JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Design and Simulation of High-speed Multimode Optical Link

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Abstract: We demonstrate a high-speed optical transmission link utilizing signal processing techniques with a tri-mode 16-QAM vertical cavity surface emitting laser (VCSEL) operating at 850 nm over OM5 multi-mode fiber. At the transmitter, a linearly polarized raised cosine (LPRC) roll-off filter is employed to enhance frequency response at GHz ranges. A discrete multi-tone (DMT) modulation scheme with pre-equalization, combined with a cosine pulse filter (CPF), is implemented to support data rates exceeding 135 Gb/s with improved signal quality. Additionally, an orthogonal frequency division multiplexing (OFDM) scheme using fast Fourier transform (FFT) coefficients facilitates high-speed digital transmission. A 2^7–1 pseudo-random bit sequence (PRBS) is used for testing the system. Performance analysis based on eye and constellation diagrams reveals low bit error rates and minimal signal distortion. Our system achieves a peak data rate of 200 Gb/s with enhanced optical modulation amplitude, high link efficiency, and low power consumption. The proposed approach outperforms existing methods in both performance and energy efficiency.

IndexTerms **- Quadrature amplitude modulation; Multi-mode Fiber; Discrete Multi-tone; Orthogonal Frequency Division Multiplexing; Fast Fourier Transform; Optical modulation amplitude.**

I. INTRODUCTION

In Today's environment, data centers are gaining importance due to trend of outsourcing data access through cloud, while supporting bandwidth intensive applications. High-speed data processing centers and optical interconnects depend stringently on thriving ultra-speed optical transmitters to overcome the heavy data traffic-induced dueto the rapid increase in usage of networking and data routing in data servers. Basically,the data transmission is for transferring the bitstream of data or exchange data betweenthe transmitter and receiver in digital communication over one point to another point and a single point to multi-point communication which requires the channels such as copper wires, fiber optics, and wireless communication channels as shown in Fig. 1. Based on the survey, more than 60 zettabytes of data will be transported or exchanged in 2020. In addition, over the past 10 years along with future of up to 2025, traffic has climbed roughly threefold. The rate of expansion is projected to continue, necessitating an increase in the number of hyperscale data centers. Thousands of high-speed interconnects run across data centers. That data transmission within the data centers accounts for most of the traffic as a result, the development of reliable, high-speed, and energy-efficient systems is pushed forward.

With expeditious development in the generations, we must originate advanced modulation techniques for data transmission with high-speed data rates, High Bandwidth and high-speed multi-Gigabit per second optical links without any overcomes in intra and inter-data centers. Based on the standard 100GBASE-SR4 and Ethernet task forcewhich operates data rates with 100 Gbit/s and 400 Gbit/s with each having four channels so the data rates are divided with 25 Gbit/s and 50 Gbit/s lanes in multimode fiber[1]. Fig. 2 shows the traffic distribution of data centers. To generate such an infrastructure it requires directly modulated laser diodes with less complexity, a photodiode for link design and for external source we require modulation technique based on requirements of the design. Initially for establishing the linkdesign module we consider the Multimode Fiber (MMF) link which is for transmittingbit streams of data through 850nm Vertical Cavity Surface Emitting Laser (VCSEL) which has an optical Transmission data link with low power efficiency, high through- put link usage and photodiode with Optical Modulation Amplitude (OMA) which is specifying the performance of the optical link.

