Adaptive Compensation of the Nonlinear Distortions in Optical Transmitters Using Predistortion

Oleg PANAGIEV

Dept. of Radiocommunications and Videotechnology, Technical University of Sofia, Kl. Ohridski 8, 1000 Sofia, Bulgaria

olcomol@yahoo.com

Abstract. *The described method refers to compensation of nonlinear distortions, originating in laser diodes, used in wideband SCM-communication systems. Its essence is presenting in forming of a function that is opposite of the function describing the W-A characteristic of the emitting diode. Main element is the predistorter, which is connected in series before the emitting diode. This way, an improving of the optical transmitter's parameters and characteristics is being realized, by using a purposive entering predistortion.*

Keywords

Nonlinear distortions, Predistorter, Laser diode, CSO, CTB, Volterra kernels.

1. Introduction

Transmitting of AM-VSB signals in HFC/CATV systems is accompanied with origin of nonlinear products at a direct intensity modulation of the laser diode (LD). The causes for that can be grouped by the following way:

- Inherent nonlinear distortions in the laser diode [1], [2];
- "Clipping" in W-A characteristic of the LD [3], [4];
- Nonlinear distortions from the fiber dispersion [5], [6];
- Nonlinear dependence between light emitting and current flowing through the laser diode [6], [7].

The described method refers to compensation of the nonlinear distortions, originating in laser diodes by forming of a function that is opposite of the function describing the W-A characteristic of the emitting diode, [9], [10]. It allows all types of nonlinear distortions in the wide frequency band (>100 MHz) to be compensated without complicating the optical part of the transmitter. Main element is the predistorter (PD) which is connected in series before the emitting diode. This way, an improving of the optical transmitter's parameters and characteristics is being realized, by using a purposive lead in predistortion [5], [8].

2. Predistorter′ Mathematical Models

Let the predistorter is described with the function $\varphi(x)$ which in the general case is approximated with polynomial of degree n[4], i.e.

$$\varphi(x) = k_1 x + k_2 x^2 + k_3 x^3 + \ldots + k_n x^n . \qquad (1)$$

If the laser diode, spreading the nonlinear products is described with the function $f(x)$, the distortions are absolutely compensated in a condition that $\varphi(x)$ is opposite to $f(x)$. The compensation degree depends on the accuracy of $\varphi(x)$ forming. A higher level of the polynomial determines a better conformity between the predistorter's and laser diode's characteristics. With x is marked the input signal and k are the linear coefficients, describing the transmission characteristics of the active and passive elements, joined in the respective loop for predistortion (of the second, third and etc. order).

"Short" orders, i.e. up to the third order ($n = 3$) are mostly used in practice. In the present treatment, the function that describes the predistorter is expanded in a Volterra series (system with "memory") to the third order (cubic predistortion). The expansion is conformed to the analyses, referring to the systems with low nonlinearity.

Using of the Volterra series, the model of the predistorter for laser diode's nonlinearity compensation (Fig. 1), represents a combination of branches ($y_1^{(1)}, y_1^{(2)}, y_1^{(3)}$). Each of them is separated in two parts:

- Linear with "memory": $k_i \equiv G_i H_i$;
- "Memoryless" nonlinear: $(\cdot) \cong (x)^i$, where i=1, 2, 3.

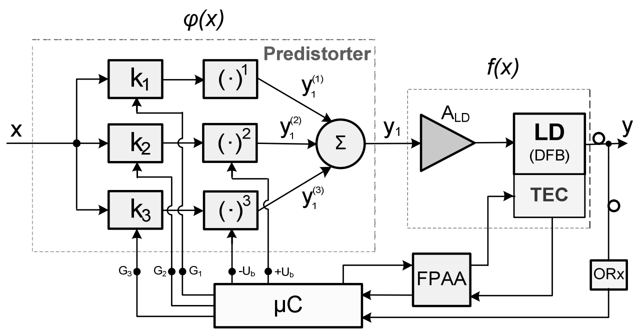

Fig.1. General block diagram for adaptive compensation of the laser diode' nonlinearity.

