tion difficulties. However, its complicated structure will result in lower yields than for other lasers used as CW sources. The DBR laser/modulator PIC is an ideal source for multichannel WDM transmission systems.

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REFERENCES

[1] S. M. Bahsoun, D. A. Fishman, and J. A. Nagel, "WDM Applications for optically amplified systems," in *Tech. Dig. OE / Fibers'92 SPIE Conf.*, Boston, MA.

[2] P. M. Gabla, J. O. Frorud, E. Leclerc, S. Gauchard, and V. Havard, "1111-km, two-channel IM-DD transmission experiment at 2.5 Gb/s through 21 in-line erbium-doped fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 4, p. 717, July 1992.

[3] M. Suzuki *et al.*, "Monolithic integration on InGaAsP/InP distributed feedback laser and electroabsorption modulator by vapor phase epitaxy," *J. Lightwave Technol.*, vol. LT-5, p. 1277, 1987.

[4] H. Soda *et al.*, "5 Gb/s transmission experiment using a monolithic electroabsorption modulator/DFB laser light source," in *Tech. Dig. OFC'89*, Houston, TX, Paper PD1.

[5] H. Tanaka *et al.*, "5 Gb/s performance of integrated light source consisting of $\lambda/4$-shifted DFB laser and E-A modulator with S.I.-InP BH structure," *J. Lightwave Technol.*, vol. 8, p. 1357, 1990.

[6] J. L. Zyskind, V. Mizrahi, D. J. DiGiovanni, and J. W. Sulhoff, "Short single frequency erbium-doped fiber laser," *Electron. Lett.*, vol. 28, p. 1385, 1992.

[7] T. L. Koch, U. Koren, R. P. Gnall, C. A. Burrus, and B. I. Miller, "Continuously tunable 1.5-μm multiple-quantum-well GaInAs/GaInAsP distributed Bragg reflector lasers," *Electron. Lett.*, vol. 24, no. 23, p. 1431, 1988.

[8] U. Koren *et al.*, "Widely tunable distributed Bragg reflector laser with an integrated electroabsorption modulator," in *Tech. Dig. OFC'92*, San Jose, CA, Paper WG5.

[9] S. L. Woodward *et al.*, "A DBR laser tunable by resistive heating," *IEEE Photon. Technol. Lett.*, vol. 4, p. 1330, Dec. 1992.

[10] P. D. Magill *et al.*, "1.3 Tbit · km/s transmission through non-dispersion shifted fiber by direct modulation of a monolithic modulator/laser," in *Tech. Dig. OFC'92*, San Jose, CA, Paper PD9.

[11] A. R. Chraplyvy, R. W. Tkach, K. C. Reichmann, P. D. Magill, and J. A. Nagel, "End-to-end equalization experiments in amplified WDM lightwave systems," *IEEE Photon. Technol. Lett.*, vol. 5, p. 428, Apr. 1993.

Equalization Technique to Reduce Clipping-Induced Nonlinear Distortion in Subcarrier-Multiplexed Lightwave Systems

Keang-Po Ho and Joseph M. Kahn

***Abstract*—A pretransmission compression and postdetection decompression scheme is proposed to reduce the clipping-induced nonlinear distortion (NLD) in subcarrier-multiplexed lightwave systems. In an AM-VSB CATV system, compression using a two-segment, piecewise-linear transfer characteristic promises to yield a 3.2-dB gain in carrier-to-noise ratio (CNR), or a 110% increase in the number of transmitted channels.**

I. INTRODUCTION

AMONG various impairments to lightwave systems using subcarrier multiplexing (SCM) with intensity modulation and direct detection, clipping-induced nonlinear distortion (NLD) at the laser transmitter provides a fundamental limit to system carrier-to-noise ratio (CNR) [1]–[6]. Analyses, simulations, and measurements of clipping-induced NLD have been reported [1]–[8]; however, to our knowledge, no means has been proposed to overcome this limitation.

