Fiber induced distortion and phase noise to intensity noise conversion in externally modulated CATV systems

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Abstract

Fiber nonlinearity and chromatic dispersion can severely degrade the signal quality in externally modulated long-haul AM-VSB CATV transport systems. Standard single-mode fiber chromatic dispersion will convert inherent laser phase noise fluctuations to intensity noise. This dispersion-induced intensity noise increases with frequency, and thereby, imposes a fundamental limit on CNR. Even in the absence of stimulated Brillouin scattering, self-phase-modulation and chromatic dispersion induces CSO distortion. For transmission over 70 km fiber, CNR and CSO degradation associated with fiber nonlinearity and chromatic dispersion limits laser linewidth and fiber launch power to less than 1 MHz and less than 18 dBm, respectively.

I. INTRODUCTION

Efforts to enlarge the dynamic range of multichannel CATV systems has received attention with the advancement of linear lasers, linearized external modulators and low noise erbium-doped fiber amplifiers (EDFAs). To improve network reliability, upgradability and video signal quality, fiber is being deployed deeper into the CATV architectures, serving a smaller number of home pockets. Operating at the 1550-nm window is attractive where EDFAs can be employed to increase the power budget of future CATV transport systems.

For a directly modulated 1550-nm laser system, significant composite-second-order distortion (CSO) is generated when the laser chirp interacts with the standard single-mode fiber chromatic dispersion. For an externally modulated 1550-nm system, CSO distortion due to chromatic dispersion is negligible. However, fiber nonlinearites such as stimulated Brillouin scattering (SBS), self-phase modulation (SPM) and modulation instability (MI) can degrade the CSO distortion in high power cascaded amplifier CATV transport systems. SPM causes frequency chirp which interacts with fiber chromatic dispersion [1]-[3] which, in turn, degrades CSO in proportion to fiber input power and fiber length.

When the externally modulated light is transmitted through a long fiber length, laser phase noise is converted to intensity noise (PM-AM) due to chromatic dispersion [4]. This dispersion-induced intensity noise depends on the laser linewidth, fiber length and increases with frequency.

In this paper, the potential CNR and CSO degradation associated with fiber nonlinearity and chromatic dispersion is experimentally observed and analytically verified.

II. ANALYSIS

A. SPM-Dispersion Induced Distortion

The SPM is generated when the intensity modulated optical carrier transmitted through a single-mode fiber undergoes a nonlinear phase shift through a third-order fiber nonlinear process. The incremental nonlinear phase shift per unit length is given by

$$\Delta\phi_{NL}(t,z) = e^{-\alpha\cdot z}\gamma\,|a(t)|^2 \qquad (1)$$

where α is the fiber loss, $\gamma = 2\pi n_2/\lambda A_{eff}$ is the fiber nonlinearity coefficient at the wavelength λ, n_2 is the nonlinear index, A_{eff} is the fiber effective core area and $a(t)$ is the optical field envelope which carries the amplitude information. The intensity of the optical field envelope is expressed as

$$|a(t)|^2 = P_O\left(1+m\sum_{i=1}^{N}\cos(\omega_i t+\theta_i)\right) \qquad (2)$$

where P_o is the average optical power of the optical signal, m is the modulation depth, N is the total number of CATV channels. The *total* nonlinear phase increases as the field propagates through the single-mode fiber distance. The optical field of the signal at a distance z without any interaction with fiber chromatic dispersion is given by

$$e(t,z)=e^{-\alpha\cdot z/2}a(t)\exp j\{\omega_O t+\phi(t,z)\} \qquad (3)$$

where ω_o is the angular frequency of the optical carrier,

$$\phi(t,z)=\phi_{NL}(t,z)+\phi_{PN}(t)+\phi_{PM}(t) \qquad (4)$$

denotes the phase information of the optical field, $\phi_{NL}(t,z)=\int_0^z \Delta\phi_{NL}(t,z')\,dz'$ is the nonlinear phase variation due to fiber nonlinearity, $\phi_{PN}(t)$ is the laser phase noise and $\phi_{PM}(t)$ is the phase modulation applied to increase the SBS power threshold. The propagation of the optical field *e(t,z)* through a single-mode fiber can be described by the propagation term $exp\{-j\beta(\omega)z\}$ where