An amplifier for ensuring of the necessary input level for work of LD is put between the PD and laser diode. The adaptive predistorter is realized with entering of feedback by which data is received for the levels of nonlinear products. Their processing is made by a microcomputer (μC), which is forming voltages for regulating of the gains (G_i) and diodes' bias ($-U_b$; $+U_b$). Aiming minimizing of nonlinearity of the laser diode's W-A characteristic from thermal influences is lead in a feedback to do the thermocompensation with Peltier element. The PID controller is realized with FPAA, as the same μC is used for the control [9]. The output signal of the nonlinear system, described with Volterra series, in the general case is presented in a type of multidimensional function [10, 11]:

$$V[x(t)] = \sum_{n=1}^{+\infty} \int_{-\infty}^{+\infty} \dots \int_{-\infty}^{+\infty} h_n(\tau_i,\dots,\tau_n) \prod_{i=1}^{n} x(t-\tau_i) d\tau_i \quad (2)$$

where Volterra kernels $h_n(\tau_1,\dots,\tau_n)$ are continuous and nondependent from $x(t)$. Because of using of a cubic predistortion and according to Fig.1, expression (2) is rewritten in the following way:

$$y_1 = y_1^{(1)} + y_1^{(2)} + y_1^{(3)} = G_1 H_1 x + G_2 H_2 x^2 + G_3 H_3 x^3 \quad (3)$$

where G_1, G_2, G_3 are gains of the active and passive elements, included in the respective links for predistortion. H_1, H_2, H_3 are Volterra kernels of the first, second and third order in frequency area, i.e. H_i=func(ω) and $\omega=\Sigma \pm r_i \omega_I$; r_i are arbitrary integers. They can be defined by the respective mathematical expressions (Tab. 1), using the direct Fourier [10] or Laplace transforms [11].

In Fig. 2, a block diagram of optical system with PD, defined by Laplace transformation, is given.

$$Y_1(p_1, p_2, p_3) = \sum_{n=1}^{3} H(p_1, p_2, p_3) \prod_{i=1}^{n} X(p_i) \quad (4)$$

where $H(p_1, p_2, p_3)$ is the third order kernel and $p=\sigma+j\omega$. At $\omega_1=\omega_2=\omega_3=\omega$, so

$$H_1(p) \equiv H(p)\,;\ H_2(p) \equiv H(2p)\,;\ H_3(p) \equiv H(3p)\,.$$

The expressions which define the components in the predistorter output are shown in Tab.2.

Note: Ideal compensation is possible only at condition that $L_1(p)L_2(p)=1$, i.e. at full parity between the amplitude- and the phase-frequency characteristics of the PD and LD.

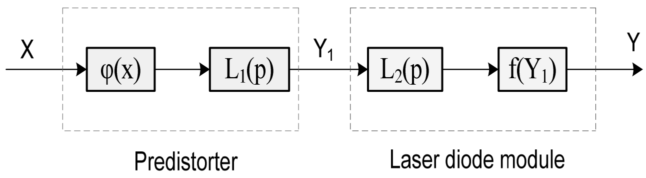

Fig. 2. Block diagram of PD-LD system described by Volterra series and Laplace transformations.

Component	Direct Fourier Transform		Laplace transform	
Linear	$y_1^{(1)}$	$G_1.H_1.x$	$k_1.L_1(p).x(p)$	$Y_1^{(1)}$
Quadratic	$y_1^{(2)}$	$G_2.H_2.x^2$	$k_2.L_1(2p).x^2(p)$	$Y_1^{(2)}$
Cubic	$y_1^{(3)}$	$G_3.H_3.x^3$	$k_3.L_1(3p).x^3(p)$	$Y_1^{(3)}$

Tab.2. Predistorter' output components.