In this letter, we propose to use a pretransmission nonlinear compressor and a postdetection decompressor to reduce the effects of NLD. As shown in Fig. 1, the laser modulation current at the transmitter is prescaled by a compressor circuit before passing to the laser. A postdetection decompressor is used at the receiver to restore the original signal. The transfer characteristics of the compressor and decompressor are inverse functions of each other, such that in the ideal case no nonlinear distortion will be caused by the compression.

Assume that the input current to the scaler $I_m(t)$ is an SCM signal consisting of N channels, each having an equal modulation index of m. The total root-mean-square (RMS) modulation index is defined as $\mu \equiv \sqrt{Nm^2/2}$. Without compression, the carrier-to-NLD ratio per channel is given by the modified Saleh formula $C/NLD(\mu) = \sqrt{2\pi}(1 + 6\mu^2)/\mu^3 e^{1/2\mu^2}$ [1], [2]; more detailed formulas can be found in [3]–[6].

In this paper, we consider a compressor and decompressor having a two-segment, piecewise-linear transfer characteristic, as shown in Fig. 2(a). The transfer characteristic is normalized to $I_b = I_{\text{bias}} - I_{th}$, where I_{bias} and

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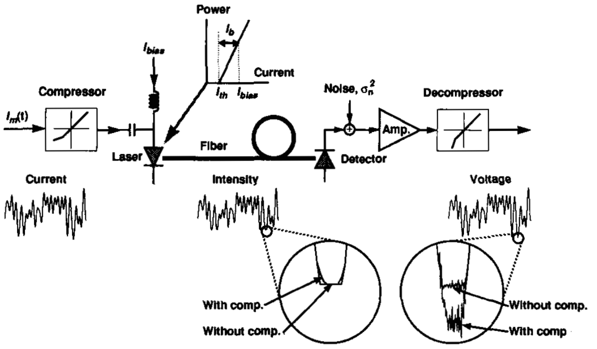

Fig. 1. Schematic of a subcarrier-multiplexed system using compression to reduce the clipping-induced nonlinear distortion. The inset shows the optical intensity and output voltage in systems with and without compression, at an instant of potential clipping.

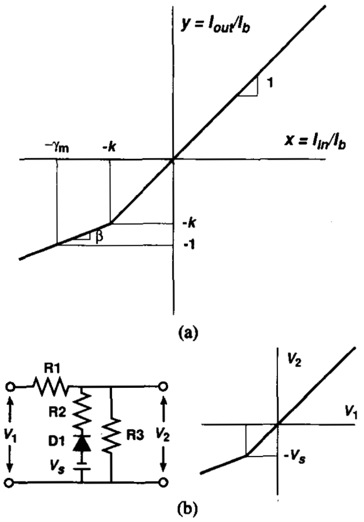

Fig. 2. (a) Transfer characteristic of the compressor (in the decompressor, the slope β is replaced by a slope β^{-1}). The input and output current is normalized by I_b. (b) A circuit having a similar transfer characteristic to (a) (V–V instead of I–I).

I_{th} are the bias current and threshold current of the laser, respectively. The transfer curve has a unit slope when $I_{in}/I_b > -k$ and has slope β when $I_{in}/I_b < -k$, where $\beta = (1-k)/(\gamma_m - k)$. This compressor curve will extend the clipping boundary from $I_m(t)/I_b < -1$ to $I_m(t)/I_b < -\gamma_m$. This curve comprises one of the simplest nonlinear transfer characteristics that can be implemented using resistors, diodes, and voltage or current sources [9] (an amplifier is needed when a slope greater than unity is required). An example of a one-diode circuit with this transfer characteristic is shown in Fig. 2(b). That circuit implements a V–V characteristic, and an I–I characteristic can be realized using the dual circuit [9] and a current amplifier. In place of the piecewise-linear compressor and decompressor, one may employ any of a wide class of transfer characteristics as long as one can realize the required characteristics.

