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Comparison of Different Wavelength Propagations over Few-Mode Fiber based on Space Division Multiplexing in Conjunction with Electrical Equalization

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Abstract—**Nonlinearities in optical fibers deteriorate system performances and become a major performance-limiting issue. This article aims to investigate the compensation of nonlinear distortions in optical communication systems based on different wavelength propagations over few-mode fiber (FMF). The study adopted Space Division Multiplexing (SDM) based on decision feedback equalizer (DFE). Various transmission wavelength of the FMF system is applied to mitigate the attenuation effect on the system. In this paper, different wavelengths (780, 850 and 1550 nm) are used in SDM. Extensive simulation is performed to assess the attenuation and Bit Error Rate (BER) in each case. The results show that the wavelength of 1550 nm produces higher power and less attenuation in the transmission. Furthermore, this wavelength produces the best distance with less BER compared to 780 nm and 850 nm wavelengths. Moreover, the validations show improvement in BER and eye diagram.**

Keywords—**Few-mode fiber, nonlinear distortions, decision feedback equalizer, eye diagram, BER**

I. INTRODUCTION

THE increasing demand for high data rates paved the way to the development of optical communication technology. Using fiber optic in communication systems met the requirement of scaling bandwidth demands. Basically, the high data rates are possible on account of the optical carrier. The optical fiber communication technologies play a role in ensuring that network bitrates scaling can continue to meet expected future communications services. The fast growth of fiber optics technology increases the user demand for Internet services. This need motivated the researchers to find new ways to improve the fiber optic capacity. However, Cisco's annual report for global Internet growth expected that Internet traffic grows each year around 25 Exabyte to reach 168 Exabytes per month by 2019 [1][2].

In optical fiber systems, three distinct types of fiber classified as Single-mode optical fiber (SMF) multimode optical fiber (MMF) and few optical mode fiber (FMF). Normally, MMF differs from SMF by its core diameter. The larger core diameter of the MMF makes it possible to have more propagating modes through its core [3][4]. The propagation properties of FMF are very similar to that in MMF. Nevertheless, it allows few propagate modes in comparing with MMF [5].

Over last three decades, a number of transmission multiplexing techniques were developed. For example, Time Division Multiplexing (TDM) followed by Wavelength Division Multiplexing (WDM) resulting in ten times in capacity growth factors every four years [6]. However, the capacity optical fiber that uses conventional TDM and WDM is restricted by implicit Kerr- type nonlinearity. In consequence, the capacity may approach a limit defamed by the Shannon-Hartley hypothesis. These limitations in channel capacity such as the effects of nonlinearity problems such as chromatic dispersion (CD) and modal dispersion (MD) which lead to distorting the received signal. Accordingly, the additional distortion confines the maximum launched power in the fiber optic [7].

In the last couple of decades, different methods have been proposed to tackle the capacity limitation associated with the traffic growth of fiber optic systems. For example, advanced modulation schemes and bandwidth utilization enhancement techniques such as TDM and WDM and Polarization Division Multiplexing (PDM) and Frequency Division Multiplexing (FDM) [8]. Recently, a promising approach is proposed to overcome the limits of SMF. Consequently, to move towards Multi Input Multi Output (MIMO) wireless transmission using the principle of SDM for FMF. According to Shannon limitation [9][10], the capacity increases with a signal to noise ratio [11-14]. In line with this, a number of multiplexing techniques have been explored with their respective positives and negatives.

Among them, we have chosen Space Division Multiplexing (SDM) that includes Mode Division Multiplexing (MDM) using MMF or FMF [5]. The SDM is a swiftly emerging as a potential candidate for increasing the aggregate bandwidth of existing fiber optic systems[15]. An SDM is an optical

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communication method where spatial modes are utilized as information channels carrying independent data streams [16]. The main idea behind SDM is to use an FMF, which allows the propagation of multiple spatial modes through a single core [17]. It is worth mentioning that all spatial modes in one fiber are orthogonal with respect to each other. Therefore, theoretically, it is possible to perform Three main steps. Firstly, modulate an independent signal on to each spatial mode. Secondly, transmit them over the same fiber. Lastly, recover the signal after transmission without any loss of information. Capacity per fiber can be multiplied by the number of spatial modes [18].

