# Optical Filtering along with Pre-emphasis Driver in Long-haul Optical Networks

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***Abstract*— This paper proposes a novel technique to optimize the performance of the optical link by using the pre-emphasis driver and optical filtering scheme in vertical cavity surface emitting laser (VCSEL) based transmitters. Optical band pass filters (OBPFs) are employed to provide optimal filtering of signals at VCSEL output. Analysis of optical system is performed for both Butterworth and super-Gaussian OBPFs. We are able to generate a non-return to zero (NRZ) signal from 10 Gb/s VCSEL based transmitter for 160 km error-free transmission with sensitivity of -27.2 dBm at bit error rate (BER) of $10^{-9}$. The obtained results validate that with the application of pre-emphasis driver the eye-opening is improved without the necessity of any dispersion-compensation schemes. Numerical results are analyzed and compared between the transmitter with and without pre emphasis techniques.**

***Keywords*— Single Mode Fiber, Bit Rate, Dispersion and Optical Filter**

## I. INTRODUCTION

The high speed and less expensive optical transmitters are strongly recommendable for expanding usage of super-fast internet access and online video services. Vertical cavity surface emitting laser (VCSEL) is progressively employed to substitute the distributed-feedback (DFB) and Fabry-Perot laser (FPL) diodes because of its price reduction [1]. The VCSEL provides multiple benefits like small footprint and low-cost packing [2], raised quantum-efficiency and optical power [3], enhanced speed [4], circular beam output [5], [6] and decreased production cost [7]. The VCSELs are cost-effective and consume less power due to its compactness when compared to distributed bragg reflector (DBR) and DFB lasers [8].

Transmitter with either Electro-absorption (EA) modulator or Mach-Zehnder (MZ) modulator is an alternative feasible solution intended for 10Gb/s optical-communication (OC) links [9]-[11], we need to indicate that at 10Gb/s the dispersion-limited reach of these transmitter is usually around 80 km of SMF. Transmitter with directly modulated VCSEL (DM-VCSEL) presents several advantages like cost-effectiveness, lesser power-consumption and small footprint compared to EA and MZ external modulator based transmitters.

DM-VCSELs are generally employed for smaller transmission length applications. The VCSEL chirp significantly reduce the transmission reach of SMF link to 10 km at 10Gb/s [12].

A number of approaches have been presented to minimize the chirp problems. Dispersion compensation modules (DCMs) [13] and inverse dispersion fibers (IDFs) [14] are widely-used to eliminate the dispersion-induced signal degradation; these methods require installation of new kinds of optical fibers with enhanced cost and size of the system. Alternate methods have already proposed to overcome chirp related problem like injection locking [15] and equalization [16], all these techniques either increase complexity of the system or need replacement of optical/electrical devices.

DM-VCSEL based transmitters are preferred way to minimize the complexity and expense of the transmitter. For the first time to the best of author's knowledge, we propose a simple technique with pre-emphasis driver and optical filtering scheme at the VCSEL based transmitter in the access networks. This paper is organized as follows: theory of the proposed system is described in section II. The results are analyzed and discussed in section III. Finally, conclusions are presented in section IV.

## II. PROPOSED SCHEME

The VCSEL based transmitters with a pre-emphasis driver is employed to decrease inter-symbol-interference (ISI) in OC systems [17].

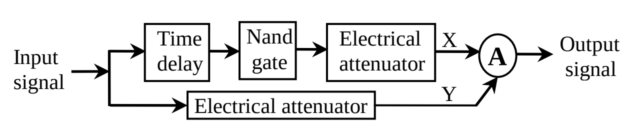


Fig. 1. Pre-emphasis scheme. X: primary signal; Y: secondary signal; A: adder

The proposed pre-emphasis scheme is depicted in Fig. 1. The input signal is divided into two paths to produce primary and secondary signals. A delay component is utilized to delay the input signal. The delay component output signal is inverted by employing a two-input electrical NAND gate. The primary signal is delayed and inverted with respect to secondary signal. The adder generates a pre-emphasis signal by adding the primary signal and the secondary signal. The attenuation and delay of the pre-emphasis driver are controlled to eliminate the effects of VCSEL chirp in SMF link. Hence, the pulse shaping technique of pre-emphasis is required for 10Gb/s optical signal transmission.