$$\beta(\omega)=\beta_0+\beta_1(\omega-\omega_o)+\frac{1}{2}\beta_2(\omega-\omega_o)^2 + \frac{1}{6}\beta_3(\omega-\omega_o)^3+\cdots+ \quad (5)$$

is the propagation constant expanded around ω_o. The terms β_0, β_1, β_2,..., denotes the derivatives of the propagation constant with respect to the angular frequency. For a standard single-mode fiber, the dominant dispersive term is $\beta_2 = -D\lambda^2/2\pi c$, whereas for operation near zero dispersion or for a dispersion shifted single-mode fiber, β_3 and higher terms dominate.

It is generally difficult to solve for the combined effect of SPM and fiber chromatic dispersion. Several numerical and analytical approaches have been used in the past [1],[2]. We will approximate the interaction of SPM with chromatic dispersion in a similar way described in [5].

The optical field after interacting with fiber chromatic dispersion, to first-order, can be approximately described as [6]

$$e(t,z)=e^{-\alpha\cdot z/2}e^{-\frac{1}{2}\frac{d\tau(t,z)}{dt}}a(t-\tau(t,z)) \cdot\exp j\{\omega_O t+\phi(t,z)\} \quad (6)$$

where

$$\tau(t,z)=\beta_2 z\left(\dot{\phi}_{NL}(t,z)+\dot{\phi}_{PN}(t)+\dot{\phi}_{PM}(t)\right) \quad (7)$$

is the total group delay generated by the interaction of the nonlinear chirp, phase noise, and phase modulation with fiber chromatic dispersion. From expression (6) the intensity of the optical carrier detected at a distance z=L can be expressed as

$$i(t)\cong e^{-\alpha L}\left|a(t-\tau(t,L))\right|^2\left(1-\frac{d}{dt}\tau(t,L)\right). \quad (8)$$

In this analysis, we have assumed that the transmitted optical field undergoes an incremental phase shift $\Delta\phi_{NL}(t,z)$ at distance z. The field is then assumed to interact with the dispersive fiber from z to L. Therefore, the nonlinear group delay can be found as

$$\tau_{NL}(t,L)=\beta_2\int_0^L (L-z')\Delta\dot{\phi}_{NL}(t,z')\cdot dz'. \quad (9)$$

The CSO due to fiber nonlinearity, (i.e., SPM), at channel $\omega_k = \omega_i \pm \omega_j$ can be found by using Bessel function of expansion:

$$CSO_{NL}(\omega_k)=\frac{K_2}{4}\left(D\frac{\lambda^2}{2\pi c}\gamma\, P_O m\omega_k^2 \cdot\frac{\left(\alpha L+e^{-\alpha L}-1\right)}{\alpha^2}\right)^2. \quad (10)$$

B. AM-Dispersion Induced Distortion

To increase the optical power threshold of SBS the optical field from an externally modulated transmitter is phase modulated. Thus, the envelope of the optical field which carries the amplitude modulated (AM) information signal is spectrally translated at multiple octaves of the phase modulating frequency. When the spectrally translated optical envelope interacts with chromatic dispersion at long fiber lengths, CSO distortion is generated. Unlike the work in [7], the AM-dispersion induced CSO distortion, when the optical spectrum is spectrally translated at multiple octaves, is found to be low. However, using a similar approach to [8] we have derived the AM-dispersion induced distortion as follows:

$$CSO_{AM}(\omega_k)=K_2\left(\sum_{n=-\infty}^{\infty}J_n(m/2)J_{n+2}(m/2) \cdot m^{-1}\cos\left(\frac{\omega_k^2}{2}\frac{\lambda^2}{2\pi c}DL(n+1)\right)\right)^2. \quad (11)$$

The amplitude of the second-order AM distortion is lower in magnitude with an opposite sign compared to the amplitude of the SPM distortion. Thus, the system CSO distortion which is composed of contributions from SPM- and AM-dispersion induced distortion. However, CSO_{AM} is much lower in magnitude than CSO_{NL}.

