Optimum Laser Chirp Range for AM Video Transmission

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Abstract

Simple expressions for the impact of DFB laser chirp on the system noise and distortion specifications of AM CATV fiber links are derived. These expressions are found to agree well with measured results. There is a narrow range of chirp for which degradation of both noise and distortion is low. 1310 nm lasers are found to have chirp within the acceptable range. 1550 nm laser are found to have chirp that is unacceptably large for most CATV applications.

I. Introduction

High dynamic range fiber optic links have recently been developed for use in CATV systems. CATV systems typically transmit 30 to 80 channels of amplitude modulated video in the VHF and UHF frequency ranges, with trial systems transmitting up to 150 channels. Fiber optic links offer a significant advantage because the link lengths can be 20 km or more compared to less than 1 km for coaxial links. The use of fiber optic links can eliminate the need to cascade large numbers of amplifiers, improving the performance and reliability of CATV distribution systems.

The requirements for CATV systems are very demanding in terms of noise and distortion. CATV fiber links require high optical power, the noise of the fiber links is typically within a few dB of the shot noise limit, and the distortion is very low, even for large modulation depths with peak modulation near 100%. Under the proper circumstances, directly modulated DFB lasers can meet all of these requirements. However, to insure that these demanding requirements will be met, all phenomena which can influence the noise and distortion of AM fiber optic links must be carefully studied. In this paper, the role of frequency chirping of DFB lasers in the noise and distortion of AM fiber optic links is discussed. The basic mechanisms for noise and distortion generation are reviewed, and experimental results for typical links are presented. Simple expressions for estimating the impact on CATV system noise and distortion specifications are presented. In many applications the maximum transmission distance is determined by the impact of fiber dispersion on linearity, rather than by the loss of the fiber. This is particularly true for 1550 nm systems, even when dispersion shifted fiber is used.

II. Impact of Chirp of Second Order Distortion

Frequency chirping of DFB lasers has been extensively studied [1-4]. Chirp can have a significant impact on bit error rates of digital transmission links, particularly for 1550 nm lasers transmitted through 1310 nm zero dispersion fiber. For digital applications, chirp is most often characterized in terms of the -20 dB width of the lasing spectrum when the laser is digitally modulated from a point near threshold to a specified high level. For analog systems, the small signal chirping characteristic for modulation about a bias point well above threshold is more relevant. This is most often described in terms of the change of optical frequency with current. The chirp for DFB lasers modulated at VHF frequencies typically ranges from 50 to 500 MHz/mA.

The specific mechanisms responsible for chirp in DFB lasers have recently been reviewed [1,2]. At CATV frequencies, the most important mechanisms are spectral hole burning and spatial hole burning. Spectral hole burning results in "blue" shifting, while spatial hole burning can cause either "blue" or "red" shifting. Because the individual mechanisms will sometimes add and other times cancel, the overall spread in the chirp observed for DFB lasers is quite large. Figure 1 shows the measured distribution of chirp for 16 1310 nm

DFB lasers and 6 1550 nm DFB lasers. The chirp was measured using a scanning Fabry-Perot interferometer. The measurement was done at 60 MHz in which case the dynamic spectrum of a DFB laser has two peaks characteristic of wide deviation FM modulation. The differences between the magnitudes of the laser chirp has significant implications for AM fiber optic links as will be discussed later. It is not clear at this time the extent to which the difference between the two distributions is fundamentally related to the laser wavelength, rather than other factors, such as the grating coupling coefficient, K.

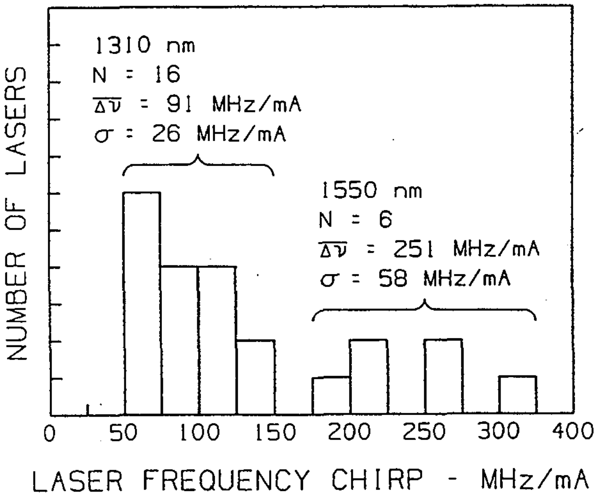

Figure 1
Distribution of measured frequency chirp for 1310 and 1550 nm DFB lasers.