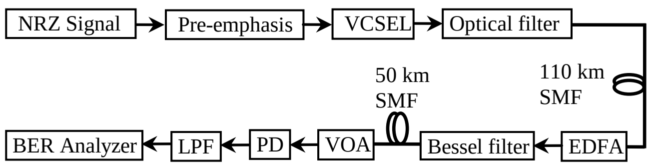


Fig. 2. VCSEL based transmitter with pre-emphasis and filtering scheme in optical transmission system

The block diagram of optical system with pre-emphasis is shown in Fig. 2. 10Gb/s non return to zero (NRZ) pseudo-random bit-sequence (PRBS) signal with a length of $2^{23}$-1 is generated by pulse generator. Pre-emphasis signal is used to drive the VCSEL. The characteristics of VCSEL chirp strongly limit the transmission distance of optical system. The laser rate equations [18,19] are utilized for implementation of VCSEL model. Butterworth and super-Gaussian optical band-pass filters (OBPFs) are employed for filtering of the VCSEL output. The OBPF is placed at the output of VCSEL. The transfer function $T_g(f)$ of the super-Gaussian OBPF is expressed as [20]:

$$T_g(f) = \exp\left(-ln(2)\left(\frac{2(f - f_c)}{\Delta f_{3dB}}\right)^{2N}\right) \qquad (1)$$

where $\Delta f_{3dB}$ is the filter 3dB bandwidth, $f$ is the frequency, $f_c$ is the central frequency of filter and $N$ is filter order. The squared transfer function $H_b(f)$ of a Butterworth OBPF is expressed as [21, 22]

$$\left|H_b(f)\right|^2 = \frac{1}{1+\left(\dfrac{2(f - f_c)}{\Delta f_{3dB}}\right)^{2N}} \qquad (2)$$

Integrating the optical filter with VCSEL permits small form-factor optical transmitters and it is a good way to extend the reach of 10 Gb/s optical system. An erbium doped fiber amplifier (EDFA) is placed after 110 km of SMF to increase the optical signal power. A Bessel filter is inserted after EDFA to remove amplified spontaneous-emission (ASE) noise. The transfer function of Bessel filter is defined as [23]

$$H_s(s) = \frac{1}{\sum_{k=0}^{N}\left(\dfrac{(2N - k)!(s)^k}{2^{N-k}\,k!(N - k)!}\right)} \qquad (3)$$

where $H_s(s)$ is the transmittance of the Bessel filter and $s$ is the complex frequency-variable. A variable optical attenuator (VOA) is used to alter the receiver input power for sensitivity measurement. The receiver section consists of photo-detector (PD), Gaussian low-pass filter (LPF) and bit-error-rate (BER) analyzer. Gaussian LPF is employed to remove PD noise.

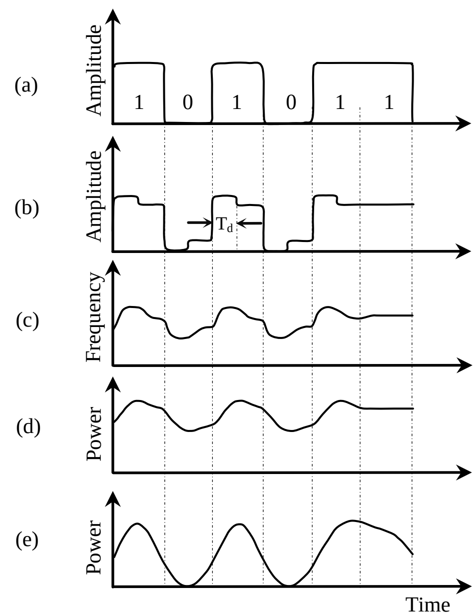


Fig. 3. Operation principle of transmitter. (a) NRZ signal, (b) pre-emphasis signal to drive VCSEL , (c) frequency profile (Chirp) of VCSEL, (d) optical power at the VCSEL output and (e) OBPF output power

