Improved Feedforward Linearization of Laser Diodes - Simulation and Experimental Results.

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Abstract

In this paper we discuss feedforward linearization of directly modulated laser diodes for AM CATV lightwave transmission systems. Theoretical simulation and experimental results are presented showing a distortion cancellation of better than 20dB over 850 MHz bandwidth. An investigation regarding tolerance and a possible dispersion penalty in the system is performed.

I. Introduction

Fiber-optic transmission of CATV signals promises many advantages over coaxial-based systems mainly due to the high bandwidth of optical transmitters and low losses of fibre. However, the AM-VSB signal format used for CATV requires a carrier to noise ratio (CNR) near 50 dB for good picture quality. In addition, the many distortion products generated by system nonlinearities must have a cumulative power that is more than 60 dB below the carrier level. Meeting these requirements using AM lightwave systems has proven to be feasible but difficult in view of the fact that a sensitive compromise exists between SNR and linearity. This tradeoff can be eased by employing various linearization schemes. In order for these schemes to be effective, however, optical sources with sufficient power and low noise must be employed to satisfy SNR and power budget specifications.

In this paper we discuss feedforward linearization of directly modulated optical transmitters which we consider suitable for the distribution of a high number of channels (60-150). For a lower number of channels, state-of-the-art commercially available lasers can satisfy the strict CSO, CTB, and SNR requirements demanded by CATV operators.

II. Simulation of Feedforward Scheme

Considerable work has been done on linearizing lasers using predistortion quasi-feedforward and feedforward techniques. Predistortion networks have had limited success since they must be matched to individual lasers and must take into account the strong frequency dependent distortion generated by semiconductor laser diodes and other undesired effects such as laser aging. Quasi feedforward linearization schemes require matched lasers, which are very difficult to obtain. Even though feedforward is a relatively complicated and sensitive scheme we consider it a promising linearization solution especially in view of the demand for high channel capacity lightwave systems. In this section the feedforward scheme will be explained and simulation results will be discused.

A simplified feedforward circuit diagram is illustrated in Figure 1. The input signal is split into two paths; one of them modulates the primary laser L1 while the other one is used as a reference signal.Detecting the signal out of L1 and comparing it with the time delayed original signal provides an error signal which is amplified and modulates the secondary laser (L2). The modulated optical signal from laser 2 combines with the optical signal of laser 1 and cancels the distortion products.

Following [1] we have used a Volterra-series analysis of the laser's rate-equations in our modelling of a semiconductor laser.We have found that the main factor determining the amount of nonlinear distortion reduction available by the feedforward approach is the linearity of the two lasers being employed. Simulation results show that a reduction of 50 to 100 dB in the composite nonlinear distortion can be achieved, depending on the lasers being utilized. This is because the main limiting factor in this scheme is the distortion introduced by the secondary laser, which is not compensated for. This distortion is minimized when L2 is driven by a relatively small error signal. It is important to

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mention that the above results should be regarded as the theoretical limit of system performance. Practical results will not be as good due to tolerances in the system, especially in the RF path. In this section, we consider only the "ideal case". A tolerance analysis is presented in the next section.

To demonstrate feedforward performance we will consider a 60 channels system with a modulation index of 4% per channel, employing a relatively, but by no means best available, linear laser(s). The highest unlinearized distortion was found to be -46 dBc (below carrier level). Simulated feedforward results showed a distortion reduction of about 92 dB to a level of -138 dBc, shown in Fig 1. Two similar lasers are not needed in this case and in fact it might be possible to achieve a cost reduction by using a less linear and therefore less expensive secondary laser L2. The feedforward scheme was theoretically tested for a channel capacity of 40 to 150 channels. Results show that this linearization technique performs equally well for a large number of channels.

Another attractive feature available from the feedforward technique is the option for two linearized outputs from the optical transmitter, which means that it might be possible to serve twice the number of subscribers by a single transmitter. This option is realized when each of the linearized optical signal receives 50% of it's power from L1 and 50% from L2. Our analysis has shown that an SNR of 50 dB, for each of the signals, should be possible if the level of received optical power, after transmission in the fibre, is kept near 0 dBm. To achieve this proper level, the use of high power sources (> 5 dBm) with low intensity noise (< -155 dB/Hz) is required.