3. Realization and Results

On the basis of the model shown in Fig. 1 an experimental setup for studying of the levels of nonlinear products of the second and third order, at presence and absence of predistortion was realized. The block diagram of that experimental setup is given in Fig. 3. The predistorter is composite of three branches. The highest branch contains an adjustable amplifier of the useful signal, as at the same time looses in the directional couplers Tap1 and Tap2 are being compensated. If it is needed for the group times to be surfaced with those from the other two branches connecting of additional delay line (DL) is possible. By the middle branch a predistortion of the second order (quadratic predistortion) is realized. The last (lowest) branch represents the cubic (of the third order) predistortion. The signals from the two last branches, beared the respective predistortions, are summed in a splitter (S). At an ideal balancing in its output, only the cubic component is received, and in the real case – the quadratic and cubic components. By Tap2 expression (3) is realized, and the adjustable amplifier with G is used for obtaining of commensurable amplitudes of the three components in signal y_1 – from one side the linear and from the other – quadratic and cubic.

Volterra kernels	Direct Fourier Transform	Laplace transform
Linear (1-st order)	$H_1 = \lvert H_1(\omega) \rvert = \left\lvert \int_{-\infty}^{+\infty} h_1(\tau_1).\exp(-j\omega\tau_1).d\tau_1 \right\rvert$	$H_1(p) = k_1.L_1(p)$
Quadratic (2-nd order)	$H_2 = \lvert H_2(\omega) \rvert = \left\lvert \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} h_2(\tau_1,\tau_2).\exp[-j\omega(\tau_1+\tau_2)].d\tau_1 d\tau_2 \right\rvert$	$H_2(p) = k_2.L_1(2p)$
Cubic (3-rd order)	$H_3 = \lvert H_3(\omega) \rvert = \left\lvert \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} h_3(\tau_1,\tau_2,\tau_3).\exp[-j\omega(\tau_1+\tau_2+\tau_3)].d\tau_1 d\tau_2 d\tau_3 \right\rvert$	$H_3(p) = k_3.L_1(3p)$

Tab.1. Volterra kernels identification.

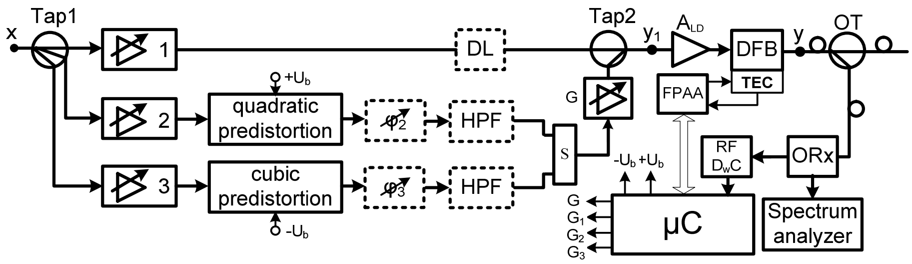

Fig.3. Block diagram for predistorter and the loop for adaptive compensation

For the last two components if it is necessary more precise restriction of the nonlinear products of the second and third order is possible the connecting of signal phase regulators and high frequency filter in each of the two branches.

The practical realization of the suggested model (Fig. 1) and the block diagram (Fig. 3) are made on the base of diode predistortion. For diodes transistors BFR96 are used connected as it is shown in Fig. 4. The operating point on the V-A characteristic of each of them is defined by dc voltage U_b with the necessary polarity through resistors *R5*/*R*6 and *R*7/*R*8. The amplifiers for compensating losses in the passive elements, and at the same time for ensuring of the needed levels of the components, are realized with ACA0861D (*IC*1, *IC*2) and RF2312 (*IC*3). Each of them has a constant gain, which is forced by high-frequency electronic regulated attenuators (*P*, *P*1, *P*1', *P*2, *P*3: π-sections from PIN diodes) on their inputs.