In the SDM system, the detrimental effects of mode coupling can be mitigated by equalization method. Since the channel is time shifting, this method is considered one of the earliest techniques to alleviate Intersymbol Interference (ISI). In the literature, several methods are used to counteract the effect of ISI in a digital communication system. One of these methods is equalization which is considered as an effective way of mitigating ISI. [19]. Therefore, several analog equalizers, such as decision feedback equalizer (DEF) and feed forward equalizer (FFE). They were implemented to remove the nonlinear ISI that caused by nonlinear operations due to the direct detection and modulation in fiber optic systems. Furthermore, they are considered as a simple and cost-effective solution [20-22].

Moreover, selection of the appropriate wavelength in SDM is also an important issue. Picking the best wavelength to achieve the best distance with less bit error rate (BER) should be considered. The most common wavelength used for optical communication ranges from 0.85µm to 1.55µm [23]. Different wavelengths were investigated with regards to the comparison of FMF performance and the modes in SDM. Hence, three systems with wavelengths 1550, 870 and 780 were compared in this paper.

DFE in this paper is applied to the receiver [24] side of the communications channel as a nonlinear equalizer. Optical data is considered as high-speed data [25] since it is transmitted at the speed of light the waves crisscross each other within a single cable. There are bound to be some irregularities (i.e., ISI) [26] caused by the distortion of signal pulses and modal dispersion. DFE is then used to remove [27] these inter-symbol perturbations optimally [20, 21]. These were chosen because the modal power loss becomes minimum at these wavelengths [28]. Consequently, relatively data can be transmitted at a much longer distance in the telecommunications channel. Moreover, FMF is used in SDM in order to selectively excite specific modes [29] in a bid to minimize mode coupling [30]. This procedure is also referred to as crosstalk, which is an inhibiting factor in data transmission. Thus, FMF is used to transmit data over longer distances [31] as compared to MMF.

In the literature, the nonlinear electrical equalization is widely used in BER optimizing. Additionally, it is also used for minimizing chromatic dispersion in the optical filtering of the optical signal [5][32]. Nonlinear equalizers mitigate efficiently the distortion resulting from robust optical filtering [32][33]. In this article, the decision feedback equalizer is used to affect mode filtering in order to clean the signal at the receiver. This post-processing [34] mechanism ensures that the received signal is sufficiently eliminated the unwanted noise at the receiver side. We used the wavelengths 1550 nm, 870 nm and 780 nm in the experiments to obtain the optimal one that can effectively transmit and perform favorably in a communications channel.

The rest of the article is structured as follows. Section II describes our proposed system. Section III presents and discusses SDM simulation results. Finally, we state our conclusion in Section IV.

II. SYSTEM MODEL

In this section, we design and simulate an FMF SDM system of four Laguerre-Gaussian (LG) modes based on DFE. All simulations were conducted using OptSim software [35-37].

Figure 1, illustrates SDM over FMF in conjunction with DFE Equalization. Our model consists of three parts: 1) transmitter, 2) FMF channel, and 3) receiver with a filter. A pseudo-random binary sequence (PRBS) is used to generate the input signal from a data generator at 3 Gbps. Firstly, in the electrical part non-return-to-zero (NRZ) sequence is modulated. After this, it is connected to a four-segmented spatial vertical cavity surface emitting laser array. Each segment is represented as Sp-VCSELs. The Sp-VCSELs, as mentioned earlier, operates on different wavelengths 1550 nm, 850 nm and 780 nm.