III. Tolerance and Dispersion Penalty Analysis

Imperfections and tolerances encountered in the practical implementation of the system were taken into account in our simulation by adding four tolerance parameters to the "ideal case" simulation, presented above. These parameters are amplitude and phase errors between the two optical signals being combined at the circuit's output and amplitude and phase error between the two electrical signals being compared in the error signal generation. In general, all these parameters are frequency dependent. An analysis in the frequency domain enables us to directly use measured data from the Vector Network Analyzer (VNA), in order to specify each error parameter over the circuit's bandwidth.

We have found that system performance is dominated by amplitude and phase match between the optical signals. Our simulations have shown that the maximum amount of nonlinear distortion reduction in a practical system is about 30 dB. This requires an optical phase and amplitude match of less than 2 degrees and 0.5 dB, respectively. Such an accuracy is very difficult to obtain over a wide bandwidth. However, distortion reduction of more than 20 dB can be obtained if these strict tolerance conditions are eased to phase and amplitude match of about 5 degrees and 1 dB, respectively.

We have also performed a theoretical investigation of a possible dispersion penalty in the system performance. This penalty is a result of a wavelength separation between the two lasers, followed by fibre chromatic dispersion which causes phase mismatch between the distorted signal out of laser #1 and the "corrective" signal from laser #2. The system can be optimized for maximal performance at a given transmission length in the fibre. A penalty will be encountered in case the actual transmission length is different. Fig.2 shows the minimum linearization available at different fibre lengths, for a system optimized for transmission through 0 Km (practically a few meters) of fibre. It can be seen, that dispersion penalty is more severe for high bandwidth systems. This is due to the fact that a given dispersion induced timing error, translates to a larger phase mismatch at higher frequency signals. Fig 3 shows the available linearization as a function of the wavelength separation between the lasers.

IV. Experimental Results

We have used a pair of ASTROTEC 238-Type AT&T DFB lasers and EPITAXX low distortion InGaAs photodiodes in our practical realization of a feedforward circuit. The system was carefully optimized using a Wiltron 360B automatic Vector Network Analyzer.

The circuit was tested by a series of one tone tests over a bandwidth of 1 GHz. Results regarding the reduction of second and third order harmonic distortion are shown in Fig 4. As can be seen a typical distortion reduction of 20 dB is achieved over a bandwidth of 850 MHz. We have found out that system bandwidth was mainly limited by the RF components being used in the circuit, especially the two 1GHz RF amplifiers, which exhibit an increasing phase nonlinearity at frequencies above 800 MHz. Reduction of third order intermodulation products of the type $2f_1$-f_2 and $2f_2$-f_1 was evaluated by a series of two tone tests at optical modulation depth of 28% per tone. A typical linearization of 20 dB was obtained.

We have also performed an experimental investigation of dispersion penalty in the system performance. We have tested the available linearization after transmission through 8.7km of fibre, of a feedforward system that was optimized for transmission length of only a few meters. Dispersion penalty was typically found to be 1-2 dB at most distortion frequencies, except at the upper end of the bandwidth,where it reaches a maximum of 8 dB at 850 MHz. These findings agree well with our theoretical prediction.

Based on our experimental results regarding one tone and two tones tests, and our simulation software, a prediction can be made regarding the system performance for a high (60-150) number of channels

V. Conclusions

In this paper we have discussed feedforward linearization of directly modulated lasers. Simulation was performed regarding the theoretical and practical limit of this linearization scheme, as well as concerning dispersion penalty in the system.

Experimental results were presented, showing a typical linearization improvement of 20 dB over a bandwidth of 850 MHz, which is the bandwidth required for the transmission of 125 channels. These results indicate that feedforward is a promising linearization technique for high capacity CATV systems.

VI. Acknowledgement

The authors wish to thank Canadian Cable Labs, Vancouver, Rogers Communications Inc., Toronto, and the National Science and Engineering Research Council of Canada (NSERC) for their ongoing support in this project.

