Demonstration of Multimode Optical Fiber Communication System using 1300 nm Directly Modulated VCSEL for Gigabit Ethernet

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Abstract— **In the recent years, the optical networks have grown to unexpected dimensions. The growth of active users and growing demand for data services set high requirements to network providers. Driving forces of this growth are multimedia, cloud computing and web services which set high bandwidth demand. The majority of currently deployed optical networks utilize passive or active network structure using dominantly singlemode optical fiber (SMF). SMF is believed to be the better choice over multimode optical fiber (MMF) for high speed optical fiber communication systems. And in some applications it definitely is. MMF has found use especially for short distance communication as it easily supports distances required for interconnecting buildings, data centres or campuses. Considering MMFs lower cost over SMF it became an interesting alternative for Ethernet connection in buildings or campuses. In this paper we present a simulation model of 1000BASE-LX Ethernet with MMF using different optical modulation techniques. The aim of this article is to demonstrate possibilities of MMF based 1000BASE-LX Ethernet with directly modulated vertical-cavity surface-emitting laser (VCSEL).**

Keywords—**Bit error rate, Ethernet, multimode optical fiber, optical modulation, singlemode optical fiber, VCSEL**

I. INTRODUCTION

The first generation of optical networking started in the late 1970s. The first generation lightwave operated systems used GaAs semiconductor lasers and operated at 0.8 μm wavelength. The first optical fiber systems used multimode fibers with core diameters of about 50 to 85 μm. A bit rate was not exceptionally high to these days - 45 Mbps and maximum distance was up to 10 km. The second generation came on scene in the early 1980s. The bit rate of these early systems was limited to 100 Mbps mainly because of fiber dispersion in multimode fibers (MMF). This limitation was quickly overcome by the use of singlemode optical fibers (SMF). Fiber dispersion is a very important design issue of optical fiber communication systems. Fiber dispersion leads to broadening of individual light pulses with propagation which cause inter-symbol interference (ISI). With the interfered signal, it becomes impossible to recover signal accurately [1][2]. This problem is more obvious in the case of MMF, since different fiber modes spread different ways and different speeds. For this reason, majority of currently deployed optical systems use SMF. Despite historical development, the use of MMF over SMF can be still beneficial, especially for short distance transmissions. The most promising application of MMF is high-speed ethernet network, local and storage area networks [3]. As we prove in our experimental setup, MMF based Ethernet reaches today's requirements for BER and OSNR (optical signal-to-noise ratio) and in some cases, goes even further [4][5][6]. The conclusions discussed in this work are based on the facts published in the following publications [7][8][9].

The section 2 provides a closer look at differences between MMF and SMF, detailed look at MMFs limitation factors and applications. In this article, we also present the practical application of MMF for the Ethernet connection. To show the performance of MMF based 1000BASE-LX Ethernet, we designed a simulation model using OptSim software. OptSim software is a professional program suite for advanced simulation of optical fiber systems. Thanks to the extension ModeSYS, we are able to fully evaluate multimode optical communication systems.

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II. DESCRIPTION OF MULTIMODE OPTICAL FIBER COMMUNICATION

There are three basic types of optical fibers as shown in Fig.1: multimode fiber with step index, multimode fiber with graded index and singlemode fiber with step index.

Singlemode optical fiber allows only single light wave, also called lowest-order mode to propagate. The core diameter of singlemode optical fiber is 5-10 μm, the typical diameter of cladding is 125 μm. SMF is required for high data rate applications with low signal loss. The major advantage of SMF over MMF is that it does not suffer from modal dispersion that is the main limitation factor of MMF. However, there is still chromatic dispersion that limits the performance of SMF [6].

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The term multimode refers to the multiple modes or paths that are possible to transmit through the fiber. The typical core diameter of a multimode fiber used for telecommunication purposes is 50/62.5/125 μm. There are two principle types of multimode fiber – step index and graded index [6].