There are several mechanisms by which laser chirp can result in distortion. Any optical component which has loss or delay which varies with optical frequency will convert laser chirp into optical distortion. Multiple optical reflections [5] and optical amplifiers [6] are two examples of situations where frequency dependent loss can occur. In most instances, wavelength dependent loss problems can be overcome by designing components with minimal wavelength dependent loss. A more fundamental problem occurs with fiber dispersion which results in wavelength dependent delay. The distortion due to chirp and dispersion has recently been analyzed [7,8].

If intensity modulated light from a DFB laser is transmitted through a dispersive medium, such as an optical fiber, then the laser frequency modulation is converted to a modulation of the transmission delay, τ, through the link. The output signal waveform, So(t) will be of the form

$$S_o(t) = \frac{S_i(t-\tau(t))}{1+\frac{\partial\tau}{\partial t}} \qquad (1)$$

where S_i(t) is the intensity modulation at the input side of the fiber and τ(t) is the time dependent fiber delay. The denominator accounts for "bunching" of the signal. The received optical power must be adjusted to account for the fact that light transmitted in a time interval Δt_T is received in a time interval Δt_R, which can be different from Δt_T. Light transmitted from time t_o to $t_o + \Delta t_T$ is received over the interval $t_o + \tau(t_o)$ to $t_o + \Delta t_T + \tau(t_o + \Delta t_T)$. Thus

$$\Delta t_R = \Delta t_T + \tau(t_o + \Delta t_T) - \tau(t_o)$$

$$= \Delta t_T\left(1 + \frac{\partial\tau(t_o)}{\partial t}\right) \qquad (2)$$

In this paper, we only consider the case where $\frac{\partial\tau}{\partial t} \ll 1$.

If the intensity modulation consists of two sinusoidally modulated signals, then the output signal waveform will contain second harmonics of the input frequencies as well as second order distortion at the sum and difference frequencies. The frequency chirping of DFB lasers at VHF frequencies is approximately linearly proportional to the modulation current and independent of the modulation frequency. For this case, the delay modulation is proportional to the intensity modulation with a proportionality constant, δ, and the second order distortion can be expressed as indicated below:

$$S_i = \cos(\omega_1 t) + \cos(\omega_2 t) \qquad (3)$$

$$\tau = \tau_o + \delta(\cos(\omega_1 t) + \cos(\omega_2 t)) \qquad (4)$$

$$\begin{aligned} S_o = {} & S_i + \omega_1 \delta \sin(2\omega_1 t) \\ & + \omega_2 \delta \sin(2\omega_2 t) \\ & + (\omega_1 + \omega_2)\delta \sin(\omega_1 + \omega_2)t \\ & + (\omega_1 - \omega_2)\delta \sin(\omega_1 - \omega_2)t \end{aligned} \tag{5}$$

Equation (5) assumes that $\frac{\partial \tau}{\partial t} \ll 1$, or equivalently, that $\omega\delta \ll 1$.

The RF power in the second order distortion products relative to the power in the fundamental signals is given by the square of the coefficients in (5). Comparing the coefficients in equation (5), distortion due to chirp and dispersion is seen to be most severe for additive second order products at frequencies $\omega_1 + \omega_2$ near the upper transmission frequency.

In an actual CATV system, there will be multiple carriers and many combinations of the various carriers that will produce distortion near the test frequencies. Composite second order distortion (CSO) is due primarily to two tone products at frequencies $f_1 \pm f_2$ because these products are 6 dB higher than the second harmonic and there are many two tone frequency combinations versus a single second harmonic product.

The composite distortion levels for multicarrier systems can be estimated from two tone second order measurements, or calculations, by using the following method.

1. Adjust the distortion level to account for the number of beats, or frequency combinations that produce distortion near the test frequency. For example, for a 62 channel NTSC frequency plan, there are 22 two tone second order products at 446.5 MHz. This would lead to an adjustment factor of 13.4 dB.

2. Adjust the level to account for inaccuracies in the rf power measurement technique. Spectrum analyzers are commonly used to measure composite distortion products. Spectrum analyzers when used according to common test methods do not accurately measure the total power for many closely spaced distortion products. Our empirical results indicate that the measured power will typically be 2-4 dB below the actual total power.

This estimation method will only be accurate if the distortion contributions from the different frequency contributions are additive. This is generally true when the second order distortion level exhibits the classic 2 dB change for a one dB change in fundamental level.