II. ANALYSIS

The proposed compression will reduce NLD by extending the clipping limit. However, in the compression region $-\gamma_m < I_m(t)/I_b < -k$ the decompressor at the receiver will increase the noise current by a factor β^{-1}, degrading the system noise level. In the clipping region $I_m(t)/I_b < -\gamma_m$ the system will still be subject to NLD. For a channel number $N > 10$, by the central limit theorem, the input $I_m(t)/I_b$ can be accurately modeled as a Gaussian random process having a zero mean value and a variance of $\sigma_I^2 = I_b^2\mu^2$. Assuming that the system has a noise variance of σ_n^2 at the receiver (including both thermal and shot noises), the total noise including the NLD is

$$\sigma_t^2 = \frac{1}{2}\sigma_n^2 + \frac{1}{2}\operatorname{erf}(k/\sqrt{2}\,\mu)\sigma_n^2 + \frac{\beta^{-2}}{2}\left[\operatorname{erf}\left(\gamma_m k/\sqrt{2}\,\mu\right) - \operatorname{erf}(k/\sqrt{2}\,\mu)\right]\sigma_n^2 + \frac{\beta^{-2}}{2}\operatorname{erfc}\left(\gamma_m k/\sqrt{2}\,\mu\right)\sigma_n^2 + NLD \tag{1}$$

where the first four terms correspond to the thermal and shot noise contributed, respectively, by the regions: $I_m(t)/I_b > 0$, $-k < I_m(t)/I_b < 0$, $-\gamma_m < I_m(t)/I_b < -k$, and $I_m(t)/I_b < -\gamma_m$. The last term in (1) represents NLD. The sum of the third and fourth terms is equal to $\beta^{-2}\operatorname{erfc}(k/\sqrt{2}\,\mu)\sigma_n^2/2$. Hence, the total CNR at the receiver is

$$\frac{1}{\rho_t} = \frac{1 + (\beta^{-2} - 1)\operatorname{erfc}(k/\sqrt{2}\,\mu)/2}{\rho_n} + \frac{1}{C/NLD} \tag{2}$$

where $\rho_t = C/\sigma_t^2$ and $\rho_n = C/\sigma_n^2$. Although compression will increase the C/NLD ratio from $C/NLD(\mu)$ to $C/NLD(\mu/\gamma_m)$, noise enhancement will induce a CNR penalty of

$$\delta_e\,(\text{dB}) = 10 \cdot \log_{10}(1 + (\beta^{-2} - 1)\operatorname{erfc}(k/\sqrt{2}\,\mu)/2). \tag{3}$$

For fixed γ_m and a specific value of μ, there exists an optimal value $k = k_{\text{opt}}$, which minimizes the CNR penalty given by (3). Fig. 3 presents k_{opt} as a function of μ, which was obtained by numerical minimization for several values of γ_m. As μ increases beyond a value of about 0.4, k_{opt} decreases rapidly and reaches zero. In this case, the compressor serves to scale down all negative values of input current. If μ is small, using the approximation $\operatorname{erfc}(x) \approx e^{-x^2}/x\sqrt{\pi}$, k_{opt} can be obtained analytically by finding the root of a third-order equation, $2\mu^2(\gamma_m - k) =$

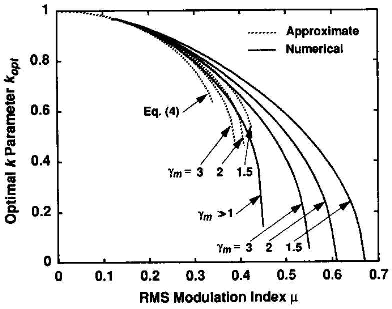

Fig. 3. Dependence of k_{opt} on the RMS modulation index, for different values of γ_m. The approximate value, which is valid for small μ, is also plotted for comparison.

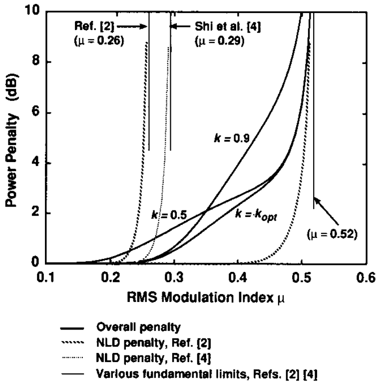

Fig. 4. Power penalties in an AM-VSB CATV system versus RMS modulation index. A compressor with $\gamma_m = 2$ is chosen.