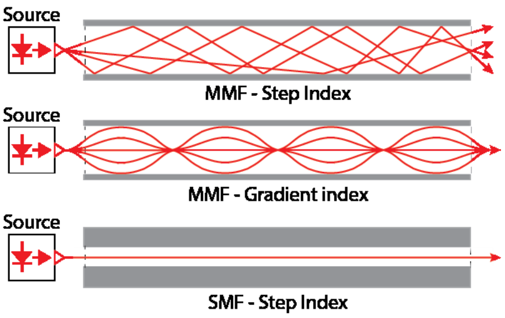

Fig. 1 Three types of optical fiber

The index of refraction profile of step index multimode fiber steps from low to high to low (from cladding to core to cladding). This type of fiber has large core diameter and numerical aperture. Step index multimode fiber is used for high bandwidth applications (over 1 GHz) supporting maximum 3 km transmission distance [10][11]. The number of modes propagating in a multimode step index fiber can be expressed as:

$$M_n = V^2/2 \qquad (1)$$

In this equation, V represents normalized frequency and it strongly relates to the size of fiber, refractive index and wavelength. Normalized frequency can be expressed in two ways:

$$V = [2\pi a/\lambda] \times NA, \qquad (2)$$

$$V = [2\pi a/\lambda] \times n_1 \times (2\Delta)^{1/2}, \qquad (3)$$

where a is the fiber core radius, λ is operating wavelength, NA is numerical aperture, n_1 is the refractive index of a core and finally, Δ is the relative refractive index difference between the core and cladding of an optical fiber [2][6][10]. The relationship between the angle of incoming light wave θi and the refracted wave θr inside step index MMF is:

$$n_0 sin\theta_i = n_1\theta_r \qquad (4)$$

Refraction is possible only for an angle ϕ meeting the following condition:

$$sin\phi < n_2/n_1, \qquad (5)$$

where n_2 is the refractive index of cladding and n_1 is the refractive index of core. Then the propagation of light wave inside the step index MMF is in Fig. 2 [10].

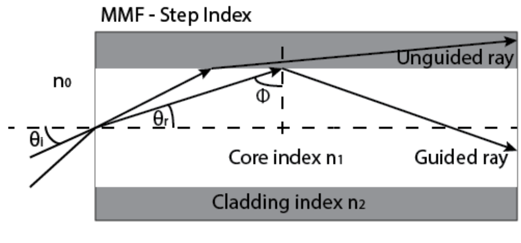

Fig. 2 Propagation of a light wave in step index MMF

Refractive index of the core of the graded index MMF decreases gradually from its maximum n_1 value at the core to its minimum value n_2 at the fibers cladding. This results into following light propagation – light wave travels faster at the edge of the core and slower in the center of the core. Individual modes travel in sinusoidal paths with equal travel time [6][9]. In comparison to step index MMF, the already mentioned travel pattern of light modes in graded index MMF significantly reduces modal dispersion. The light wave propagation in graded indexed MMF is illustrated in Fig. 3 [2][12].

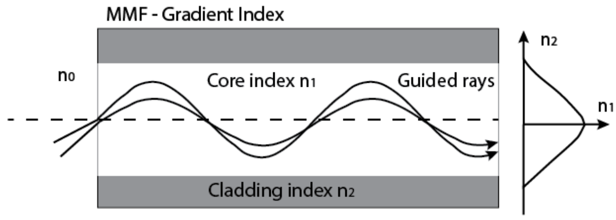

Fig. 3 Propagation of a light wave in graded index MMF

The major limitation in multimode fiber optic communication system is intersysmbol interference (ISI) due to modal dispersion. This phenomenon is reduced in graded index MMFs, but it is still present. Modal dispersion can be eliminated using light sources that excite only the desired light modes which can be achieved by using spatial light modulators [12]. There are two main approaches when avoiding the signal degradation caused by modal dispersion. The first one is a mode filtering method. This method reduces higher order mode in the receiver. The second approach is a center-launching method which launches light directly into the center of the core of MMF which prevents the higher order mode occurrence.

