CSO Distortions Due to the Combined Effects of Self- and External-Phase Modulations in Long-Distance 1550-nm AM–CATV Systems

M. C. Wu, *Member, IEEE,* C. H. Wang, and W. I. Way, *Senior Member, IEEE*

Abstract— **We found that the combined effects of self- and external-phase modulations must be considered in order to precisely predict the composite second-order distortions in a long-distance 1550-nm externally modulated AM–cable TV (CATV) system, especially when the applied phase modulation index and modulating tone frequency to the integrated phase modulator are high. This result has important implications to the optimum design of 1550-nm transmitter for long-distance AM– and QAM–CATV systems.**

Index Terms—**Cable TV, communication system nonlinearity, fiber chromatic dispersion, nonlinear distortion, subcarrier multiplexing.**

I. Introduction

RECENTLY, there has been intense interests in long-distance 1550-nm external-modulation AM–CATV systems based on conventional single-mode fibers [1]–[7]. When the optical power launched into these long-distance systems is below the stimulated Brillouin scattering (SBS) threshold, it has been found that the transmission distance is mainly limited by the fiber dispersion-induced composite second-order (CSO) distortions. These CSO distortions in turn were believed to be caused by self-phase modulation (SPM) [3]–[5], and by the residual intensity modulation from an imperfect phase modulator [6]. However, analyses developed for either of the above mechanisms were not accurate in predicting the resultant CSO values in long-distance AM–CATV transmission systems [5]–[7].

It is noted that all commercially available 1550-nm CATV transmitters have an integrated phase modulator and a Mach–Zehnder interferometer (MZI) modulator. In order to increase the SBS threshold, a $\sim$2 GHz tone (or a few tones $>\sim$2 GHz) is usually applied to the phase modulator, and a high SBS threshold can be obtained by using a high phase modulation (PM) index (β) [8]. However, the resultant high launched optical power into the system can unavoidably increase the SPM effects. In addition, when the applied PM index β or the PM modulating tone frequency are high, or when the transmission distance is long, both SPM and external phase modulation (EPM) can be mixed with intensity modulation in a nonlinear dispersive optical fiber system. The resultant CSO distortions due to their combined effects, however, have not yet been thoroughly investigated. This paper presents both experimental and numerical results on the above subject.

Manuscript received December 2, 1998; revised February 3, 1999. This work was suppported by the National Science Council, R.O.C., under Contract NSC87-2215-E009-002.

The authors are with the Department of Communications Engineering, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C.

Publisher Item Identifier S 1041-1135(99)04220-2.

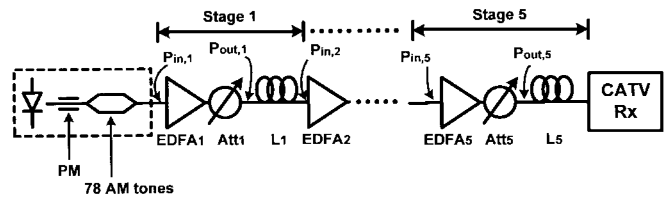

Fig. 1. Experimental setup.

II. Experimental Setup

The experimental setup is shown in Fig. 1. In the experiment with only a booster erbium-doped fiber amplifier (EDFA), we used an 1551.7-nm transmitter with an integrated phase modulator and a Mach–Zehnder interferometer (MZI) modulator. The linewidth, and output power of the transmitter were 1 MHz and 8.6 dBm, respectively. The phase modulator was modulated by three tones at 1.9, 3.8, and 5.7 GHz, with β's of 3.9, 3.9, and 1.3, respectively. The resultant SBS threshold is as high as 17 dBm. The MZI modulator was modulated by 78 AM tones from a matrix generator with an optical modulation index (OMI) per channel of 2.8%.

In the experiment with four additional inline EDFA's, the center wavelength, linewidth, and output power of the transmitter were 1561.1 nm, 2 MHz, and 8 dBm, respectively. The launched optical power from each EDFA $(P_{\mathrm{out},i}, i \geq 1)$ was adjusted to be 12 dBm for an interstage optical fiber span of 60 km, and the input power $(P_{\mathrm{in},i}, i \geq 2)$ of each in-line EDFA was 0 dBm. A 1.9-GHz tone with a varying rf voltage level was used to drive the phase modulator, and the combined effects of SPM and EPM at various β's were studied. In the mean time, the CSO value at channel 2 was constantly monitored to ensure that the SBS effect could be ignored [9].

The effective core area (A_{eff}) and the attenuation (α) at 1550 nm of the transmission fiber were measured to be 90 μm^2 and 0.2 dB/km, respectively.