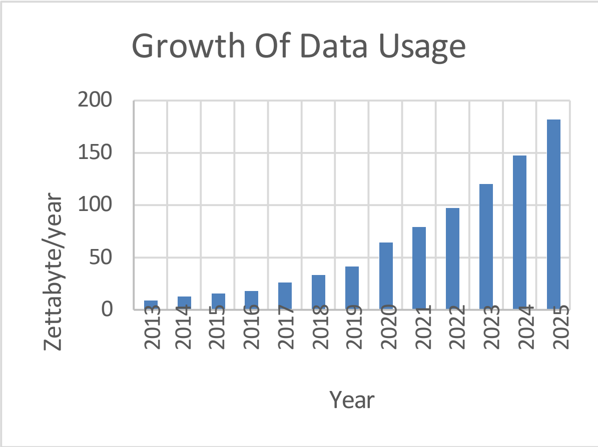

Fig. 1: Data usage growth over the years

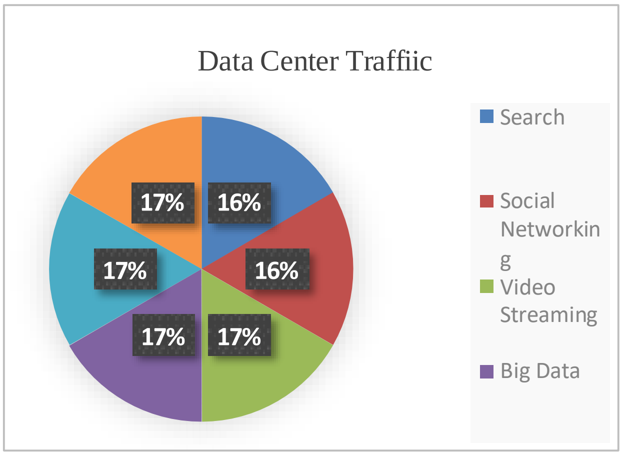

Fig. 2: Data center traffic

II. LITERATURE SURVEY

Optical fiber communication systems are designed mainly using VSCEL and PD over amultimode fiber optical link using CMOS circuits to achieve giga-bit speed transmissionof data. Initially, a standard 90-nm bulk CMOS was fabricated using laser diode driverand receiver ICs to achieve 25 Gb/s of data transmission [2]. Here they illustrate the reliability of VCSEL based link based on the parameters speed and efficiency to reachnext generation for large data centers. This system contains pre-amplifier stage built by two Cherry-Hooper differential amplifiers carried by differential current mode logic(CML). Testing was executed by using readily available pattern of 2^7-1 Pseudo RandomBit Stream (PRBS). At last, this work was achieved only 15 Gb/s of data transmissionwith no loss in Bit Error Rate (BER), tried to increase the data transmission rates from15 Gb/s to 22 Gb/s but it occurred that BER is also increasing to obtain a result criterion, but the power efficiency is high. At the speed below the optimum rate according to work the power consumption is minimum but the BER is not up to the require criteria, but at the higher data rates it has low BER, but the power efficiency is increasing by IC supply voltages, VCSEL modulation and bias current were increased to minimize error rate.

In 32nm SOI CMOS system they design an optical link which can carry a data up-to 35 Gb/s using 32-nm Silicon on Insulator CMOS circuit with faster transistors which has 1pJ/bit of low power consumption at 25 Gb/s and maximum data rate of 35 Gb/s [3]. SOI CMOScircuit is design with an oxide layer isolation, source/drain parasitic capacitances are reduces so that the delay and power consumption of the device will be low then the bulk CMOS. The design of Transmitter is on chip with 2-stage pre- amplifier and laserdiode driver using current mode logic (CML) algorithm at signal level. At the receiverit contains Trans- impedance (TIA) has a pair of CMOS inverters along with renitent feedback, 5-stage Limiting Amplifier (LA) and Pre-Amplifier (PA) uses alike active-feedback and a Low Pass Filter (LPF) it will raise the DC level restoration. They use two VCSELs which

are arranged in a parallel way where the one VCSEL will act as dummy to maintain balance load when the link is operated so that it can obtain requiredlow power efficiency.

14nm FinFET CMOS design is mainly focused on the integration of optical I/O which is directlyfabricated to Fin-FET CMOS chip to increase package I/O bandwidth density and to de-crease the overall system power and cost, As Fin-FET technology has more advantagesthan other CMOS technologies such as higher speed, lower leakage, and lower power consumption. The working methodologies are at transmitter side it uses three taps, in that 1/2 unit is for interlude spaced feed-forward equalizer to enhance the output ofeye closure and at the receiver side, it uses low bandwidth, low noise Trans- ImpedanceAmplifier and 1-tap Decision Feedback Equalizer for high sensitivity [4]. The data is mainly serialized by MUX before reaching the VCSEL driver circuit to get modulatedcurrent, release modulated light from VCSEL is integrated through MMF with more orless loss in signal, then the light beam from MMF passes through PD again with loss, here the light is converted into current by PD and again it converts into voltage by TIAand now the data is de-serialized by De-MUX.