$k(1 - k)(\gamma_m + 1 - 2k)$. Fig. 3 also shows values of k_{opt} obtained by solution of this equation. For $\gamma_m \gg 1$, solution of this yields

$$k_{\text{opt}} = \left(1 + \sqrt{1 - 8\mu^2}\right)/2, \qquad \text{if } \gamma_m \gg 1, k/\sqrt{2}\,\mu \gg 1. \tag{4}$$

For $\mu < 0.25$, (4) will be a good approximation to k_{opt} when $\gamma_m > 2$.

In order to evaluate the improvement that can be obtained by compression and decompression, we study an AM-VSB CATV transmission system. For AM-VSB CATV, the required CNR is 55 dB [1], [2]. Fig. 4 presents the power penalty incurred in an AM-VSB system with and without compression. With three different choices of k, we choose a value $\gamma_m = 2$ to reduce the clipping. The power penalties without compression are calculated using the modified Saleh formula [2]. The fundamental limit (power penalty = ∞) is extended by a factor of two from $\mu = 0.26$ to $\mu = 0.52$ when compression is employed. In the region of interest, $\mu = 0.25$–0.4, the noise-enhancement penalty (3) will be the dominant impairment, and NLD can be neglected. If one employs a fixed value $k = 0.5$, then the compressed system will be noisier than the normal system in the region $\mu < 0.23$. For a fixed value $k = 0.9$, the CNR obtained is nearly optimal over the range $\mu < 0.35$.

For most cases of interest, the CNR of the system is approximately proportional to m and thus proportional to μ, and the CNR improvement provided by compression is significant. For example, assuming that either with or without compression a total power penalty of 1.46 dB is permitted (corresponding to $C/NLD = 60$ dB without compression [4]), then compression will extend the RMS modulation index from $\mu = 0.243$ to $\mu = 0.353$ (assuming $k = k_{\text{opt}}$). This represents a 3.2-dB sensitivity improvement, or a 110% increase in the number of channels. This RMS modulation index μ is 36% higher than that given by the original fundamental limit ($\mu = 0.26$).

Comparison with the Saleh limit will overestimate the improvement achievable using compression, because the Saleh formula overestimates the NLD [3], [4]. Other studies take into account the power spectrum of the noise and obtain less NLD and smaller penalties. Among [3]–[6], Shi *et al.* [4] gives the smallest NLD and thus the smallest CNR penalty. As an example, we consider the third channel of a typical 42-channel AM-VSB system [6]. A 1.46-dB power penalty corresponds to $\mu = 0.274$. In this case, compression yields a 2.2-dB sensitivity improvement, or a 66% increase in the number of channels.

The transfer characteristic in Fig. 2 may be implemented in straightforward fashion using an ideal diode and resistors; however, it is not an optimal compressor. The optimal compressor transfer characteristic can be obtained using the calculus of variations as a solution of Euler's differential equation [10]. The optimal transfer characteristic will be of the form $y(x) = \text{erf}(x/\sqrt{6}\,\mu)/\text{erf}(\gamma_m/\sqrt{6}\,\mu)$. This kind of transfer characteristic may be difficult to implement and will not be discussed further here.

The proposed compression/decompression scheme seeks to eliminate a small NLD by introducing and subsequently removing a large NLD. In practice, there will be some mismatch of compressor and decompressor characteristics, and mismatch will introduce NLD to the system. Matching the slopes of the compressor transfer characteristic (β and 1) to those in the decompressor (β^{-1} and 1, respectively) can be achieved through the use of precision resistors. Each of these slopes is defined by a ratio of resistances; since this ratio will not change appreciably as the temperature changes, neither will the slopes of the compressor and decompressor. It is also critical to match the kink in the decompressor transfer characteristic to that in the compressor. Numerical study [11] has shown that the kinks of the compressor and decompressor must match within 0.3% for both composite second order (CSO) and composite triple beat (CTB) less than −65 dBc. Assuming a total signal swing of the order of 1 V, this implies a tolerable mismatch of several millivolts, which can be easily achieved using standard band-gap reference techniques. If necessary, the decompressor kink may be adjusted under closed-loop control at the receiver. For example, one may leave a single channel empty and may monitor the noise power in that channel to obtain an error signal. The decompressor kink can be adjusted either by changing the voltage V_s in the circuit of Fig. 2(b), or by using an automatic gain control amplifier [12] to adjust the decompressor input signal level.