VII. References

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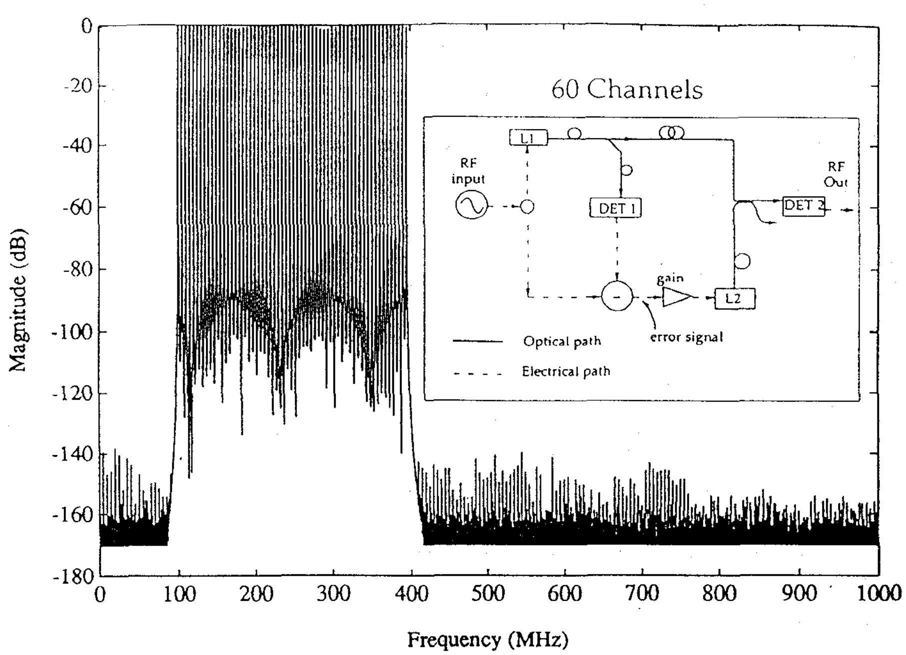

Figure 1 - Performance and Block Diagram of laser feedforward

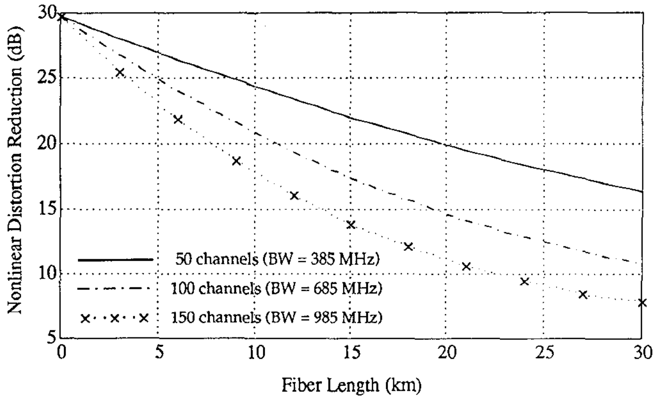

Figure 2 - Dispersion Penalty as a Function of Fibre Length. Wavelength Separation Between the Two Lasers = 2 nm, Fibre Chromatic Dispersion (at canter wavelength) = 0.75 ps / nm·km

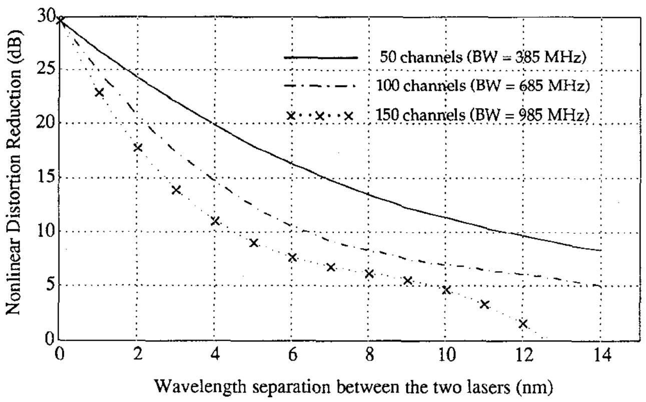

Figure 3 - Dispersion Penalty as a Function of Wavelength Separation Between the Two Lasers. Fibre Length = 10 km, Fibre Chromatic Dispersion (at canter wavelength) = 0.75 ps / nm·km

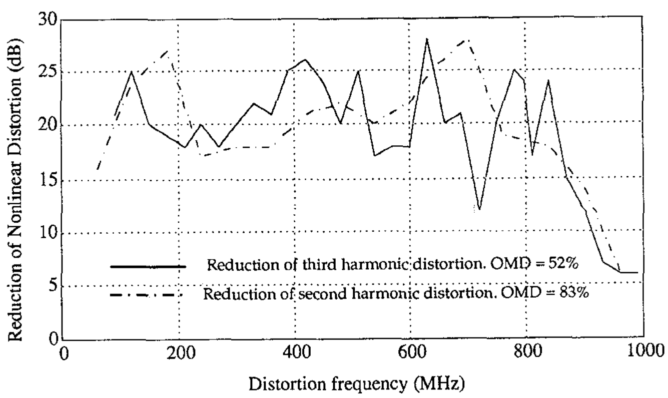

Figure 4 - Feedforward experimental results