Following this method, the estimated CSO due to chirp and dispersion are given by:

$$\begin{aligned} CSO = {} & 20\log(\delta\omega) \\ & + 10\log(N_2) - 3dBc \end{aligned} \tag{6}$$

where N_2 is the numbers of second order products falling at the frequency ω, and a spectrum analyzer correction factor of 3 dB has been assumed. For a 62 channel NTSC system, there are 22 second order products falling 1.25 MHz above the upper carrier (445.25 MHz). The corresponding estimated CSO vs. δ is shown in Figure 2. The symbols represent measured data of CSO for a 1550 nm laser. The data for small δ is for transmission through dispersion shifted fiber. The data for large δ is for transmission through 1310 nm zero dispersion fiber. The deviation between measured and calculated values for large δ is due to a breakdown in the additivity approximation which requires $\omega\delta << 1$.

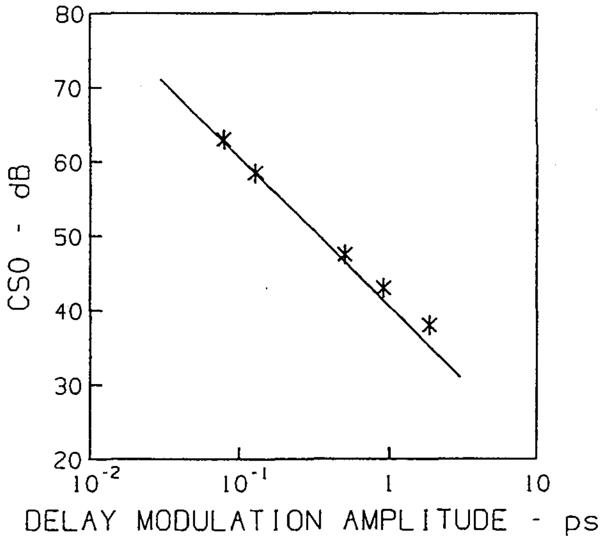

Figure 2
Calculated and measured CSO for a 62 channel NTSC CATV system due to chirp induced delay modulation.

Fiber optic links for AM video distribution, typically must operate at CSO values in the -60 to -65 dBc range. This includes distortion contributions from the amplifier driving the laser, the laser, the optical receiver, and any other mechanisms, such as fiber dispersion. Due to the technical challenges of fabricating DFB lasers with very good CSO, most of the distortion allocation is generally given to the laser. To minimize degradation due to dispersion, the CSO contribution due to dispersion should be no more than -70 dBc, unless the distortion is compensated by pre- or post-distortion. However, the distortion compensation option requires individual adjustment for each laser and fiber used which is often unacceptable for practical systems.

From equation (6), we can see that to meet the goal of -70 dBc CSO contribution due to dispersion, δ should not exceed 0.034 ps for the 62 channel NTSC example. The corresponding constraint on laser chirp can be determined from the relation:

$$\delta = DL\Delta\lambda \qquad (7)$$

where D is the fiber dispersion, L is the link length in km, and $\Delta\lambda$ is the amplitude of the wavelength chirping, in nm, due to the current modulation from a single channel. Taking D to be 1 ps/nm-km, which allows for a 11 nm mismatch from the zero dispersion point at 1310 nm or a 12 nm mismatch at 1550 nm, and L = 20 km.

$$\delta = 20\Delta\lambda \qquad (8)$$

Alternatively, if the chirping is expressed in MHz, the relation for 1310 nm systems is:

$$\delta = 1.14x10^{-4}\Delta\upsilon \text{ ps} \qquad (9)$$

where $\Delta\upsilon$ is the amplitude of the chirp due to the modulation current of a single channel in MHz.

For 1550 nm systems the relation is:

$$\delta = 1.60x10^{-4}\Delta\upsilon \text{ ps} \qquad (10)$$

For this particular example, we arrive at a maximum acceptable chirp of 296 MHz/ch for 1310 nm and 211 MHz/ch for 1550 nm. These numbers, together with the measurements of actual chirp shown in figure 1 are of tremendous practical significance. In the case of the 1310 nm systems, the laser with the largest chirp could be modulated with up to 2 mA/ch before reaching the chirp constraint, and this is slightly more than the typical modulation current for a 62 channel system of 1.8 mA. However, in the case of 1550 nm, the laser with the lowest chirp is limited to only 1.15 mA/ch which is 4 dB less than typical for 62 channel systems. This results in a corresponding decrease in system C/N. The 1550 nm laser with maximum chirp is limited to 0.6 mA/ch, or nearly 10 dB less than typical. If 1310 nm zero dispersion fiber with a dispersion of 18 ps/nm-km at 1550 nm is used, the 1550 nm laser with the lowest chirp is restricted to 0.074 mA/ch, or a reduction of 29 dB from typical.

