, g_{12}, denotes the Raman gain between interacting wavelengths and is inherent to the fiber. It is typically approximated by a line with slope of 6.0E-14 m/W from 0 to 100 nm [7]. The gain peaks at approximately 100nm of wavelength separation and falls off sharply thereafter.

From analysis of Equation (1) it can be noted that Raman crosstalk is predominantly dependent upon optical power of the interfering signal, wavelength separation between the signals (see P_{int} and g_{12} terms in numerator), and the modulating frequency of the interfering signal (see ω term in the denominator).

SRS CROSSTALK MEASUREMENTS

CATV systems are particularly sensitive to SRS effects due to demanding CNR requirements. The focus of SRS-induced crosstalk has primarily been on video overlay PON (Passive Optical Network) architectures, where Raman crosstalk exists between the 1490 nm data carrier wavelength and the 1550 nm wavelength carrying amplitude modulated video signals, and DWDM forward path video distribution systems [8]-[12]. SRS effects on a CWDM return path system have been somewhat overlooked as most services on these systems have greater tolerance of noise and unwanted interference than an AM-VSB video signal. Despite the greater tolerance to impairment, SRS effects on services in a CWDM return path system must be quantified and limited to acceptable levels.

Experiments were constructed to show crosstalk as a function of the critical parameters of optical launch power, wavelength spacing, and modulating frequency on a typical CWDM CATV reverse path system.

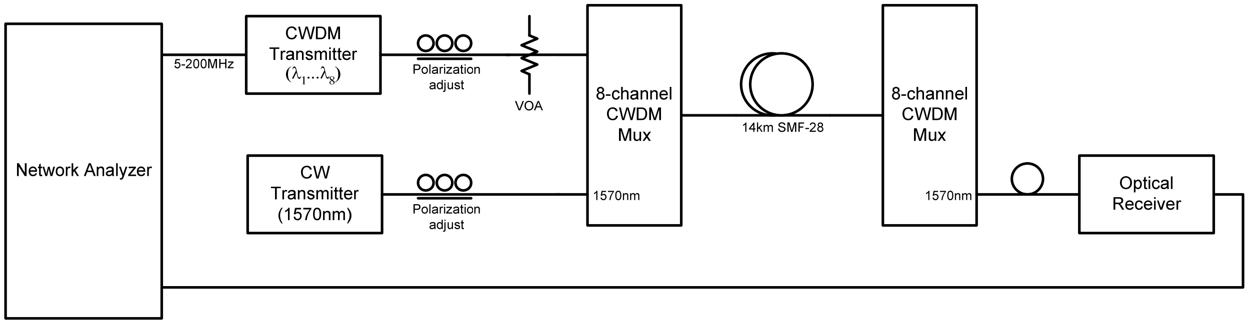

Figure 1. Experimental setup with two transmitters over 14km SMF.

Test Setup

The measurement setup shown in Figure 1 consists of two CWDM DFB transmitters combined through a CWDM mux to 14km of single mode fiber. One wavelength is directly modulated with a swept RF signal while the other is unmodulated (CW). An optical attenuator, inline with the modulated wavelength, varies the optical power of the interfering channel. A CWDM demux at the end of the link selects the test channel wavelength which is fed to the receiver. Polarization was adjusted on each wavelength for worst case behavior. Crosstalk due to the optical mux and demux were determined not to contribute to the SRS crosstalk measurements. Crosstalk measurements are made by measuring the ratio of RF signal power on the unmodulated CW wavelength to the RF signal power on the modulated wavelength, with each referenced to the same average power.

Test and Simulation Results

Figure 2 shows crosstalk from 5 to 200 MHz between two CWDM transmitters spaced 100 nm apart (1470 nm and 1570 nm) with 3 dBm launch powers over 14 km of single mode fiber. Combining mux loss was approximately 2 dB per port. Worst case crosstalk was measured at -46 dB at 5 MHz. Local nulls seen in the crosstalk over frequency are due to the cosine term in the numerator of Equation (1). Changes in fiber length or wavelength spacing of the carriers will result in a shift of the null frequencies.

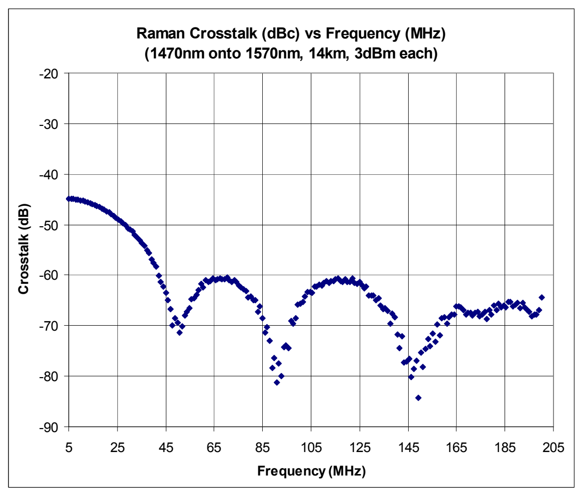

Figure 2. Measured 1470nm crosstalk onto 1570nm (3dBm each, ~2dB mux loss, 14km SMF-28)

Figure 3 shows the dependence of crosstalk on optical power and wavelength separation. The plot shows measured crosstalk at 5 MHz onto a CW channel at 1570 nm from each of the other wavelengths in an eight channel CWDM system (1470 nm to 1610nm) with the output power of the interfering signals varied from -6 dBm to +3 dBm. It is seen that SRS crosstalk increases 2 dB for each 1 dB increase in interfering wavelength power and increases with frequency separation. The plot also illustrates that crosstalk from a neighboring wavelength is a function of the difference in wavelength and is largely independent of whether the interfering signal is higher or lower in wavelength.

