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Experimental Study on FPGA Based Nonlinearity Reduction in a Laser Diode

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Abstract*: This work aims to reduce the Total Harmonic Distortion (THD) in a laser diode by predistorting the input signal. A predistorted signal is generated using FPGA and this signal is fed to the inherently nonlinear laser diode. The combined effect of predistorted signal and the nonlinear diode characteristics render an overall linear characteristics for the optical transmitter. The design of the FPGA predistorter is the crux of the present work. The optical power versus injection current graph is plotted for the laser diode and based on the characteristics, certain mathematical manipulation is performed to obtain an analytical expression to faithfully reproduce the entire curve. In order to design the predistorter, the inverse function of the nonlinear expression is computed. Based on these data, a lookup table based VHDL code is downloaded onto the Field Programmable Gate Array (FPGA) chip. The FPGA operates entirely in the digital regime, thus suitable interfacing circuitry were rigged up. The harmonic distortion is studied using spectrum analyzer.

Index Terms*: FPGA, Harmonic Distortion, Laser Diode, Nonlinearity, Predistortion.

I. INTRODUCTION

Fundamentally, the light wave transmission system consists of an optical transmitter, the optical channel and the receiver operating in the optical region. This concept was extremely successful due to tremendously low loss when compared to its copper counterpart, encountered by light in its journey through the optical fiber.

The optical transmitter would pump out light when excited by an electrical drive current. The core ingredient in this module is the laser source. Among the myriad types of laser sources available, the semiconductor laser is popular. Here the injection current would encourage the electrons to fill up the metastable state of the atom after another photon of a specific wavelength bombards the electron, two identical photons emerge with almost identical characteristics. The generated photons would be in mammoth numbers, they in turn would further motivate other fellow atoms to follow their footsteps, and hence amplification is achieved [1].

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A. Nonlinearity in Laser Diode

The transfer characteristic of a Laser Diode (LD) is shown in Fig.1.1. It is observed from the graph that the behavior of the optical device does not have a fixed slope throughout the curve. The optical power feebly increases up to the threshold value of the injection current. The value of the optical power rises phenomenally above threshold value. This trend does not continue forever, but the linear region of operation is restricted. When the current crosses above a certain limit the device enters the saturation domain and the laser ceases to exist as a linear device [2].

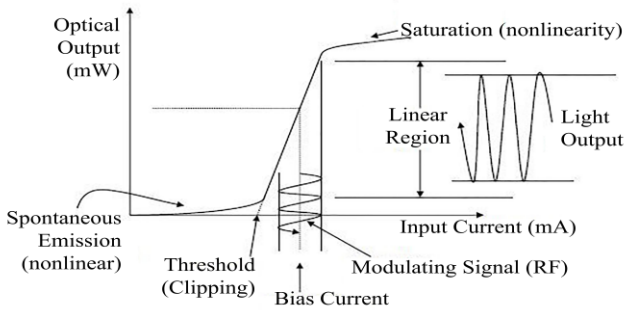

Fig.1.1. Optical power versus injection current in a typical laser diode.

The static nonlinearity is studied through the use of a third order polynomial equation. This is given by,

$$P_{optical}(t) = P_0[1 + ms(t) + A_2 m^2 s^2(t) + A_3 m^3 s^3(t)] \quad (1)$$

where $s(t)$ is input electrical signal, P_0 is average optical power, m is optical modulation index, A_2 and A_3 are device dependent nonlinearity coefficients [3].

From the above equation, it is evident that if the input is a monotonic signal the output would contain second and third harmonics in addition to the original frequency component, and it is called harmonic distortion. It is also observed that if the input signal consists of more than one frequency component, as in the case of amplitude modulation, the output optical signal consists of the scaled sum and difference of frequencies present, and is referred to as intermodulation distortion [4].

B. Predistortion: A strategy to combat nonlinearity

This method effectively compensates the amplitude and phase nonlinearity present in the laser diode. The inherent nonlinearity cannot be eliminated but the overall characteristics can be effectively made linear [4] [5].