In the absence of lower chirp 1550 nm DFB lasers, system designers are forced to make undesirable compromises in order to use 1550 nm DFB lasers. The choices are:

1. Accept system CSO degradation due to chirp.
2. Restrict modulation currents and thereby reduce C/N.
3. Limit transmission distances and thereby sacrifice the advantage of low loss at 1550 nm and the potential for extending transmission distances using Er doped fiber amplifiers.

4. Match laser wavelengths precisely to the fiber zero dispersion point.

5. Distortion compensate individual laser/fiber combinations.

It is important to stress that the serious dispersion problems with 1550 nm DFB lasers discussed above occur when dispersion shifted fiber is used. In the case of 1550 nm lasers with 1310 nm fiber the problem is much more severe.

III. Impact of Chirp on Noise in Fiber Optic Links

In the preceeding section, the affect of DFB laser chirp on distortion for AM video transmission was discussed. Chirp is undesirable with respect to distortion. However, the opposite is true for noise. The C/N of AM links is unavoidably degraded by double backscattering of light. This effect has recently been analyzed [9,10]. The mixing at the photodiode of light that is transmitted directly from the laser to the photodiode with light that has been twice reflected generates noise which extends over frequencies proportional to the chirped linewidth of the laser. The total amount of noise depends on the fraction of doubly reflected light. Therefore, the more laser chirp, the lower the spectral density of this noise mechanism. It should also be noted that if the laser chirp is much less than the minimum operating frequency of the link, then most of the noise will be out of band. This low chirp case is not attainable with direct modulation of DFB lasers, but can be achieved with external modulation of solid state lasers. The noise that does appear in externally modulated links, however, is at frequencies close to the carrier which is particularly objectionable.

As has been previously reported, the double Rayleigh scattering noise mechanism has the following dependences on fiber length and chirp.

$$\text{Noise} \sim L-\frac{1}{2\alpha}[1-e^{-2\alpha L}]$$

$$Noise \sim \frac{1}{\Delta\upsilon} \qquad (11)$$

We have measured the noise degradation for many 1310 nm lasers and numerically fit the results to the expressions above. To evaluate the noise increase due to double backscattering, we measure the link C/N for the same laser for transmission through a length of fiber and for an optical attenuator of the same loss. The double backscattering introduces an additive equivalent laser relative intensity noise (RIN). Our numerical estimate for this noise for 1310 nm links is given below.

$$\text{RIN}_{dbs}=\frac{3.6x10^{-14}\left[L-\frac{1}{2\alpha}(1-e^{-2\alpha L})\right]}{\Delta\upsilon_{RMS}} \qquad (12)$$

where $\Delta\upsilon_{RMS}$ is the RMS frequency chirping in MHz, L is the link length in km, and α is the link attenuation (0.80 km^{-1} for the fiber we used). Because this measurement involves estimating a relatively small noise contribution in the presence of other noise sources, the estimate has a potential error of ±1 dB. We do not have a similar estimate for 1550 nm links, but preliminary measurements indicate that the noise contribution is nearly the same as for a 1310 nm laser with the same RMS frequency chirp.

The equivalent RIN due to double backscattering is shown in Figure 3. For comparison, a receiver with a DC photodiode current of 0.5 mA, which is typical for AM links, has noise due to shot noise of the photodetection process that is equivalent to a RIN of -151.9 dB/Hz. The impact of double backscattering noise can also be seen in figure 4, which shows link C/N for a 20 km, 62 channel link for various values of laser chirp. In Figure 4, the following link parameters, which are typical of 62 channel 1310 nm links were assumed. The laser power was 6 mW with a modulation depth of 4.5%/ch. The receiver noise current was taken to be 5 $\text{pA/Hz}^{1/2}$ and the responsivity was 0.9 A/W. The link loss was taken to be 0.4 dB/km + 1 dB.