Because of dispersion limitation, multimode fibers could be used especially for short links, for example in Ethernet networks. Later in this paper we present a simulation model of such a network. 1000BASE-LX is a fiber optic Gigabit Ethernet standard specified in IEEE 802.3 Clause 38. It has been developed for implementing Gigabit ethernet networks. Specification of optical interface for 1000BASE-LX is shown in Table 1 [13].

III. EXPERIMENTAL MODEL OF 1000BASE-LX ETHERNET

For the purpose of evaluating performance of 1000BASE-LX Ethernet with MMF we used OptSim software and extention module ModeSYS. When building this model, we respected IEEE 802.3 Clause 38 which specifies 1000BASE-

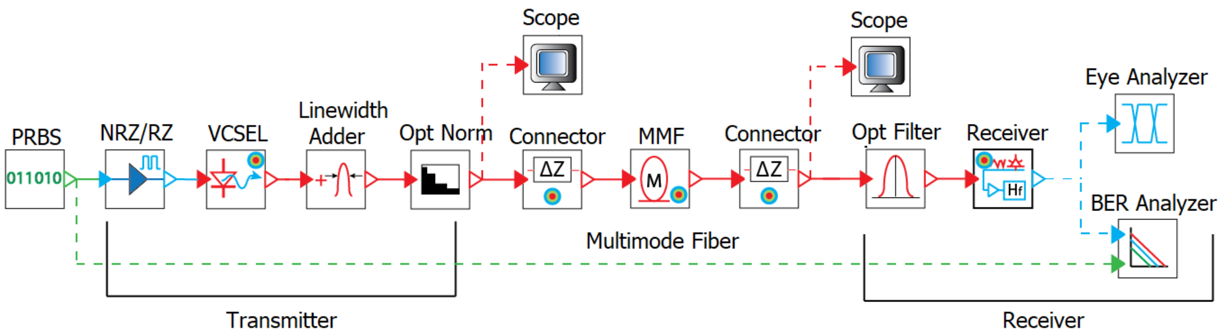

Fig. 4 Block scheme of 1000BASE-LX Ethernet simulation model

LX standard. Block scheme of designed 1000BASE-LX Ethernet network with MMF and the vertical-cavity surface-emitting laser (VCSEL) is shown in Fig. 4. Detailed description of simulation scheme is in the following subsections.

TABLE I. SPECIFICATIONS OF 1000BASE-LX ETHERNET

Parameter	Value
Bitrate	1/1.25 Gbps
Optical interface	MMF and SMF
Fiber diameter	50/62.5/125 µm (MMF), 9/10 µm (SMF)
Transmission distance	550 m for 62.5/125 and 50/125 for MMF cable 10 km for 9/125 SMF cable
Operating wavelength	1270 – 1355 nm
Launch power	-11.5 to -3 dBm
Receive power	-19 to -3 dBm
Receiver saturation	-3 dBm
Receiver sensitivity	-19 dBm

A. Transmitter section

Transmitter of proposed multimode fiber based 1000BASE-LX Ethernet consists of pseudorandom binary sequence (PRBS) generator which is difficult to predict and exhibit statistical behaviour. Transmission rate is 1.25 Gbps. Data are then modulated using electrical modulator driver – NRZ or RZ, depending on simulation setup. NRZ/RZ signal is then modulated to an optical carrier using VCSEL. A vertical-cavity surface-emitting laser (VCSEL) is a high efficiency semiconductor- based laser optimized for use with multimode fibers. VCSEL emits beam verticaly from its top surface. High speed fiber links based on multimode fiber use VCSELs and GaAs photodetectors. Development of these components is extremely important for future multimode fiber systems development [8]. Central wavelength of VCSEL in our scheme is 1300 nm. Excitation ratio is 9 dB, linewidth is 4nm and launch power is -11.5 dB. Transverse mode of VCSEL used in our simulation model is shown in Fig. 5.