Fig. 3 illustrates the operation principle of proposed transmitter. The PRBS NRZ signal from the pulse generator is shown Fig. 3(a). The pre-emphasis pulses with duration $T_d$ at each bit transition are generated by using pre-emphasis driver is shown in Fig. 3(b). The pre-emphasis pulse contains negative and positive peaks; the duration of peak is determined by delay time of pre-emphasis driver. The VCSEL chirp is shown in Fig. 3(c). VCSEL adiabatic chirp is equal to half of the bit rate, which means mark bit has 5 GHz frequency shift related to the space bit. The adiabatic chirp of $\Delta f$ = 1/2$T$ is generated by varying the laser device parameters and driving signal amplitude. 5 GHz adiabatic chirp is generated from VCSEL to provide a phase shift of

$$\Delta\phi = 2\pi\int_0^T \Delta f(t)dt = 2\pi\times\frac{1}{2T}\times T = \pi \qquad (4)$$

during space bit-period ($T$). VCSEL is operated at the high bias current compared to threshold value for reducing transient chirp. Frequency modulation (FM) characteristics of VCSEL are determined by adiabatic-chirp. The output power of the VCSEL as shown in Fig. 3(d); the extinction ratio at the VCSEL output is 2.1 dB. The chirp-induced FM signal is converted into amplitude modulated (AM) signal by passing through the OBPF as shown in Fig. 3(e); the extinction ratio at the filter output is enhanced by attenuating space bits and passing the mark bits. The main function of filter is to produce chirp-free optical signals except for the middle portion of the space bit; this result in π phase shift rapidly during the center portion of the space bit period. At the OBPF output, the power fluctuation between single "1" bit and long sequence of "1" bits are minimized as a result of pre-emphasis driver.

## III. RESULTS AND DISCUSSION

The performance of optical system with pre-emphasis scheme is analyzed by using practical OC system design and Matlab software. The delay of pre-emphasis driver is 50 ps. The primary and secondary signals of pre-emphasis are attenuated by 23 and 3 dB respectively before sending through the adder. The VCSEL model is utilized in numerical calculations with the following parameters: volume of active layer = $80e^{-12}$ $cm^3$, quantum efficiency = 0.4, photon life time = 8 ps, injection efficiency = 1, carrier density at transparency = $1e^{17}$ $cm^{-3}$, carrier life time = 2 ns, gain compression coefficient = $8e^{-17}$ $cm^3$, differential gain coefficient = $1e^{-15}$ $cm^2$, spontaneous emission factor = $1e^{-6}$, line width enhancement factor = 3.2, mode confinement factor = 0.9, modulation current = 8 mA, bias current = 9.62 mA and wavelength = 1550.127 nm.

The bandwidths of second-order super Gaussian and fourth-order Butterworth OBPF are 10 and 9 GHz respectively, these filters are running at 1550 nm central wavelength. The SMF is employed in computations with the following parameters: chromatic dispersion = 16.75 ps/nm/km, wavelength = 1550 nm, effective core area = 80 $\mu m^2$, attenuation = 0.2 dB/km, slope of dispersion = 0.075 $ps/nm^2/km$ and nonlinear refractive index = $2.6e^{-20}$ $m^2/W$. Noise figure and gain of EDFA are 4 and 20 dB respectively. The bandwidth of first-order Bessel filter is 29 GHz. Responsivity and dark current of avalanche PD are 1 A/W and 10 nA respectively. Second-order Gaussian LPF cut off frequency is 6 GHz.

The power signal after 160 km of SMF without pre-emphasis for super-Gaussian and Butterworth filter as shown in Fig. 4(a) and Fig. 4(b) respectively, it is visible that the power of single mark bit is decreased compared to continuous sequence of mark bits; this results in less opening of eye pattern due to inter symbol interference (ISI) and decrease the performance of the optical link.

The receiver input power with pre-emphasis at 160 km of SMF is shown in Fig.5. With the application of pre-emphasis driver, the optical power difference between the single mark bit and the continuous sequence of mark bits is decreased by 50% compared to transmitter without pre-emphasis; this results in high sensitivity and wider eye opening at the receiver. The optical link performance is compared between the proposed technique and narrow optical filtering (NOF) [24] scheme. Pulse generator, VCSEL and optical filter are components of NOF transmitter.

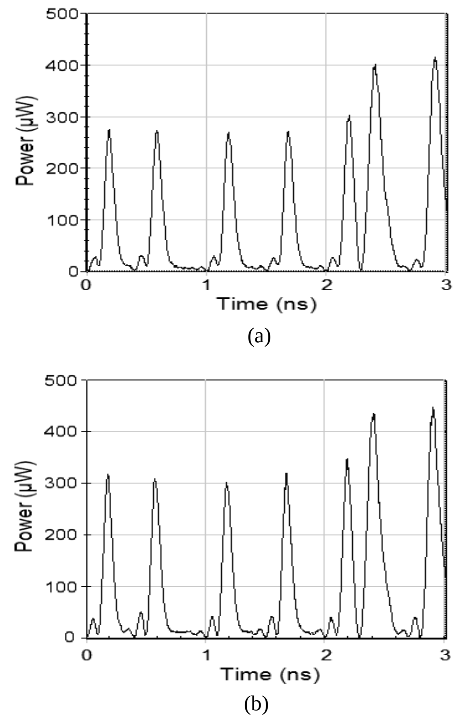


Fig. 4. Receiver input power without pre-emphasis. (a) super-Gaussian filter and (b) Butterworth filter for 010001000001000010000101100011 bit sequence