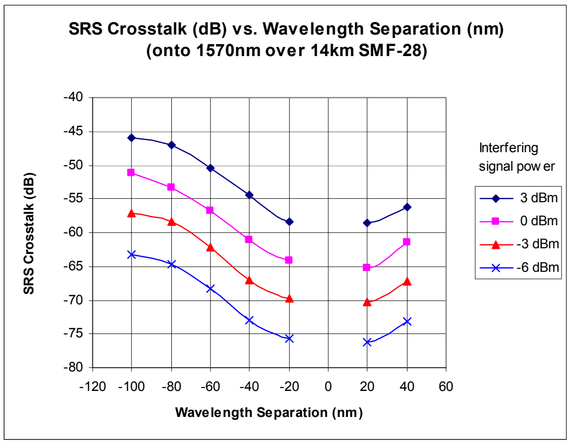

Figure 3. Measured crosstalk at 5MHz onto 1570nm vs. wavelength separation for various interfering signal output powers (1570nm at +3dBm out, ~2dB mux loss, 14km SMF-28).

At a given modulation frequency, total SRS-induced crosstalk on a system will be due to the vector addition (amplitude and phase) of all interfering signals and governed by equations (1) and (2). Simulations using these equations predict worst case crosstalk approaching -30 dB in an eight-wavelength reverse path CWDM system over 14 km when the optical power per wavelength is +7 dBm. Additional increases in transmit optical power or fiber length can increase crosstalk even further.

As shown, Raman crosstalk is strongly dependent upon optical power in the fiber. From Equation (1), this crosstalk is also shown to be a function of fiber length (see term *L*). Using Equation (1), Figure 4 shows simulated plots of crosstalk between wavelengths of 1470 nm and 1570 nm at various modulating frequencies as a function of fiber length. For each frequency plotted, the crosstalk is shown to increase from a minimum (with no fiber) to an initial maximum value and then vary about a final crosstalk value as fiber length is increased. Others have shown under certain conditions, using a more complex model [12], that crosstalk may reach another peak (in excess of the initial peak) at a longer fiber distance.

Raman crosstalk is also very sensitive to signal polarization states [12]. Crosstalk is maximized between two wavelengths when the signals are in perfect polarization alignment during propagation. As the polarization overlap factor between the interfering wavelengths can vary between 0 and 1, we have assumed the overlap to be 0.5 for simulation purposes. In actual systems, time-varying polarization states between the signals while traversing the fiber span will cause the measured crosstalk to vary.

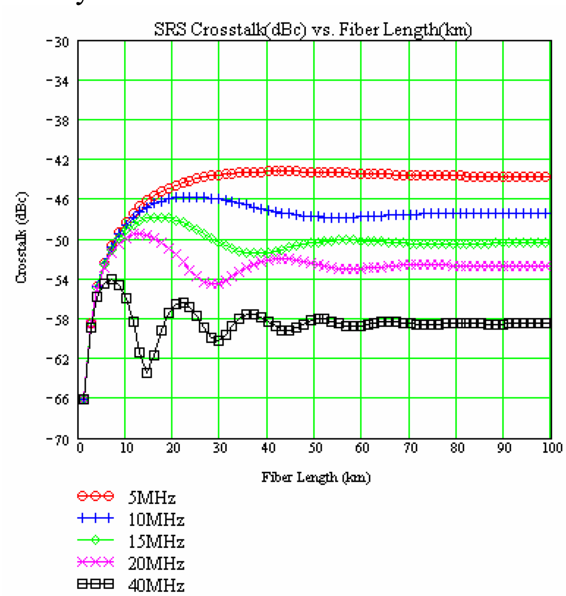

Figure 4. Crosstalk vs. fiber length for various frequencies (1470nm to 1570nm at 3dBm output per wavelength, ~2dB mux loss, SMF-28)

CWDM SYSTEM DESIGN GUIDEINES

Desired crosstalk performance for a WDM reverse path system is generally better than -40 dB. Careful system planning is necessary to achieve this performance for CWDM systems where crosstalk due to SRS tends to dominate. SRS crosstalk can be minimized by paying heed to the critical parameters that govern it. Below are guidelines to help reduce crosstalk effects based on the system parameters of optical power, wavelength spacing, and modulating frequency.

- Optical launch power per transmitter should be kept to the minimum necessary to achieve required CNR goals. Keep in mind that CNR margin may need to be added due to crosstalk effects.
- Services requiring high carrier-to-interference ratios should be located in that part of the RF spectrum not occupied by modulation on another wavelength.
- If all wavelengths are not being utilized, use those wavelengths that are closest together or greater than 100 nm apart.
- Place the most sensitive services at the high end of the RF modulation spectrum where crosstalk effects are reduced.

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