Next in the chain is optical linewidth adder and optical power normalizer. To simulate insertion loss between optical transmitter and optical fiber we used connector components with insertion loss 0.75 dB.

B. Transmission section

To eliminate modal dispersion, we opted for gradient index multimode fiber. Multimode fiber used in our simulation is 550 m long, which is the maximum excepted length, with diameter of 50 µm and attenuation of 1.5 dB/km. Fiber bandwidth is 500 MHz. Peak refractive index is 1.475 and index step is 1%. Dispersion slope is 0.11 ps/km nm^2. Plot of refractive index of MMF is illustrated on Fig. 6.

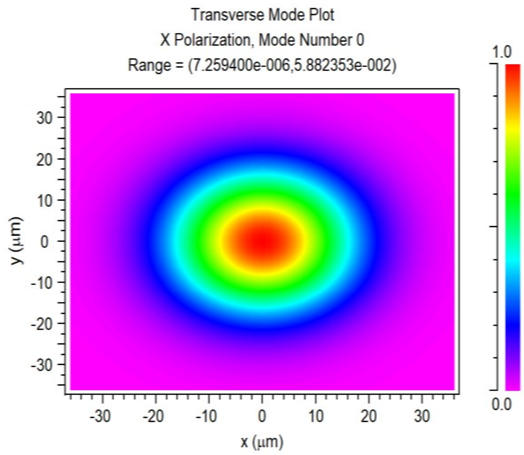

Fig. 5 Transverse mode of VCSEL

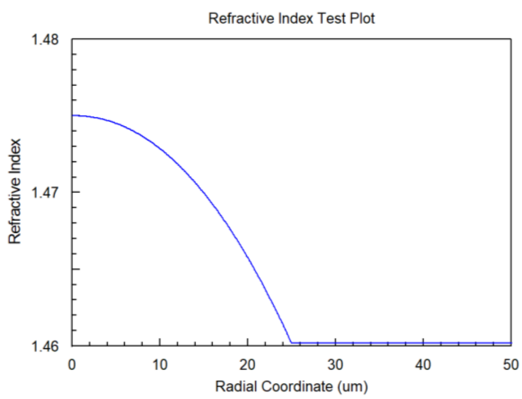

Fig. 6 Refractive index of MMF

C. Receiver section

Receiver section is formed with optical low pass Bessel filter and APD (avalanche photodiode) detector with 0.8 quantum efficiency. This compound component also contains optical preamplifier and electrical Bessel filter. Receiver sensitivity is set to -19 dBm and electrical filter bandwidth is 1.5 GHz. Optical scopes are used to analyze optical spectrums. Eye analyzer is used to observe eye diagram display. BER analyzer calculates BER and Q factor performance.

IV. RESULTS AND DISCUSSION

To evaluate performance of 1000BASE-LX Ethernet we established two experimental setups. First experimental setup uses NRZ encoding method and VCSEL optical direct modulation. NRZ encoding scheme is defined as follows – higher signal value is represented by logic 1 and the lower value is always logic 0 and the duration of the bit interval does not change. The change occurs by changing the value of the following information bit. The second experimental setup uses RZ encoding scheme with VCSEL optical direct modulation. With RZ encoding scheme, duration of information bit is reduced to half. RZ encoding scheme requires double bandwidth compared to NRZ which is the reason why are RZ pulses are broadened more by fiber dispersion.

To fully evaluate system performance, we scanned various parameters of proposed simulation model that are key to the system performance. Input optical spectrums for NRZ and RZ encoding scheme are shown in Fig.7 and Fig. 8.

Performance of the system was evaluated using BER and Q factor measurement. These measurements were obtained by analyzing eye diagram display. Eye diagram is used to observe the quality of received signal in digital domain. We can extract a lot of parameters just by analyzing the display. The most obvious one is eye opening - the most open part means the best OSNR (optical signal-to-noise ratio). Q factor, function of OSNR, is another parameter that can be extracted. Q factor provides a qualitative description of receiver performance.