The works established a 102 Gb/s PAM-2 transmission using 850nm VCSEL on 50m over OM5 fiber below the low overhead FEC threshold which is occurred as the fastest error-free transmission using signal processing [5]. Based on that this work experimentally developed beyond 160 Gb/s over 500 OM5 fiber with 850nm VCSEL using PAM-4 signal processing with increased bandwidth above 28 GHz. Equalization is achieved by implementing pre-emphasis at the transmitter side and static Feed-Forward Equalizer (FFE) at the receiver side, furthermore a raised cosine (RC) filtering is included to establish the assistance of pulse shaping the electrical signal for a typical equalized VCSEL link channel [6,7]. For testing the results of data transmission VCSEL were driven by Arbitrary Wave- form Generator (AWG) with 45 GHz of analogue bandwidth with a test pattern of 215−1 PRBS. The pre-emphasis was generated by AWG at the transmitter in a restricted form which is restricted with the DAC 6-tap filter and the receiver was applied using a real-time Key-sight UXR1102A oscilloscope and counteract for remaining channel distortion through a static 5-tap FFE based on the baud rate. Finally, this work demonstrated 146 Gb/s PAM-4 error-free transmission and 168 Gb/s PAM-4 with FEC allocation transmission using 850nm on 50m over OM5 as shown in Fig. 3.

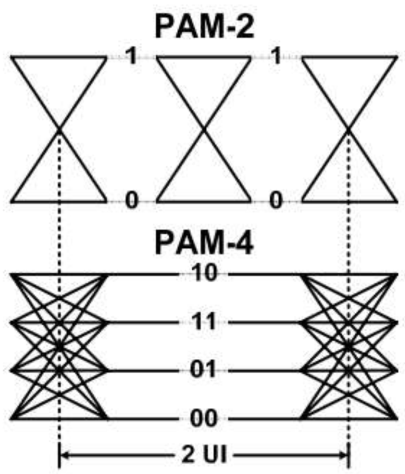

Fig. 3: Pulse amplitude modulation – simple binary PAM-2 (1bit/symbol) and PAM-4 (2bits/symbol).

With growing demand for high-speed data applications, we propose a multimode optical link using 16-QAM modulation to achieve data rates over 100 Gb/s. This approach ensures low interference, improved signal quality, and higher link efficiency, outperforming traditional PAM-4 systems in terms of speed, reliability, and power efficiency. This work focuses on the following methodologies to achieve the objectives: Pre-equalization along with Discrete Multi-tone algorithm to enable beyond 500m OM5 MMF link beyond 135 Gb/s; Pre-leveling will improve the desired data rates i.e, SNR; Raised Cosine filter is used to improve the quality of the signal to enable Bit error rate.

III. METHODOLOGY

This work designs the link based on VCSEL a semiconductor-based laser diode. In optical communication, VCSEL gained a better result because it has intrinsic advantages like low production costs, energy efficiency, easy to deintegration for mass production and it was specially designed with their sub -threshold currents and bandwidths in excess of 20GHz. It uses as an optical source in optical transmitters within the wavelength regions of 850nm for short and 1310/1500nm for long. It has characteristics like wide spectral range, optical coherence tomography, fiber Bragg-grating sensing and light ranging sensors. VCSEL has different applicationsand most recent developments according to the latest technologies in digital communications such as short, and long-wavelength VCSELs, High bandwidth VCSEL sourcesbased on intensity modulation and advanced modulation formats in optical communication systems, Tunable VCSEL sources for communications and sensing. Fig. 4 shows the VCSEL and its equivalent electrical model.