III. Experimental, Numerical, and Analytical Results

The analytical result for SPM-induced frequency-dependent CSO's is given by [3]–[5]

$$\mathrm{CSO}_{\mathrm{SPM}}(\Omega) = \left[\frac{1}{2}\, m \cdot \frac{\lambda^2}{2\pi c}\, D \cdot k \cdot n_2 \cdot \frac{P_0}{A_{\mathrm{eff}}} \cdot \Omega^2 \cdot \overline{z^2}(L)\right]^2 N_{\mathrm{CSO}} \quad (1)$$

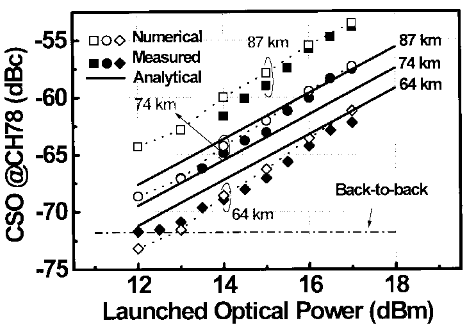

Fig. 2. CSO @ channel 78 as a function of launched optical power into a repeaterless AM–CATV system with three different transmission distances: 64, 74, and 87 km. Numerical results are for CSO's caused by both SPM and EPM effects, while analytical results are based (1). Key parameters include: OMI/ch $= 2.8\%$, number of AM channels $= 78$, $\lambda_0 = 1551.7$ nm, $D = 17$ ps/nm/km, $n_2 = 2 \times 10^{-20}$ m^2/W, fiber loss $=$ 0.2 dB/km, and $A_{\rm eff} = 90$ μm^2. β's for the three tones at 1.9, 3.8, 5.7 GHz are 3.9, 3.9, and 1.3, respectively. Soild lines, open symbols, and solid symbols represent analytical, numerical, and measured results, respectively.

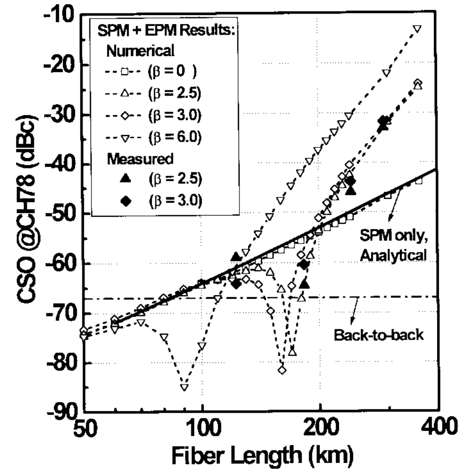

Fig. 3. Measured, numerically calculated, and analytical CSO's @ channel 78 as a function of the total fiber length in an equal-span, multistage-repeatered AM–CATV system. Interstage fiber span is 60 km. The launched optical power from each EDFA ($P_{{\rm out},i}, i \geq 1$) was 12 dBm. (OMI/ch $= 3\%$, $\lambda_0 = 1561.1$ nm. Single tone phase modulation at 1.9 GHz. Other parameters are the same as those given in Fig. 2).

where m is the OMI per channel, $k = 2\pi/\lambda$, n_2 is the nonlinear refractive index of the fiber, P_0 is the launched optical power, $\overline{z^2}(L) = (\alpha L + e^{-\alpha L} - 1)/\alpha^2$, L is the fiber length, Ω is the angular frequency at which CSO occurs; $N_{\rm CSO}$ is the product count of second-order intermodulation products, and D is the fiber dispersion. For a long-distance system with cascaded EDFA's and equal interstage fiber spans (EDFA gain = fiber span loss), (1) is still applicable except that the term $\overline{z^2}(L)$ should be replaced by

$$\overline{z^2}(L) + (1 - e^{-\alpha L/N}) \cdot \sum_{i=1}^{N-1} \overline{z^2}((N-i) \cdot L/N)$$

where N is the EDFA stages, L/N is the fiber span per stage [4].

Our numerical calculations, which can include both the SPM and EPM effects, are based on the split-step Fourier transform method. A sampling frequency 262.144 GHz was used to include all optical spectral components. Each CSO data is the average result of 50 times of different carrier phase combinations. The accuracy of our numerical results was confirmed by making sure that the numerical and analytical results differ by less than 1 dB when the PM index $\beta = 0$.