C. PM-Dispersion Induced Intensity Noise

The group delay generated by the interaction of the laser phase noise and fiber chromatic dispersion is determined as follows:

$$\tau_{PN}(t,L)=\beta_2 L\dot{\phi}_{PN}(t). \qquad (12)$$

The variance of the laser frequency noise is

$$\sigma^2_{\dot{\phi}_{PN}} = 4\pi\Delta\nu \qquad (13)$$

where $\Delta\nu$ is the laser linewidth. The signal current at the photodetector output, after traveling through a fiber of length z=L, is given by

$$i(t) \cong e^{-\alpha L}\left|a(t-\tau(t,L))\right|^2 \cdot \left(1 + D\frac{\lambda^2}{2\pi c}L\ddot{\phi}_{PN}(t)\right). \qquad (14)$$

The RIN due to laser phase noise to intensity noise conversion can be easily found as follows:

$$RIN_{PM-AM}(\omega) = 4\pi\Delta\nu\left(D\frac{\lambda^2}{2\pi c}L\right)^2\omega^2. \qquad (15)$$

Inspection of expression (15) shows that the RIN is proportional to $\Delta\nu(\omega L)^2$.

III. RESULTS

Figure 1 shows the schematic of our experimental setup. The 1550-nm distributed-feedback laser (DFB) source has an optical power of 20-mW and a laser linewidth of 1 MHz. The optical signal is externally modulated by 77 AM-VSB NTSC channels, amplified and transmitted through L_1= 25, 50 and 70 km of standard single-mode fiber. The input power launched into the fiber was about 18 dBm. In the second part of the experiment, we employed a 16 dBm output power in-line amplifier. In this experiment, the externally modulated optical signal is transmitted through L_1=50 km of fiber, amplified and then passed through another L_2=45 km of fiber. The total fiber length employed in the second part of the experiment was about 95 km.

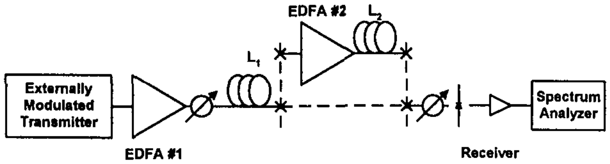


Figure 1. Experimental setup employed to investigate SPM-dispersion induced CSO distortion.

To increase the optical power threshold limited by SBS, we have both phase and frequency modulated the optical field by applying out-of-band RF tones. The optical modulation depth measured over the CATV band has a down tilt of about 1.8 dB due to the transmitter response. The modulation depth was measured to be 2.7%, 2.5% and 2.2% at channels 2, 41, 78, respectively. In our calculations, we have used the modulation depth measured at the mid-channel (i.e., m=2.5%).

Table 1. List of Parameters used in our Model

Parameters	
λ	1553 nm
n_2	$2\cdot10^{-20}$ m^2/W
A_{eff}	80 μm^2
α	0.0576 Np/km
D	17 ps/nm·km
K_2	29

Figure 2 plots the CSO of the system as a function of fiber input power. Inspection of Figure 2 indicates that as the input power to the fiber is increased the SPM-dispersion induced CSO degrades. At 18 dBm fiber input power the measured CSO is -66.8 and -62 dBc when m=2.5% and 3.4%, respectively.