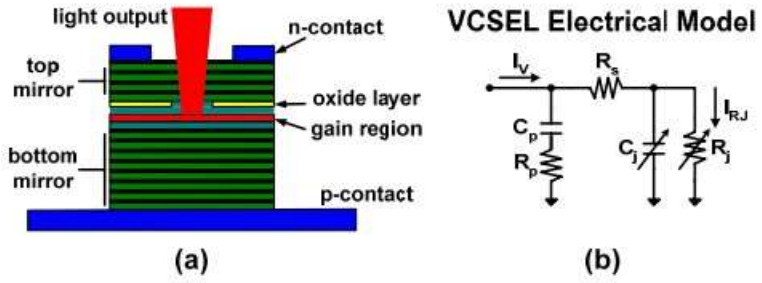

Fig. 4: VCSEL (a) Device cross-section, (b) Electrical Model

A PIN diode used as an optical receiver for better reception of optical signals without distortion. The transmitter and receiver are connected via optical channels, usually, the optical fibers. The transmission of data across optical fibers is generally attained by conveying a sequence of pulses of light energy. However, as an individual pulse propagates, it spreads out due to the dispersive properties of the fiber. Pulse dispersion is the spread in the optical pulse as it progresses along with the fiber. Dispersion limits how fast information is transferred. There are two different types of dispersion in optical fibers Differentwavelengths of a light pulse that enters the fiber at one time exit the fiber at different times. Chromatic dispersion – Chromatic Dispersion is a combination of material dispersion and waveguide dispersion. Transmitter has a primarily losses of spectral width and typical choice of correct wavelength. Modal dispersion occurs when light moves through the fiber Chromatic dispersion or intra-modal dispersion occurs because discrete colors of light travel through separate materials and waveguide structures at different speeds [8-9].

$$\Delta t_{modal} = \frac{n_1 Z}{c}\left(\frac{\Delta}{1-\Delta}\right) \quad (1)$$

Where, Δt_{modal} = Dispersion

N = Core refractive index Z = Total fiber length

C= velocity of light in air

Δ = Fractional refractive index $\left(\frac{n1-n2}{n_1}\right)$

Materials dispersion occurs because of the spreading of a light pulse which is de- pendent on the wavelength interaction with the refractive index of the fiber core. A different wavelength travels at different speeds in the optical fiber. Different wavelengthsof the light pulse that enters a fiber at one time exit the fiber at different times. The Material dispersion for unit length (L = 1) is

$$D_{mat} = \frac{-\lambda}{c} x \frac{d^2 n}{d\lambda^2} \quad (2)$$

Where, c = light velocity

λ = Center wavelength

$\frac{d^2 n}{d\lambda^2}$ = Second derivative of index of refraction w.r.t wavelength

Waveguide dispersion occurs because the mode propagation constant is a functionsize of the core of the fiber which is relative to the wavelength of operation. Waveguidedispersion also occurs because light propagates in the core than in the cladding area. Modal dispersion or intermodal dispersion occurs only in multimode fibers which causes the input light pulse to a spreading pulse where the input pulse signal is made up of different modes. As the light energy distributed over the modes is delayed by different properties, here the pulse is spread because each mode propagates through thefiber at different speeds and travels in a different direction and some are travelling a long distance over the same time period because of this condition the pulse of output data is spread. Modal dispersion decreases by decreasing the length of the fiber.

The group delay (τ_{wg}) arising due to waveguide dispersion.

$$(\tau_{wg}) = \frac{L}{C}\left[n_2 \Delta \frac{d(kb)}{dk}\right] \quad (3)$$

Where, b = Normalized propagation

Constant k = $\frac{2\pi}{\lambda}$ (group velocity)

Any change in the output signal transmitted by the source that alters the basic waveform, noise is added to the signal or interface occurred or the signal is delayed in time then that signal is distorted. To minimize the distortion, maintain the low capacitance optical fiber cable in the shortest length possible for the link. Let us consider a system has an input signal $x(t)$ and output signal $y(t)$ then the distortion less system will be defined as

$$y(t) = kx(t - \Gamma) \quad (4)$$

where k is the scaling constant and Γ is the time delay. To derive the condition for a signal to be the distortion less in the frequency domain, let us take the Fourier transform to the above equation. If $Y(\omega)$ is the Fourier transform of $y(t)$ and $X(\omega)$ is the Fourier transform of $x(t)$, we get