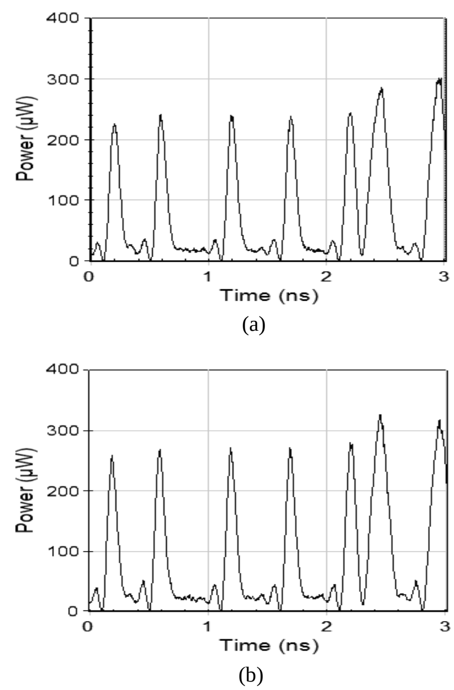


Fig. 5. Receiver input power with pre-emphasis. (a) super-Gaussian filter and (b) Butterworth filter for 010001000001000010000101100011 bit sequence

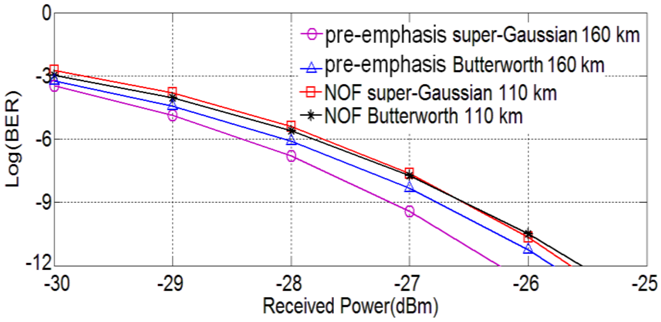


Fig. 6. BER values for pre-emphasis approach and NOF method

The sensitivities of receiver are calculated at BER of $10^{-9}$ for pre-emphasis scheme at 160 km and NOF scheme at 110 km as shown in Fig.6. The receiver sensitivities of NOF with super-Gaussian and Butterworth are -26.5 and -26.5 dBm respectively. The sensitivities of pre-emphasis with super-Gaussian and Butterworth are -27.2 and -26.75 dBm respectively. With the pre-emphasis scheme sensitivity is increased by 0.7 dBm compared to NOF scheme as result of pre-emphasis driving signal. At the receiver input, the difference of power level between single mark bit and consecutive mark bits is decreased with pre-emphasis compared to without pre-emphasis; this important feature increases the sensitivity in the SMF link.

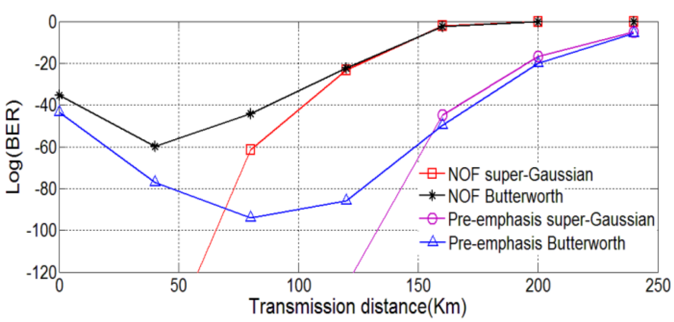


Fig.7. BER and transmission distance relationship for NOF and pre-emphasis techniques.

Fig. 7 depicts the BER performance along the SMF for different transmission distances. The BER performance with pre-emphasis scheme after 227 km transmission distance is greater than $10^{-9}$. BER value for NOF method is greater than $10^{-9}$ after 137 km of SMF.