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The Fig.1.2. shows the basic principle of linearizing transfer curve using predistortion. The drive current values of a laser diode are manipulated so that when injected, the laser diode produces light power which when plotted with the original current values yields linear characteristics.

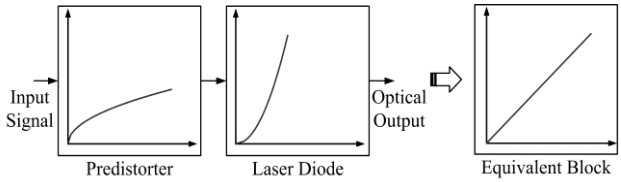

Fig.1.2. Principle of laser predistortion.

When the predistorter is cascaded with the laser diode, the overall circuit yields a linear power-current (P-I) characteristics which in turn reduces the harmonic distortion [6], [7]. In our work, we propose a FPGA based nonlinearity compensation in laser diodes. A predistorter in conjunction with optical transmitter is designed and implemented.

II. EXPERIMENTAL SETUP

A. P-I characteristics of the laser diode

Initially, the laser diode characteristics is characterized. The injection current versus optical power output for the given laser diode is plotted. The data obtained from the characteristics is utilized to create a Look Up Table (LUT) for the FPGA.

The DC source provides analog drive voltage which is varied in steps of 50mV. A driving circuitry which matches with the specifications of the laser diode was implemented. The laser diode has its own upper and lower limits of voltage rating which are specified as safe region of operation. It must be ensured that the laser diode is operating in the prescribed zone. Basically, the drive circuitry would consist of voltage down converter. A digital milliammeter is rigged up in series with the driving circuitry and laser diode. The accuracy of linearity is dependent on the precision of the current meter.

Now the analog signal is fed to the laser diode in order to study the spectral characteristics of the diode. The Fig.2.1. shows the experimental setup. Here, the signal generator produces analog signal of a specific frequency, f_o Hz. The frequency of this signal is an indicator of the data rate of the input data signal such as speech, music or images in real world. The purpose of using a monotone signal generator is to solely characterize the laser diode in the frequency domain. Due to the nonlinear nature of the laser diode, the spectrum of the optical signal would consist of other frequency components apart from the incoming frequency [8].

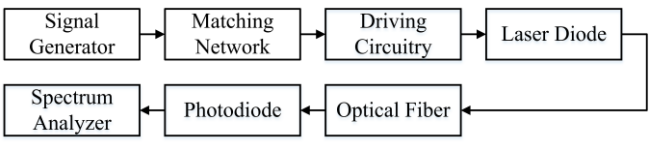

Fig.2.1. Experimental Setup to plot spectral characteristics of a laser diode.

There are umpteen types of matching networks, simplest being the L-type circuit. The output of the matching network is given to the driving circuitry to illuminate the laser through suitable injection current. The power launched by the diode is connected to the optical fiber using a suitable optical connector. The same holds good at the other end of the fiber.

A photodiode is used to convert the incoming light signal to electrical signal. But the characteristics of the photodiode is also nonlinear [9] therefore the performance analysis is based purely on the relative evaluation of the total harmonic distortion. Even though the spectrum of the input signal is expected to be monotonic, due to practical constraints on the design, it emits other frequency components but in feeble magnitude. After the input spectrum is evaluated, the spectrum of the detected light is also observed to compare with the input which reveals the nonlinear nature of a laser diode. In the experimental setup, the output spectrum is observed with and without predistorter in order to evaluate the improvement in total harmonic distortion. The expected graph shows an ideal response of both the signal generator and the received signal. The attenuation encountered in the optical fiber would be suitably compensated using a preamplifier. Thus we can visualize the harmonic distortion components which emerge from the laser diode. A typical graph is shown in Fig 2.2.

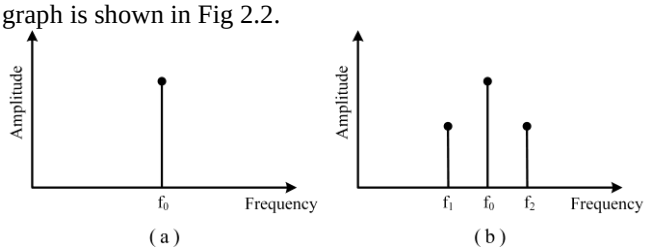

Fig.2.2. Spectrum of (a) input signal and (b) output signal of optical transmitter.