$$Y(\omega) = ke^{-j\omega\Gamma}X(\omega) \quad (5)$$

It means that if a system has a frequency response $ke^{-j\omega\Gamma}$ then it does not produce any distortion of the signal, but it must satisfy two conditions - The amplitude response must be constant (k); the phase response should be liner (Γ). Reasons why the signal will get distortion while propagating on optical fiber are: the attenuation of fiber is the loss of optical fiber with wavelength dependent. That makesk a function of frequency; For different wavelengths and modes of optical fiber travel with different speeds therefore it has a wavelength-dependent delay. This phenomenon is called dispersion. Signal attenuation of an optical fiber is what should be the maximum distance between transmitter and receiver, based on the

attenuation repeater are place. The signal travels for a long distance the pulses will overlap with adjacent pulses, it leads to error in receiver and capacity of information is distorted. Therefore, attenuation is a measure of signal strength of the fiber, it is mainly occurred by absorption and scattering losses of a signal.
Let consider the couples optical power is P (0) i.e., at origin (z = 0) Then the power at distance z is given by

$$P(z) = P(0)\, e^{-\alpha_p z} \quad (6)$$

Where, α_p is fiber attenuation constant (per km)

$$\alpha_p = \frac{1}{z} \ln\left[\frac{p(0)}{p(z)}\right]$$

$$\alpha_{dB/km} = 10.\frac{1}{z}\log\left[\frac{p(0)}{p(z)}\right]$$

$$\alpha_{dB/km} = 4.343\, \alpha_p \text{ per km}$$

This parameter is known as fiber loss or fiber attenuation.

The design of an optical link consists of various interconnected components among thefiber source, before obtaining the full link it may undergo several steps to achieve an error-free link. The main parameters to be considered are performance and cost and power efficiency of design so that the components should be chosen wisely in orderto reach the desired level of performance and to meet the required parameters for the proposed system. The typical optical transmission system design mainly consists ofa transmitter, optical source, and medium of transmission, detector, and receiver. The link was designed in an opti-system software tool, here the layout should be created before creating a link, in that layout the link is developed by inter-changing the requiredcomponents.

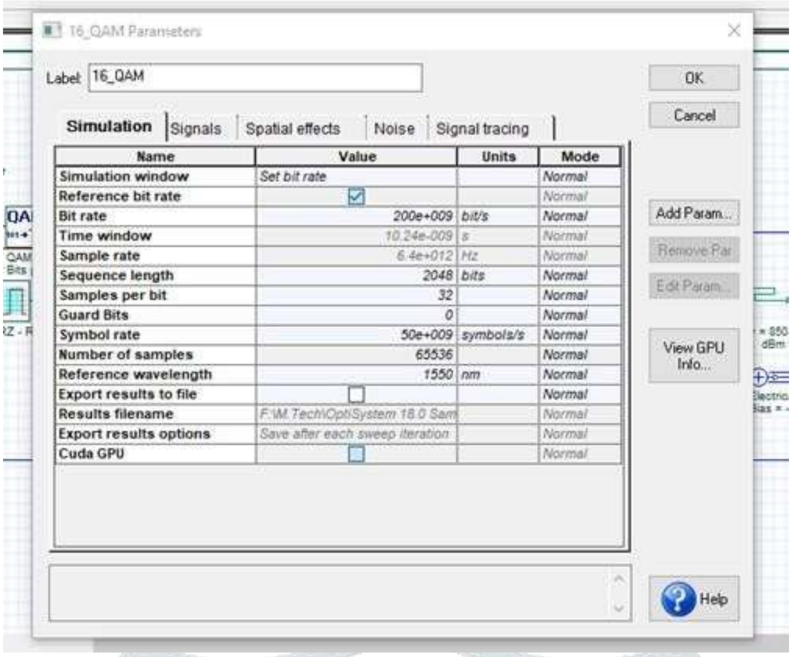

Fig. 5: Layout Parameters

The transmitter consists of data source, QAM sequence generator, laser diode, OFDMmodulator and quadrature modulator. The data source is generated by binary data as a pseudorandom sequence for above 150 Gb/s data rate and the reference signal is taken by non-return-zero signal. The transmitted data from PRBS is given to the QAM sequence generator with 4 bits per symbol where the signal is modulated using the QAM technique to modulate two individual signals through the same channel so that the band- width will increase. The output of the QAM sequence generator is connected to two m-ary