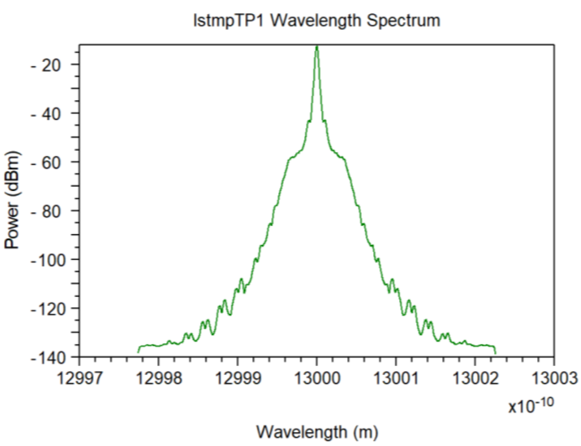

Fig. 7 Input optical spectrum for NRZ

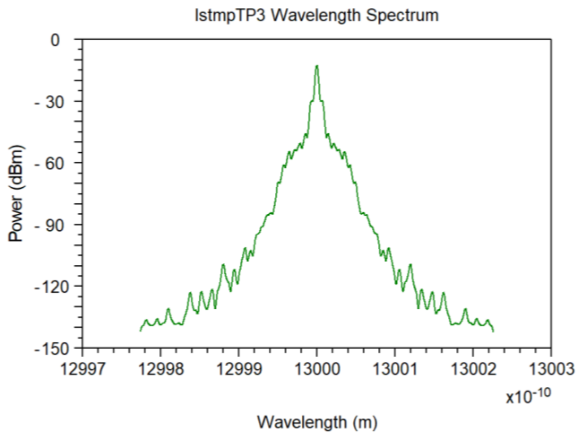

Fig. 8 Input optical spectrum for RZ

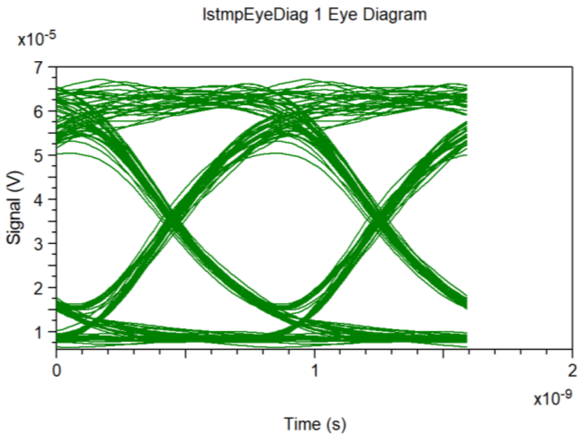

Fig. 9 Eye diagram for NRZ and 550 m MMF

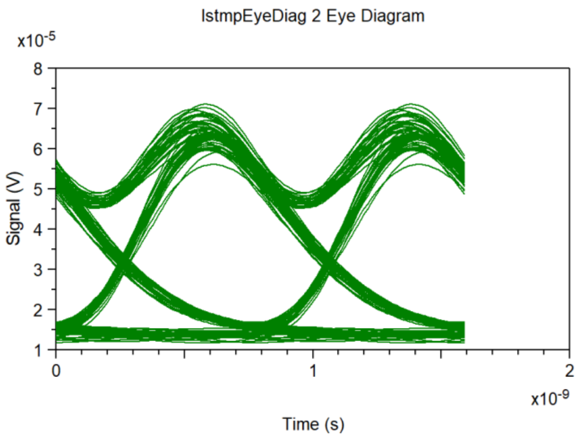

Fig. 10 Eye diagram for RZ and 550 m MMF

First experimental run was performed for 550 m MMF with 1.5 dB/km attenuation while launch power was -11.5 dB and operating wavelength 1300 nm. From the obtained eye diagrams shown in Fig. 9 and Fig. 10 one can say, that system performance in these conditions are exceptionally good. Values of BER and Q factor are provided in Table 2.