The compressor generates higher order harmonics of the input signal, broadening its spectrum and requiring greater transmitter and receiver bandwidth than is needed by the system without compression. Numerical study [11] has shown that if the overall system (from compressor input to decompressor output) has a first-order response or a small-damping second-order response, then it must have a 3-dB bandwidth of about five times the signal bandwidth to yield CSO and CTB less than −65 dBc. If the overall system has a second-order Butterworth response, then the bandwidth requirement is reduced to about twice the signal bandwidth; this reduced bandwidth requirement arises from the simultaneously uniform magnitude and linear phase characteristics of the Butterworth response. It may thus be advantageous to equalize the overall system to a second-order Butterworth response. If the dominant bandwidth limitation lies at the receiver and the input-referred receiver noise is white, then this equalization may be performed without penalty. On the other hand, if transmitter limitations dominate the overall system bandwidth, then equalization will result in noise enhancement.

III. CONCLUSIONS

We have proposed and analyzed the use of pretransmission compression and postdetection decompression to reduce the laser threshold-induced clipping NLD. A simple piecewise-linear two-segment compression transfer characteristic has been studied and optimized. For an AM-VSB CATV system, the power penalties induced by this nonlinear equalization are computed and compared to those present without equalization. Our calculations indicate that the RMS modulation index can be increased by 45%, which would represent a 3.2-dB sensitivity improvement, or a 110% increase in the number of channels. Even a conservative calculation gives a sensitivity improvement of 2.2 dB, or a 66% increase in the number of channels.

REFERENCES

[1] A. A. M. Saleh, "Fundamental limit on number of channels in subcarrier-multiplexed lightwave CATV system," *Electron. Lett.*, vol. 25, pp. 776–777, 1989.

[2] T. E. Darcie, "Subcarrier multiplexing for lightwave networks and video distribution systems," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 1240–1248, 1990.

[3] K. Alameh and R. A. Minasian, "Ultimate limits of subcarrier multiplexed lightwave transmission," *Electron. Lett.*, vol. 27, pp. 1260–1262, 1991.

[4] Q. Shi, R. S. Burroughs, and D. Lewis, "An alternative model for laser clipping-induced nonlinear distortion for analog lightwave CATV systems," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 784–787, 1992.

[5] N. J. Frigo and G. E. Bodeep, "Clipping distortion in AM-VSB CATV subcarrier multiplexed lightwave systems," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 781–784, 1992.

[6] N. J. Frigo, M. R. Phillips, and G. E. Bodeep, "Clipping distortion in SCM lightwave CATV systems: Models, simulations, and measurements," *J. Lightwave Technol.*, vol. 11, pp. 138–146, 1993.

[7] J. A. Chung and I. Jacobs, "Practical TV channel capacity of lightwave multichannel AM SCM systems limited by threshold nonlinearity of laser diodes," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 289–292, 1992.

[8] G. R. Joyce and R. Olshansky, "Implication of clipping distortion for compressed digital video transmission," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 787–790, 1992.

[9] L. O. Chua, C. A. Desoer, and E. S. Kuh, *Linear and Nonlinear Circuits.* New York: McGraw-Hill, 1987.

[10] R. Courant and F. John, *Introduction to Calculus and Analysis*, vol. 2. New York: Wiley-Interscience, 1974.

[11] K-P. Ho and J. M. Kahn, "Channel compression in subcarrier-multiplexed lightwave CATV systems," *J. Lightwave Technol.*, submitted for publication.

[12] G. F. Williams, "Lightwave receivers," in *Topics in Lightwave Transmission Systems*, T. Li, Ed. San Diego: Academic, pp. 79–149, 1991.