pulse generators, major benefit of this is for efficient usage of bandwidth, as because QAM has a greater number of bits per carrier, from m-ary con- stellation representation is shown by constellation diagram. From m-ary the signal is given to OFDM modulator where it incorporates the benefits of quadrature amplitude modulation and frequency division multiplexing to obtain a high data rate link in a communication system. Now the individual signals are connected to two individual LPcosine roll-off filter which produces a frequency response with complete gain at higherfrequencies, by using this filter excess bandwidth symbol rate is reduced. The output from filters as in-phase and quadrature are carried by quadrature modulator, here the individual signals are combined by modulator this is the overall modulation process in the transmitter. The experimental setup of the transmitter is shown in Fig. 6.

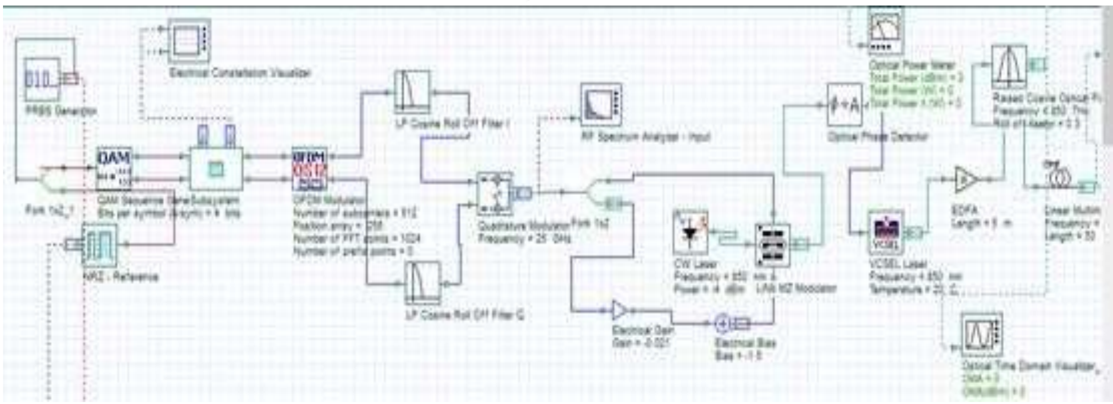

Figure 6: Transmitter experimental setup

The data signal which is modulated and transmitted through multimode optical fiber is passed through an optical attenuator to reduce the power level of a transmitted optical signal. The output signal from OAis given to PIN- Photodiode, it is a kind of photodetector where the optical signal is converted into electrical signals. Now, this electrical signal is passed through trans-impedance amplifier circuit configuration changes an input current source into an output voltage. This signal is to be demodulated to regain the original signal, firstly the signal is given to quadrature demodulator here the combined signal is demodulated as individualsignal as in-phase and quadrature signals and again it is given to OFDM demodulator and QAM sequence decoder through this demodulation technique the data is reformedand transmitted towards receiver over multimode fiber. The output result of a link is shown in the constellation visualizer with a 16-QAM constellation diagram. Fig. 7 shows the receiver setup used of the simulation.