B. Implementation of the predistorter

The predistorter is implemented using high speed FPGA and data convertors. The entire setup for experimental study on laser diode nonlinearity with predistorter is shown in Fig.2.3.

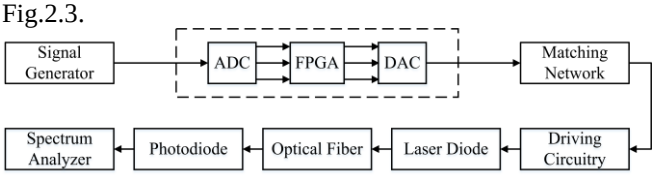

Fig.2.3. Block diagram of experimental setup for linearizing laser diode characteristics.

The expected spectra of input signal and that of the output signal after linearization are shown in Fig.2.4.

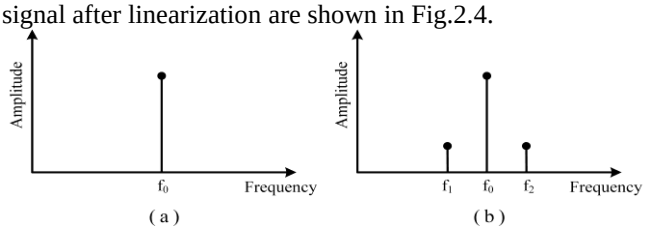

Fig.2.4. Spectrum of (a) input signal and (b) linearized output.

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The output spectrum with predistorter is compared with the output spectrum without predistorter. It would be in such a way that the magnitude of the unwanted frequency components in spectrum with predistorter is less, compared to the one without the predistorter. It should be noted that the photodiode is also nonlinear, thus the harmonic distortion products and intermodulation distortion products would not be zero [10].

III. RESULTS & DISCUSSION

The injection current and output optical power values are noted from the experiment described earlier. These values are suitably normalized. A curve is obtained for power versus injection current, certain mathematical techniques are used to fit the data to obtain a polynomial representation of the entire curve. The incoming current is digitized and represented by a binary number. This binary number is converted to decimal number using MATLAB. This decimal number is plugged into the equation obtained from the curve fitting of the graph. The actual power of the incoming current is obtained and the desired linear graph is already known. The value of the desired power is computed using the linear equation. But it is required to know the corresponding current for the desired power level. The inverse polynomial from the original curve is found to obtain the injection current level for a desired power. But this new injection current value would also be in decimal number which has to be converted back to binary in order to output the value from FPGA. By repeating this procedure for all possible values, LUT is obtained. This has two arrays, the incoming current and the desired current. This is further converted to analog signal and fed to the laser diode which would give a linear response.

Xilinx 9.2i was familiarized by simulating simple combinational and sequential circuits using VHDL. The simulator used was ISE simulator. The P-I characteristics were plotted with the values obtained from the hardware. Curve fitting toolbox of MATLAB was used to obtain various curve fitting polynomials, ranging from linear fit to a polynomial fit of 5th degree. A monotonic test signal of 500MHz was used. This test signal was input for the 5th order polynomial, since this function closely resembles the data set. Fig.3.1. shows different curve fits obtained using MATLAB.

The spectrum of the output signal is obtained in a RF spectrum analyzer and it is clear that harmonic distortion occurs as depicted in Fig.3.2. The frequency component M1 refers to the fundamental signal and the components M2, M3, and M4 are second, third, and fourth harmonics respectively. The relative amplitudes of harmonics in dBm are depicted in the figure. The same procedure was adopted in the laser diode along with the predistorter. Fig.3.3. shows the output signal spectrum after linearization of the laser diode characteristics. It has been found that the use of the predistorter suppresses the harmonic components significantly as depicted in Fig.3.3.