Because in each term of (2) there are not only addends of the respective order, but also of all lower degrees, we can write down the following for the output signals from Fig. 1 and according to [5, 11],:

a) of the first order

$$y_1^{(1)} = G_1.H_1.x\,, \tag{5}$$

b) of the second order

$$y_1^{(2)} = G_1.H_1.x + G_2.H_2.x^2\,, \tag{6}$$

c) of the third order

$$y_1^{(3)} = G_1.H_1.x - G_2.H_2.x^2 + G_3.H_3.x^3\,. \tag{7}$$

That forces the separating of nonlinear branch in two as in the one of the parts the main signal is being amplified, and at the other part amplified is the inverted with *T*1 main signal, but with level, compensating the levels of nonlinear products from expressions (6) and (7). In the real case the signal passed to the laser diode is

$$y_1 = G_1.H_1.x + G.(G_2.H_2.x^2 + G_3.H_3.x^3) \tag{8}$$

where *G* is the common gain of *IC*3 and *P*. Balancing perfectly the predistorter's characteristic, the quadratic components mutually destroy each other

$$y_1 = G_1.H_1.x + G.G_3.H_3.x^3\,. \tag{9}$$

In formula (8) is set that the quadratic component through *T*2 is with higher level than through *T*3.

The results from the theoretical and experimental researches of the nonlinear products in output *y* are shown in a graphical form separately for the levels of composite distortions of the second and third other (Fig. 5 and Fig. 6).

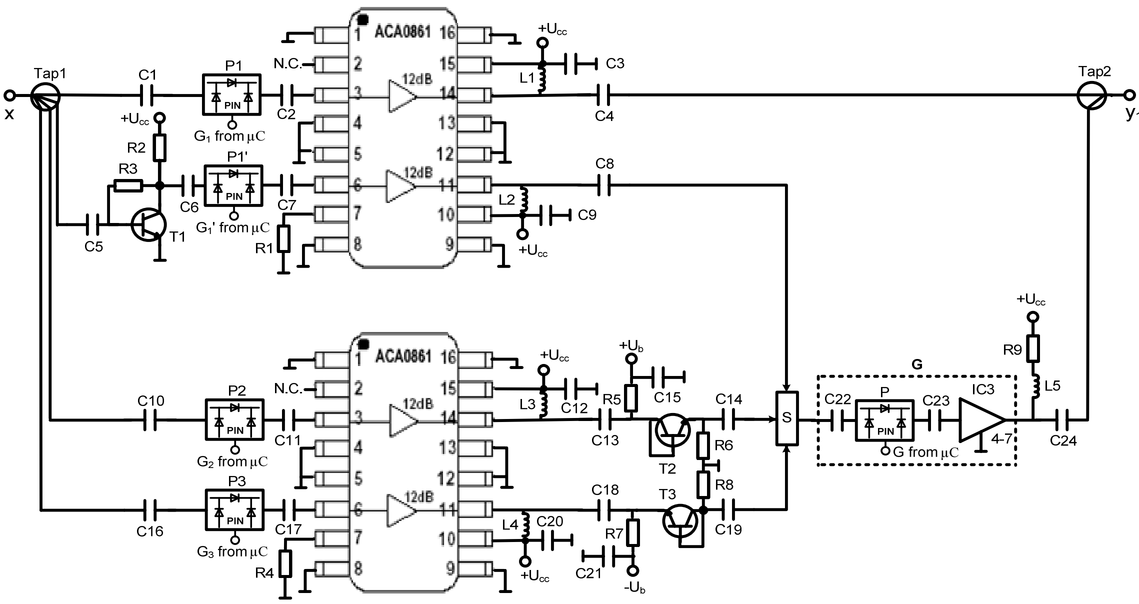

Fig.4. Predistorter electrical circuit diagram.