TABLE II. BER AND Q FACTOR RESULTS

Parameter	NRZ - Value	RZ – Value
Measured BER	8.5438e-012	1.01e-027
Measured Q factor	16.56 dB	20.71 dB
System margin	-0.39	3.76
Required BER	1e-012	
Required Q factor	16.94 dB	

System performance of 1000BASE-LX Ethernet is examined for different lengths of optical fiber, fiber loss, launch powers and bitrate. The values of BER has been recalculated for different operating points. The aim of this experimental setup is to find out limitations of multimode fiber and to determine which one of two encoding schemes remains the best performance. BER values of NRZ based 1000BASE-LX Ethernet depending on fiber length, fiber loss, transmitter power and bitrate are shown in the following figures (Fig.11 – Fig. 14).

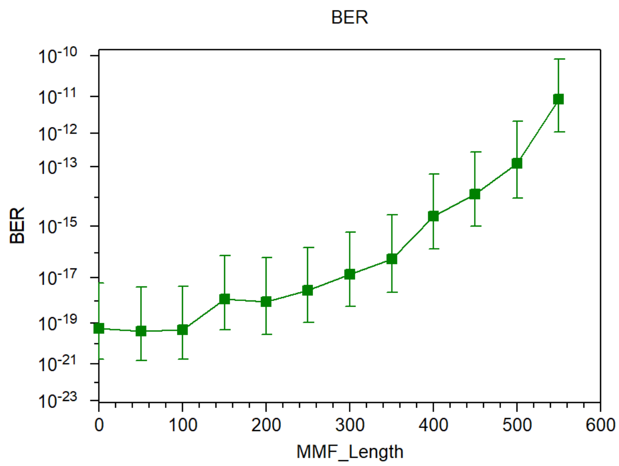

Fig. 11 NRZ - BER vs MMF length

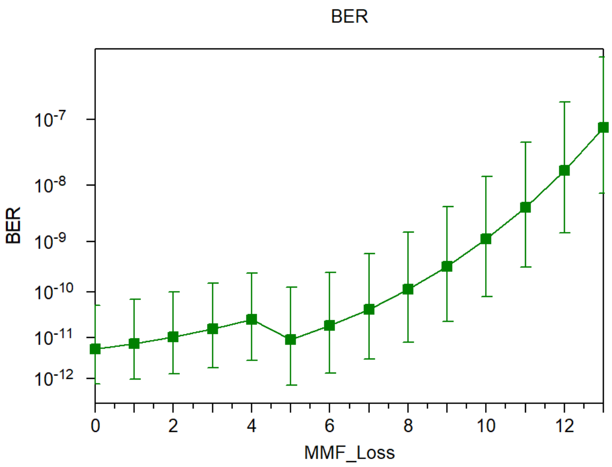

Fig. 12 NRZ - BER vs MMF loss

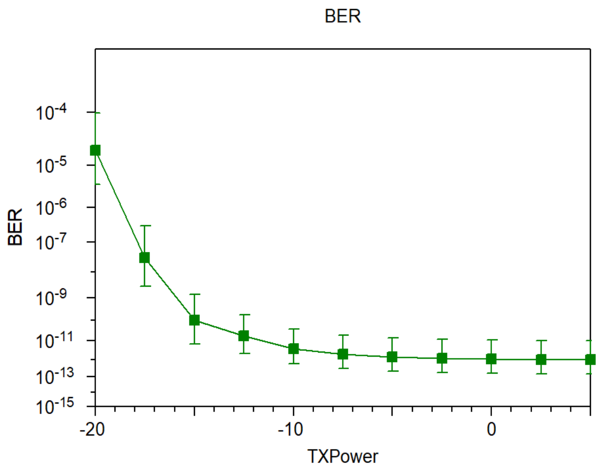

Fig. 13 NRZ - BER vs transmitter power

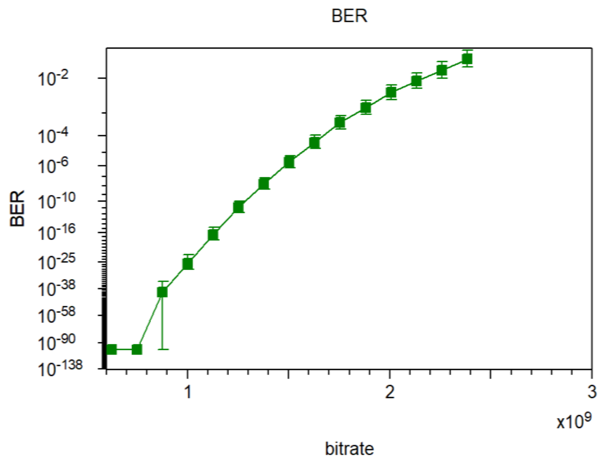

Fig. 14 NRZ - BER vs bitrate

The performance of proposed system decreases as the length of fiber increases. Fiber length varies from 0.1 m to 550 m with 50 m step. Maximum BER value is 5.7182e-020, Q factor is 19.156 dB.

When increasing fiber loss, from 0 to 13 dB/km, the BER gradually decreases. In this case length of MMF was 550m and did not changed during the simulation process. BER reaches 5.3567e-012 for 0 dB/km loss and maximum value is 7.6645e-008 for 13 dB/km. In this case system margin increases gradually. BER is inverse proportional to transmitter power. It means that the probability of error decreases as the power increases as seen in Fig. 13. Tested power ranges from -20 dBm to 5 dBm. In the last experiment in this section we tested how different bitrates affect BER performance. The premise is that probability of error increases proportionally to bitrate. Bitrate varied form 0.6255 Gbps to 2.3825 Gbps. BER value for 1.1275 Gbps is 4.0233e-017 and 1.1700e-011 for 1.2530 Gbps. For 1.3785 Gbps transmission rate probability of error is 1.7713e-008 which does not fit in to the requirements for high speed optical networks. As the bit rate increases, BER increases as well.

The last experimental setup facilitates 1000BASE-LX Ethernet with RZ encoding scheme. BER values of RZ based 1000BASE-LX Ethernet depending on fiber length, fiber loss, transmitter power and bitrate are shown in Fig.15 – Fig. 18.