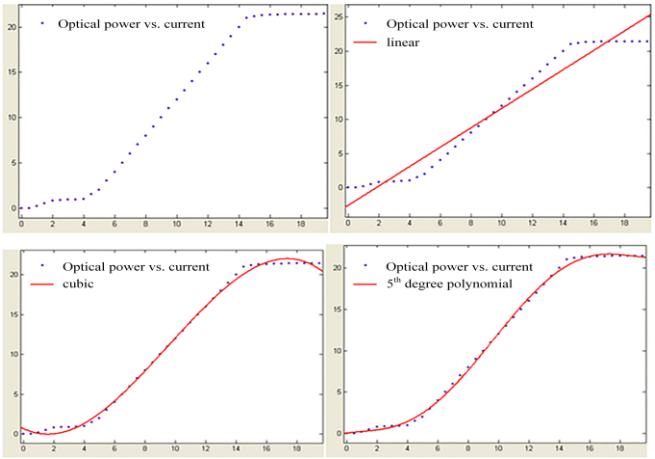

Fig.3.1. Various curve fits obtained using MATLAB.

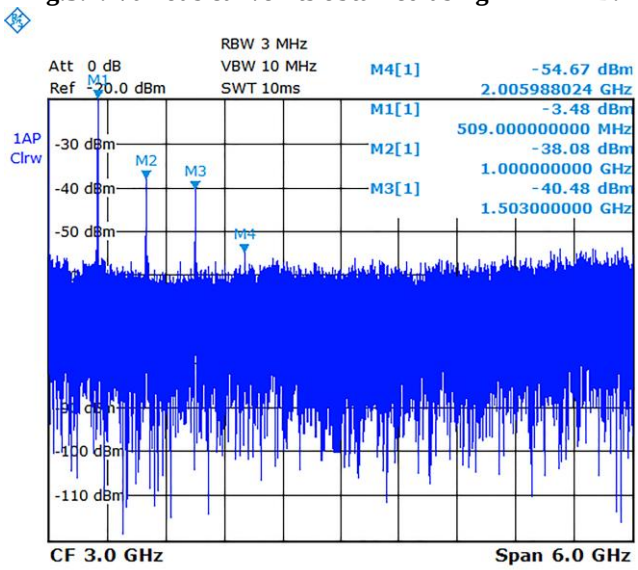

Fig.3.2. Spectrum of signal detected in a nonlinear laser diode.

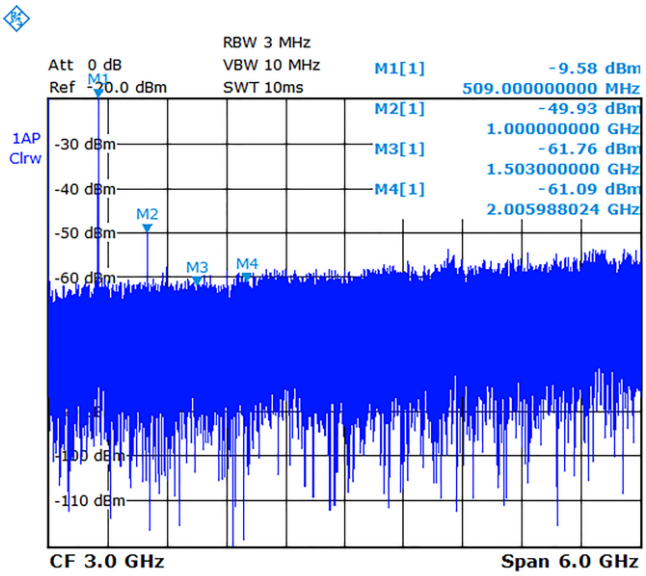

Fig.3.3. Output signal spectrum after linearization.

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IV. CONCLUSION

The inherently nonlinear P-I characteristics of a laser diode was transformed into a linear one using a FPGA based predistortion. The spectral analysis of the response due to a monotonic signal was experimentally carried out using a RF spectrum analyzer to demonstrate the improvement in total harmonic distortion of the laser diode. The impact of the laser diode nonlinearity is a problem to be addressed in the performance impairment of systems like Radio over Fiber links.

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