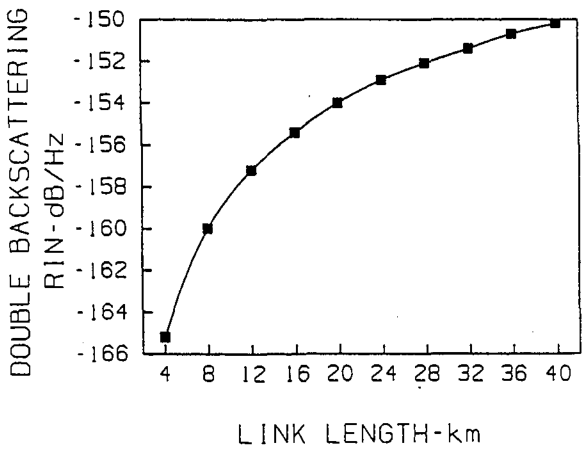

Figure 3
Equivalent relative intensity noise generated by double Rayleigh scattering in 1310 nm fiber link. RMS laser chirp is 1000 MHz.

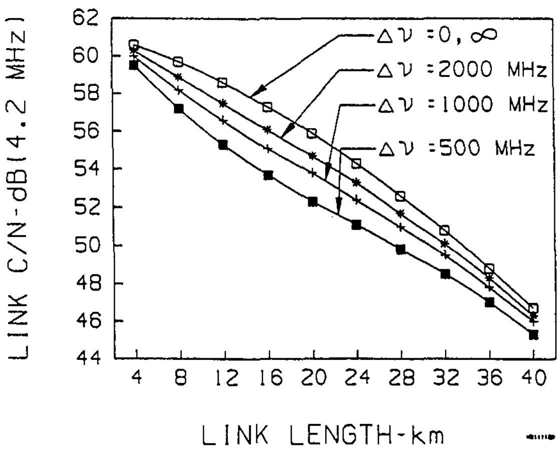

Figure 4
Effect of double backscattering noise on the C/N of a 62 channel CATV fiber link.

In the previous section, an upper limit for 1310 nm laser chirp amplitude of 296 MHz/ch, to avoid excessive distortion in a 62 channel, 20 km link was obtained. This corresponds to an RMS frequency chirp of 1650 MHz from the modulation of all 62 channels. Due to double backscatter noise, a lower limit on the acceptable chirp can also be defined. Figure 5 shows the minimum laser chirp required for 1, 2, and 3 dB system noise penalties as well as the maximum chirp for -70 dBc CSO contribution. As can be seen, for laser RMS chirp around 1000 MHz, the CSO constraint is satisfied and the noise penalty is less than 2 dB for links up to 20 km in length. We believe this represents the best compromise between noise and distortion. Fortunately, the majority of the 1310 nm lasers have chirp near this target level. All of the 1550 nm DFB lasers are significantly above the target for normal modulation currents. It should also be noted that the 1000 MHz target was for a specific set of link parameters. For other link parameters, the acceptable range will change. However, for most AM links of practical interest, laser chirp plays a significant role in determining the C/N and distortion of the link.

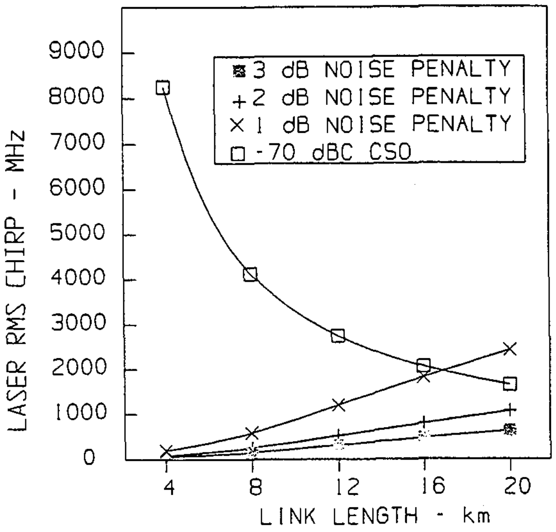

Figure 5
System noise and distortion constraints for laser chirp.

IV. Summary

In this paper, the basic mechanisms by which DFB laser chirp can affect the noise and distortion of AM fiber optic links has been reviewed. Expressions are presented for estimating the impact of these phenomena on the CATV system specifications of C/N and CSO. These expressions have been found to be in good agreement with measured results. Laser chirp can adversely impact link linearity, but is important in minimizing noise due to double Rayleigh backscattering. There is a relatively narrow range for chirp in which the impact on both noise and distortion is acceptable. 1310 nm DFB lasers consistently fall within this range. Preliminary measurements indicate that 1550 nm DFB lasers have chirp which is greater than the upper limit of the acceptable range. This results in serious linearity problems for 1550 nm links even when dispersion shifted fiber is used.

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