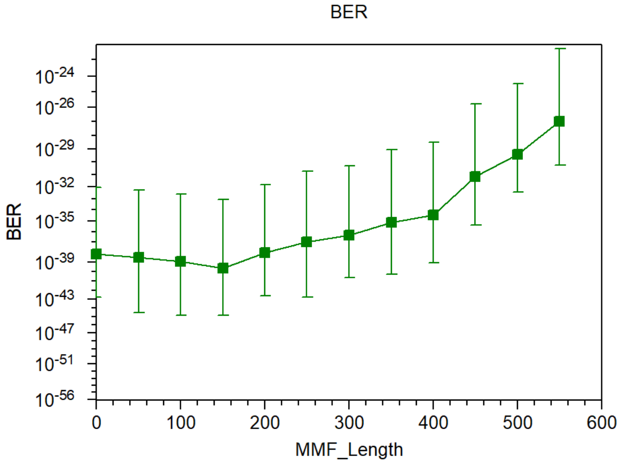

Fig. 15 RZ - BER vs MMF length

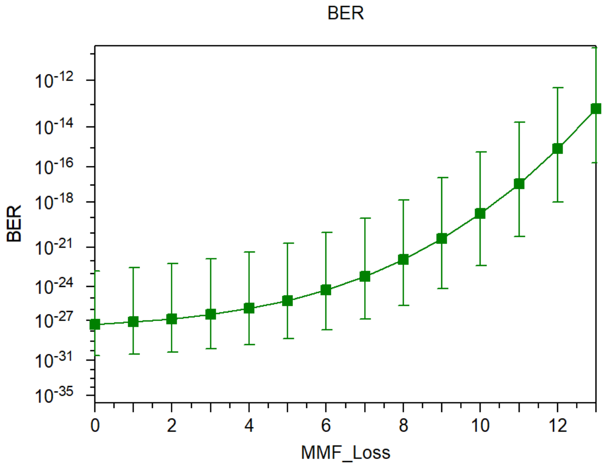

Fig. 16 RZ - BER vs MMF loss

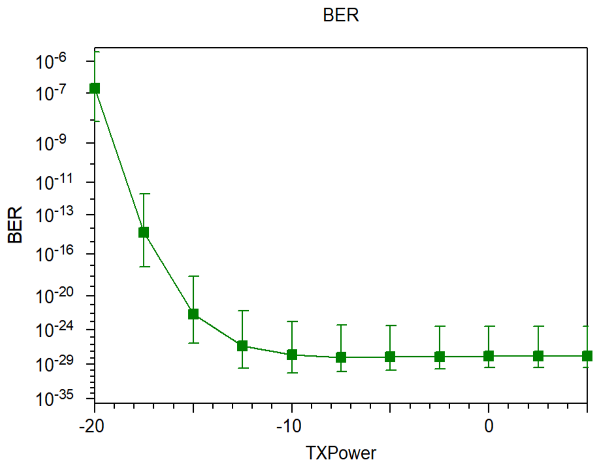

Fig. 17 RZ - BER vs transmitter power

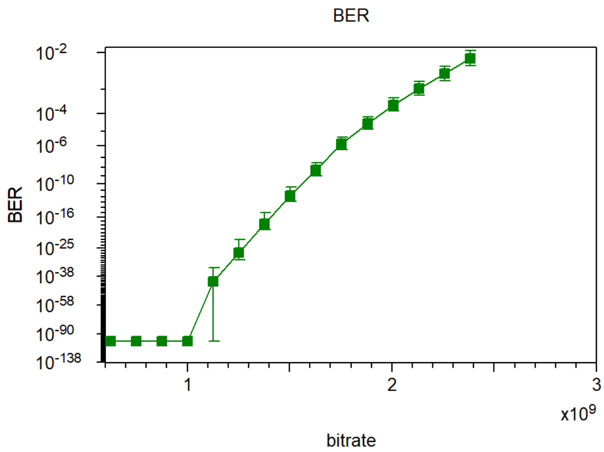

Fig. 18 RZ - BER vs bitrate

Performance of 1000BASE-LX Ethernet has significantly improved just by implementation of RZ encoding scheme. This phenomenon can be seen in Fig. 15. RZ based 1000BASE-LX Ethernet system reaches much lower BER values than NRZ based one.

As in the previous case, BER is proportional to the length of multimode fiber. Minimal value of BER is 1.01e-027 for 550 meters of fiber and maximal value is 6.32e-039 for 0.1 meters of fiber. Probability of error is proportional to the fiber loss as well. BER increases almost exponentialy to the fiber loss. In this case fiber length was 550 meters. All BER values obtained in this experimental setup are acceptable for real-life applications. When increasing transmitter power BER decreases. Transmitter power varied form -20 to 5 dBm. Finally, the growth of BER depending on increasing bitrate is very similar to the one for NRZ encoding scheme. Bitrate varied form 0.6255 Gbps to 2.3825 Gbps. Maximum reachable bitrate, excepting BER requirements, is 1.504 Gbps which gives 1.4221e-012.

Please notice that OptSim works in ideal conditions. Optsim software is used to design optical networks and to verify attributes of real optical systems. Simulation results may vary from the real equivalent optical systems [14].

V. CONCLUSION

In this paper, we examined the application of multimode optical fibers for 1000BASE-LX Ethernet with direct optical modulation using VCSEL. Experimental results proof superior performance of multimode optical system on short distances. Obtained results show that we can ensure requirements for BER and Q factor for today's optical communication systems by carefull choice of fiber lenght, transmitter power, bitrate or fiber loss. As a result of simulation, we can say that RZ encoding scheme improves the transmission quality of multimode optical system.

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