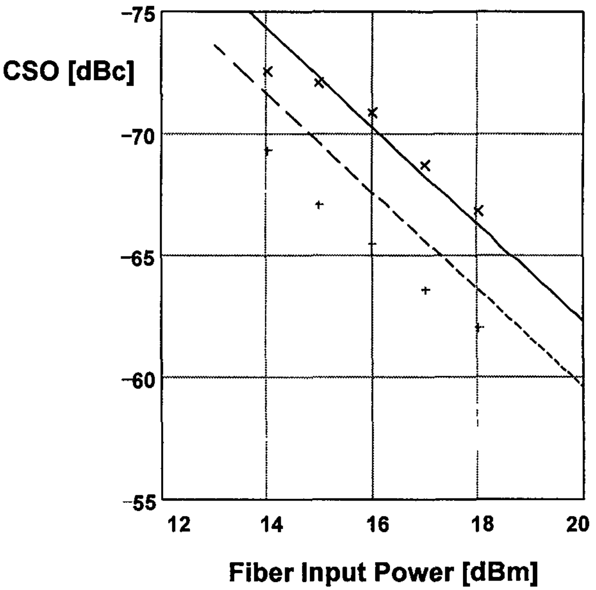


Figure 2. Plots of measured (x and +) and calculated (solid and dashed lines) CSO versus fiber input power at channel frequency 547.25 MHz and 50 km fiber. Solid line and (x) indicate CSO for m=2.5%; and dashed and (+) indicate CSO for m=3.4%.

Figure 3 plots the CSO of the system as a function of fiber length. Inspection of Fig. 3 indicates that at fiber lengths greater than about 50 km the measured and calculated CSO behave somewhat differently as the fiber length is increased. The discrepancy observed between the measured and calculated CSO is currently under investigation.

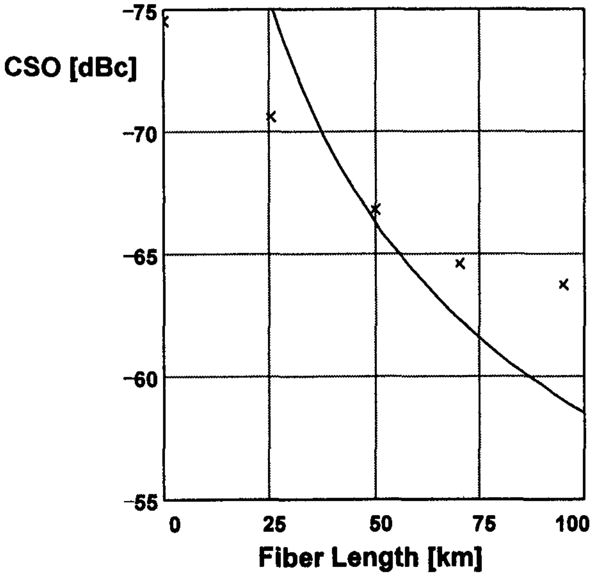
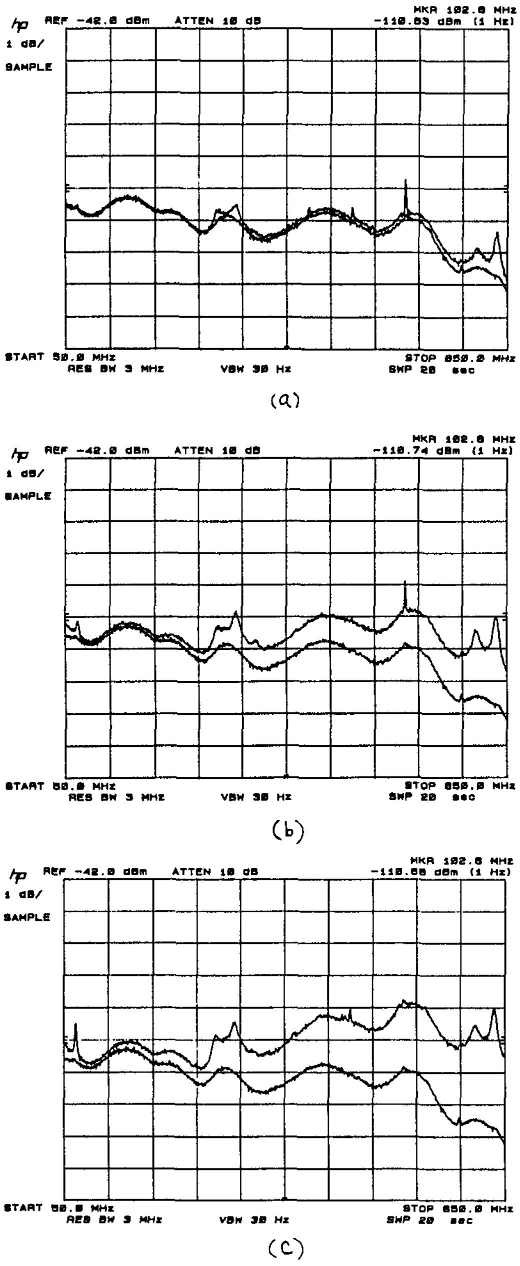