For the repeaterless experiment, Fig. 2 shows the worst-case CSO in channel 78 as a function of launched optical power ($P_{\rm out,1}$, see Fig. 1), for three transmission distances of 64, 74, and 87 km. We can see that the analytical results, which account for the SPM effect only, have clustered data for the three distances. Meanwhile, the measured and numerically calculated results spread farther than the analytical results for the three distances. It should be noted that a previous analysis of wave-envelope equation, even though with EPM included, did not find any CSO generated by the mix of EPM and intensity modulation [6]. This is probably due to the fact that the perturbation analysis in [3]–[5] did not include frequency-, β-, and L-dependent PM-to-IM conversion and carrier compression, whereas we believe that these effects play important roles in generating new CSQ terms. The above dispersion-induced effects should not be neglected especially

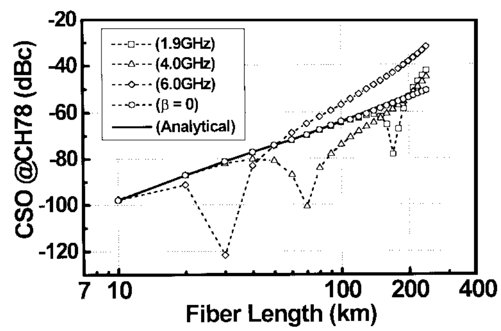

Fig. 4. Numerically calculated and analytical CSO's @ channel 78 as a function of the total fiber length in an equal-span, multistage repeatered AM–CATV system. ($\beta = 2.5$ for all PM modulating tone frequencies. Other parameters are the same as those given in Fig. 3.)

when: 1) the transmission distance is very long; 2) the PM index β is large; and 3) the PM modulating tone frequency is very high. This conjecture was confirmed by our experimental and numerical results shown in Figs. 3 and 4. The measured results in Fig. 3 were obtained when the fiber length and $P_{{\rm out},k}$ ($k \geq 1$, see Fig. 1) of each stage were 60 km and 12 dBm, respectively, and the total length was 300 km. We can see that the analytical results based on (1) is accurate only when the PM index β is small (e.g., $\beta = 2.5$ or 3.0) and the transmission distance is short (e.g., <120 km), while the numerically calculated results match well with the measured results for all β's and distances. Note that in the case when $\beta = 0$, the analytical and numerical results match perfectly. In Fig. 4, the numerically calculated results of CSO at channel 78 versus fiber length were obtained by fixing the PM index β at 2.5, and varying the PM modulating tone frequency from 1.9 to 6 GHz. We can see that in the case of the 6 GHz tone, the numerical results deviate away from the analytical results even when the distance is as short as 20 km (with a difference of about 4 dB). In the cases of 4 and 1.9 GHz, significant differences between the numerical and analytical results start to occur at distances >40 km and >120 km, respectively.

IV. Conclusion

By carrying out a 78-channel CATV transmission experiment with a link distance up to 300 km, and a numerical split-step transform method, we have confirmed that the CSO's can be accurately predicted by considering the combined effects of SPM and EPM. The calculated CSO's become inaccurate if one considers SPM only, especially when 1) the applied phase modulation index or tone frequency is high, and/or 2) the transmission distance is long (e.g., around 100 km). This conclusion has important implications to the optimum design of 1550-nm transmitter for long-distance AM– and QAM–CATV transmission systems.

References

[1] C. Y. Kuo, D. Piehler, C. Gall, J. Kleefeld, A. Nilsson, and L. Middleton, "High-performance optically amplified 1550-nm lightwave AM-VSB CATV transport system," in *OFC'96 Tech. Dig.*, pp. 196–197.

[2] H. Dai, S. Ovadia, and C. Lin, "Hybrid AM-VSB/M-QAM multichannel video transmission over 120 km of standard single-mode fiber with cascaded erbium-doped fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 1713–1715, Dec. 1996

[3] M. R. Phillips, T. E. Darcie, D. Marcuse, G. E. Bodeep, and N. J. Frigo, "Nonlinear distortion generated by dispersive transmission of chirped intensity-modulated signals," *IEEE Photon. Technol. Lett.*, vol. 3, no. 5, May 1991.

[4] C. Desem, "Composite second order distortion due to self-phase modulation in externally modulated optical AM-SCM systems operating at 1550 nm," *Electron. Lett.*, vol. 30, no. 24, pp. 2055–6, Nov. 1994.

[5] D. A. Atlas, "Fiber induced distortion and phase noise to intensity noise conversion in externally modulated CATV systems," in *1996 NCTA Tech. Papers*, pp. 289–293.

[6] M. R. Phillips, D. W. Anthon, and K. L. Sweeney, "Chromatic dispersion effect in CATV analog lightwave systems using externally modulated transmitters," presented at OFC'96, postdeadline paper PD17.

[7] F. W. Willems, W. Muys, and J. C. van der Plaats, "Experimental verification of self-phase-modulation-induced nonlinear distortion in externally modulated AM-VSB lightwave systems," in *OFC'96 Tech. Dig.*, pp. 281–282.

[8] F. W. Willems, J. C. van der Plaats, and W. Muys, "Harmonic distortion caused by stimulated Brillouin scattering suppression in externally modulated lightwave AM-CATV systems," *Electron. Lett.*, vol. 30, no. 4, pp. 343–345, Feb. 1994.

[9] M. R. Phillips, "Distortion by stimulated Brillouin scattering effect in analog video lightwave systems," presented at the OFC'97, postdeadline paper PD23.