The eye-diagrams for NOF and pre-emphasis scheme are shown in Fig.8. The maximum eye-opening factors of NOF with super-Gaussian and Butterworth are 0.73 and 0.74 respectively. The eye-opening factors of pre-emphasis with super-Gaussian and Butterworth are 0.93 and 0.93 respectively. The clear eye-opening is achieved with proposed scheme compared to NOF scheme due combined effect of pre-emphasis and filtering scheme.

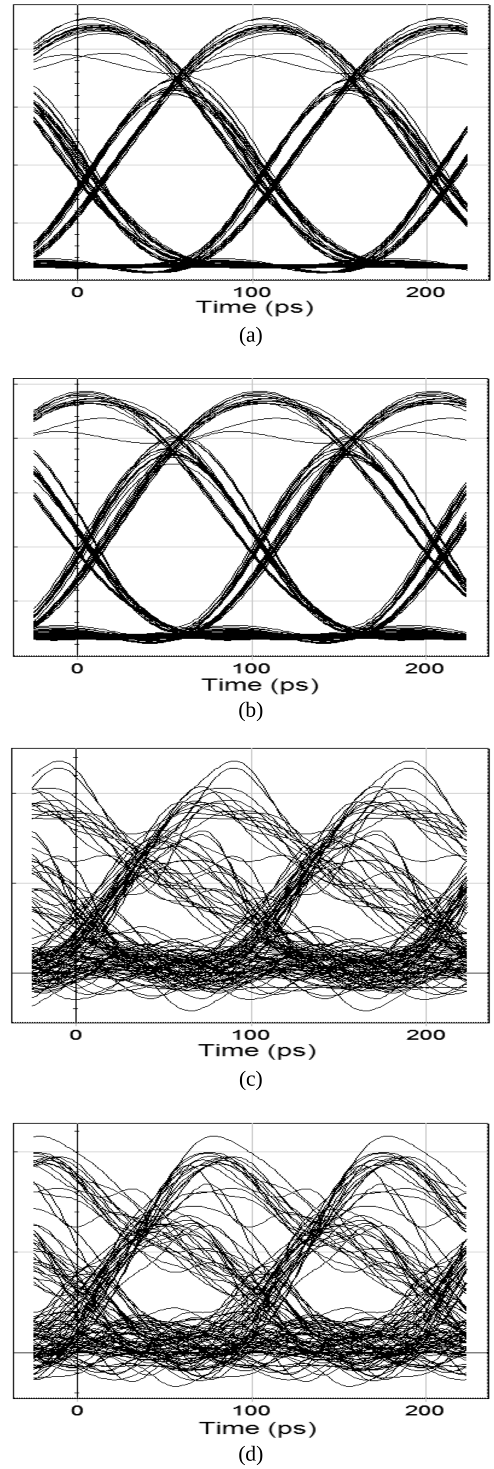


Fig. 8. Eye patterns at 150 km of SMF. (a) pre-emphasis with super-Gaussian filter, (b) pre-emphasis with Butterworth filter, (c) NOF with super-Gaussian filter and (d) NOF with Butterworth filter

The performance of pre-emphasis scheme is compared with other prior approaches in Table I. The current approach has longer transmission distance and higher sensitivity compared to previous methods.

Table I: Comparison of present work with earlier schemes

| parameter | Pre-emphasis with Butterworth | Pre-emphasis with super-Gaussian | NOF [24] | IDF [14] | VCSEL [12] |
|---|---|---|---|---|---|
| bit rate (Gb/s) | 10 | 10 | 10 | 4.25 | 10 |
| fiber length (km) | 160 | 160 | 110 | 45.4 | 10 |
| fiber type | SMF | SMF | SMF | SMF and IDF | SMF |
| laser type | VCSEL | VCSEL | VCSEL | VCSEL | VCSEL |
| wavelength (nm) | 1550 | 1550 | 1550 | 1550 | 1550 |
| Sensitivity (dBm) | -26.75 | -27.2 | -26.5 | -24.5 | -17.88 |

## IV. CONCLUSION

The pre-emphasis scheme has been employed to compensate performance degradation due to laser chirp in 10Gb/s VCSEL based SMF links. The computed results show that new approach enhances the clearness of eye opening originally closed as a result of dispersion in SMF. The combination of pre-emphasis and optical filtering scheme is considered for implementation of cost-effective dispersion tolerant transmitters used to provide long-reach signal transmission in next-generation access networks.

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