In the both cases the composite distortions at a lack (no_p) and a presence (yes_p) of predistortion are depicted (theoretical - yes_pt, and experimental – yes_pe, results). The frequency distribution is made according to the CENELEC EN 50083-3 (Appendix C) standard requirements. The number of transmitting channels is 60 in the frequency range of 49,75 MHz ÷ 550 MHz. For the theoretical calculation of CSO and CTB the dependences brought out in [4, 10] are used. The experimental measurements are made by a spectrumanalyzer PROMAX, according to Fig. 3. For realizing of adaptive compensation of the distortions of the second and third order optical receiver (ORx) and RF down converter (RF DwC) is lead in a feedback [1] with optical tap (OT). Depending on the nonlinear products amplitudes, the necessary voltages for controlling of the predistorter's parameters and characteristics (Fig. 3 and Fig. 4) are worked out from µC.

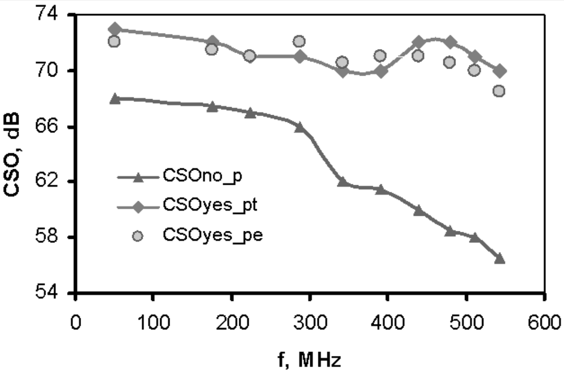

Fig.5. Alternation of the composite distortions from second order

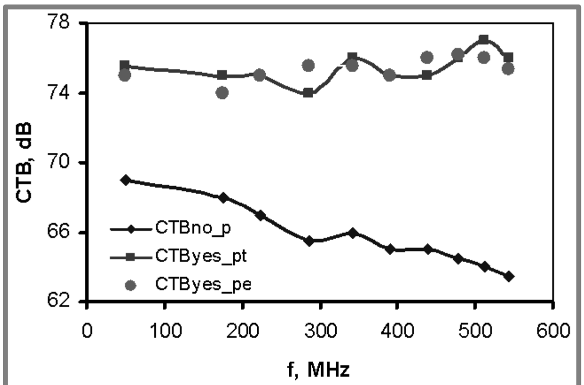

Fig.6. Alternation of the composite distortions from third order

4. Conclusion

In this paper, we discussed the applying of adaptive compensation with predistortion for achieving of improvement in the CSO and CTB with 8 ÷ 12 dB, as they arise respectively to 73 dB and 77 dB (Fig. 5 and Fig. 6). That improvement is brighter visible for the channels distributed from 400 MHz to 600 MHz, while the predistortion efficiency is lower for low frequencies. The experimental research of the predistorter determined that for compensation of nonlinear product from any of the orders with 20 dB are admissible ± 0.8 dB deviations of the amplitude, and for phase characteristic ± 6 ° from the ideal.

The good coincidence between the theoretical and experimental results confirms the right choice of mathematical method and its circuit realization. Besides, the influence of the LD and environmental temperature alternation is put out to a minimum, using thermo-stabilization with Peltier element (TEC-thermoelectric cooler, Fig. 1). A big priority is the simple circuit solution (without complication in the optical part).

In a future work the extension of the given model is possible by increasing the compensation efficiency (Fig. 3 with a dotted line): connecting of additional delay line, leading in of additional adaptive control of the signal phase and the HPF bandpass. But this complicates the optical transmitter's circuit.

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About Author...

Oleg PANAGIEV was born in Varshets, Bulgaria in 1962. He received his MSc degree in 1988 and his PhD degree in 2007 from the Technical University of Sofia. His interests are broadband cable (optical and coaxial), satellite and radio-communication systems: theory, design, simulation, construction, measurements and repair.