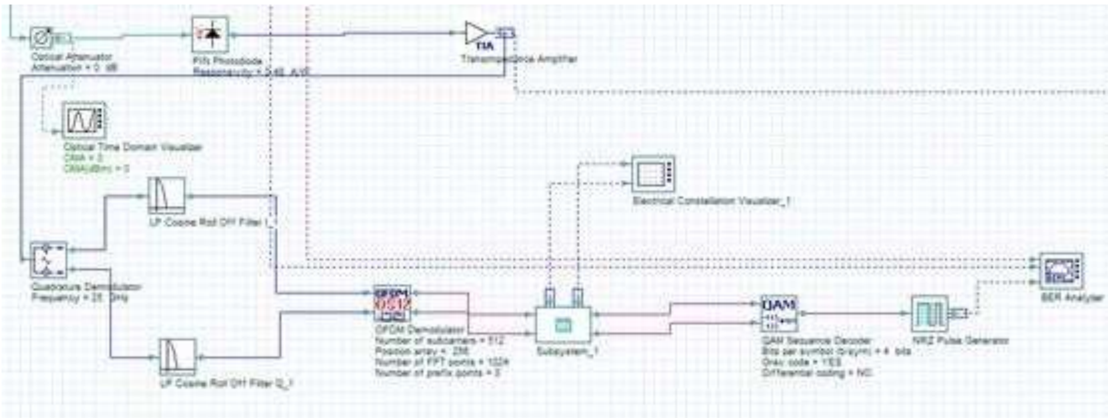

Figure 7: Receiver experimental setup

To expand a given channel's greatest information rate, numerous correspondence frameworks use balance strategies to drop inter symbol obstruction brought about by channel twisting. Balancers are executed either as straight channels (both discrete

and constant time) that endeavor to smooth the channel recurrence reaction, or as non-direct channels that straightforwardly drop ISI considering the information arrangement. Contingent upon framework information rate necessities comparative with channel data transmission and the seriousness of likely commotion sources, various blends of communicate or potentially get evening out are utilized. Communicate adjustment, executed with a FIR channel, is the most well-known method utilized in rapid connections. This TX "pre-accentuation" (or more precisely "de-accentuation") channel, endeavors to transform the channel bending that an information bit encounters by pre-mutilating or forming the beat more than a few piece times. While this sifting could likewise be executed at the collector, the principle benefit of executing the balance at the transmitter is that it is by and large more straightforward to construct high speed computerized to-simple converters (DACs) versus get side simple to-advanced converters. Notwithstanding, because the transmitter is restricted in how much pinnacle power that it can send across the channel because of driver voltage headroom limitations, the net outcome is that the low-recurrence signal substance has been constricted down to the high-recurrence level.

Raised cosine filter is a roll-off factor specifies the bandwidth of the filter with infinite number of taps. It is used for pulse shaping or fine tuning to get the expected data. By changing the roll-off factor the received signals or data with less noise, here there are some data taken without roll off factor and with roll off factor by seeing the eye diagram we can easily understand about the cosine pulsed roll off factor equalization.

IV. RESULTS AND DISCUSSION

The VCSEL is observed clearly in the Chapter-3 among all the VCSEL types of tri- mode has better efficiency for higher data rates it has 5 µm aperture size, threshold current 0.49 mA and optical power as 1.99 mW. Fig. 8 shows MM VC Fig. 8: MM VCSEL and Tri-mode VCSEL.