Figure 3. Plots of measured (x) and calculated (solid line) CSO versus fiber length for 18 dBm fiber input power and at channel frequency 547.25 MHz. Solid line and (x) indicates CSO for m=2.5%.

Figure 4 shows the system noise spectrum within the CATV band for various fiber lengths. The system noise spectrum is composed of a noise floor due to shot, thermal, laser intensity and amplifier noise; and frequency dependent noise due to fiber chromatic dispersion induced PM-AM noise. At lower frequencies, the noise spectra converges to the noise floor, while at higher frequencies the noise increases proportionally to the square of the frequency and fiber length. The system CNR penalty due to PM-AM noise is reduced by using a source laser with very narrow linewidth. Figure 5 shows the CNR penalty as a function of $\Delta\nu L^2$. The CNR penalty is calculated using the following parameters: received power 0 dBm, thermal noise 7 pA/√Hz, laser RIN -164 dB/Hz and amplifier RIN -156 dB/Hz. To achieve a CNR penalty of less than 0.5 dB for transmission over 50 km or 70 km of fiber length, the required laser linewidth is 440 kHz or 225 kHz at 550 MHz, respectively.

IV. CONCLUSIONS

We have investigated the interaction of SPM and laser phase noise with chromatic dispersion in an externally modulated AM-VSB lightwave CATV system. The CNR degradation associated with PM-AM noise is minimized by employing narrow linewidth laser sources. The CSO performance due to SPM-dispersion interaction can be a limiting factor in high power long-haul CATV trunk systems. The CATV system must be designed according to these limitations.



(a)

(b)

(c)

Figure 4. Plots of system noise spectrum with (a) 25 km, (b) 50 km and (c) 70 km of standard fiber (upper traces) and short fiber (lower traces).

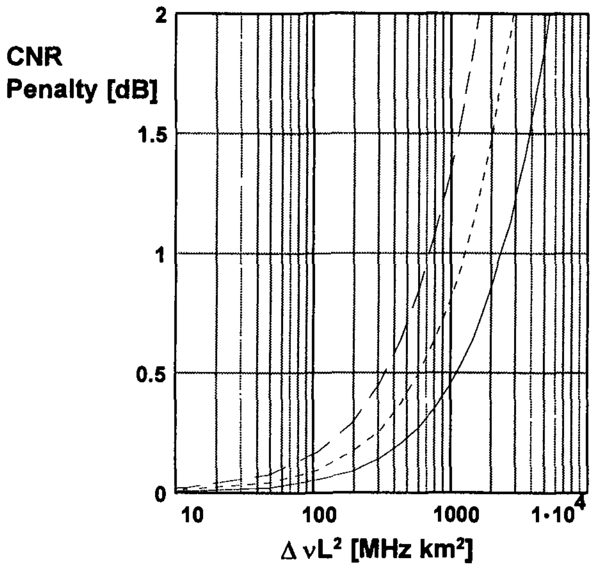


Figure 5. Plots of calculated CNR penalty versus $\Delta \nu L^2$. Solid, dotted and dashed lines indicate the penalty at 550 MHz, 750 MHz and 1000 MHz, respectively.

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