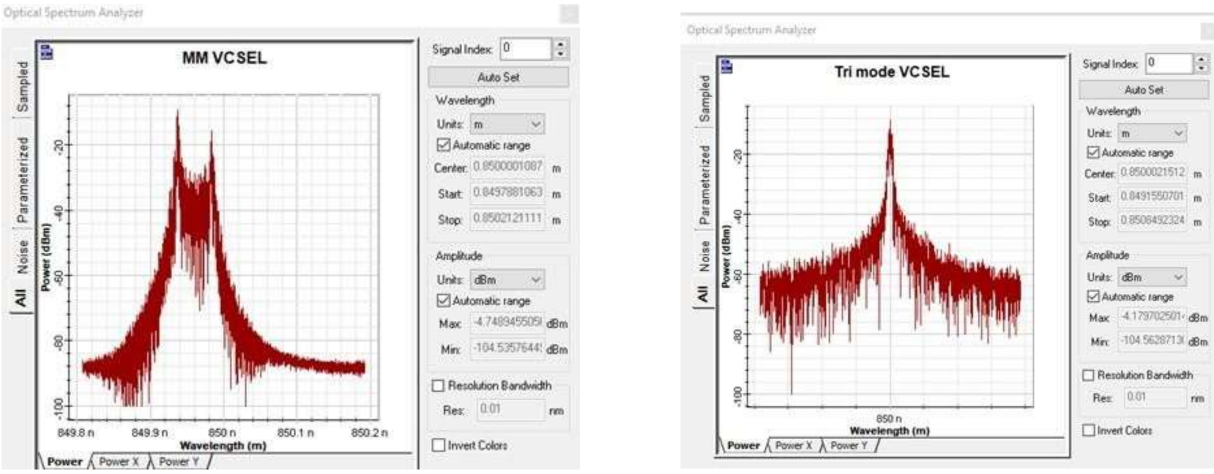

Fig. 8: Comparison of MM and Tri-mode VSCELs Table 1. Results comparison

Parameters	Proposed System	Existing System
Data rates	Up-to 200 Gb/s	Up-to 71 Gb/s & 168 Gb/s
Signal Distortion	Less	More
Modulation	16-QAM	PAM-2, PAM-4
VCSEL used	Tri-mode VCSEL	Directly modulated VCSEL
OMA (dBm)	1.3	2.4
Optical Power Mw	1.99	2.6

From Table 1, it is observed that the throughput response of the tri-mode VCSEL is better compared to those observed from multi-mode, few modes and single-mode, here both MM and tri-mode are shown in figure 5.5 and figure 5.6 tri-mode VCSEL has better RIN level that of MM VCSEL over 850nm wavelength.

16-QAM modulation will get typically arranged in a square grid with equal horizontal and vertical spacing though it has binary output, here in optical communicationthe channel is fiber optics so the constellation diagram will be in a circular arrangementof constellation points. It doesn't have any noise as it is clearly seen that there is no improper alignment of constellation points. OMA of a signal is an important parameterthat is used in specifying the performance of optical links used indirectly influences thesystem bit error ratio (BER). It is defined as the difference between the high (P_1) and low (P_0) levels.

$$OMA = P1 - P0 \quad (9)$$

$$Extinction\ ratio(r_e) = P1/P0 \ or \ re = 10log(P1/P0)(dB) \quad (10)$$

The relationship of the extinction ratio re and OMA to average optical power P_{AVG} is

$$PAVG = OMA(r_e + 1)/2(r_e \breve{} 1)watts \quad (11)$$

OMA (dBm) = 1.3.

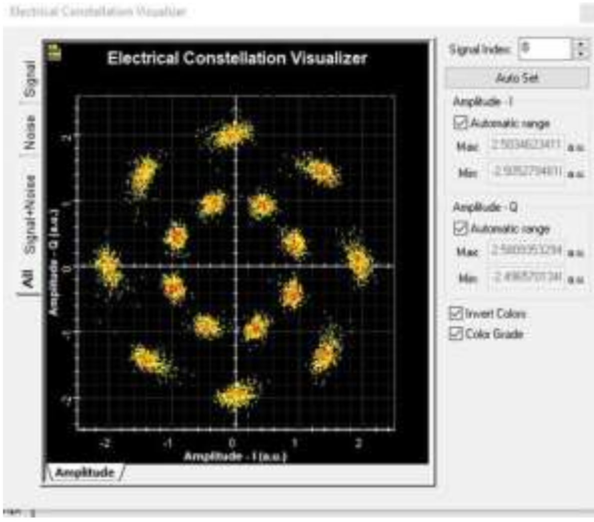

Fig. 9: 16-QAM Constellation output

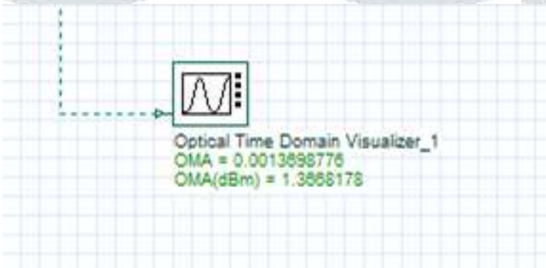

Fig. 10. OMA Output

V. CONCLUSION

High speed multimode optical link was established with tri-mode VCSEL and PIN- photodiode over OM5 Multimode fiber, data transmission for 16-QAM OFDM full linkbetween source and destination along with modulation and de-modulation to process the digital data stream. Compare with FM VCSEL and MM VCSEL they have individual advantages but in Tri-mode it has both the advantages of FM and MM VCSEL. The link achieved for 180 Gb/s data rates of error free transmission with optical modulationamplitude of 1.3 dBm and power efficiency is 2.8 pJ/b.

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