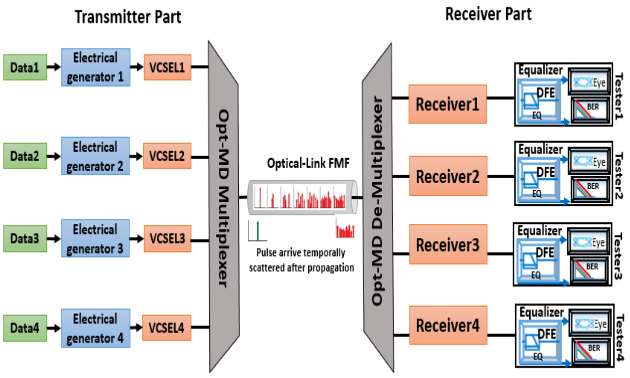


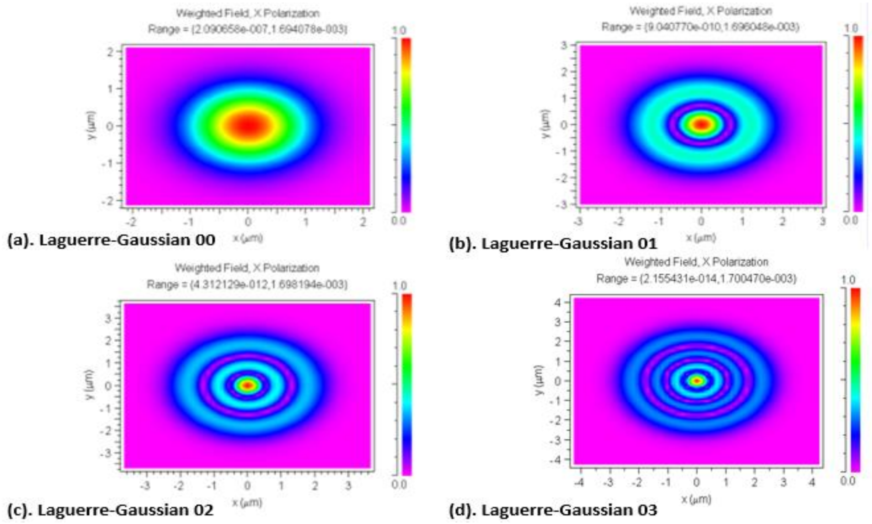
Fig. 1. SDM over FMF in conjunction with DFE equalization

Fig. 2, shows the four LG modes; LG 00, LG 01, LG 02 and LG 03. Each Sp-VCSELs has an array emitting one LG mode on a single wavelength. Given 3 Gbps is transmitted by each mode. Thus, with 4 modes the total data rate will be 12 Gbps. The FMF channel is 9 km long distance. FMF parameter is the attenuation 0.25, and the core radius is set to 20. Finally, after FMF, the receivers are used to retrieve the signals from FMF.

The first part of DFE is a feed-forward filter, and it is set as the parameter using tap number 9. The other part of DFE is a nonlinear filter (feedback filter) uses tap 12 with MMSE-optimization. This optimization is operated between the target data and actual data. Based on the error of MMSE, it will update the weight of the tap filter to get a better result. Moreover, the performance of eye diagram and BER are analyzed for the LG modes before and after feedback filter.

III. RESULT AND DISCUSSION OF FMF-SDM SYSTEM

In this section, we present the numerical results of the proposed model based on a simulation study. We started by modeling four channels of SDM for LG mode over FMF with DFE in OptSim simulation. We now exam the improvement of the BER, eye diagram and bandwidth after using DFE.



(a). Laguerre-Gaussian 00

(b). Laguerre-Gaussian 01

(c). Laguerre-Gaussian 02

(d). Laguerre-Gaussian 03

Fig. 2. Four Laguerre-Gaussian over FMF based on SDM.

The first part of DFE is a feed-forward filter, and it is set as the parameter using tap number 9. The other part of DFE is a nonlinear filter (feedback filter) uses tap 12 with MMSE-optimization. This optimization is operated between the target data and actual data. Based on the error of MMSE, it will update the weight of the tap filter to get a better result. Moreover, the performance of eye diagram and BER are analyzed for the LG modes before and after feedback filter.

Figure 3, depicts BER over a different distance of FMF based on a 1550 nm wavelength. Starting from 3 km (3.44E-32), (3.46E-38), (4.47E-34) and (3.58E-45) for channel (1), channel (2), channel (3) and channel (4) to 9 km (4.30E-09), (4.07E-09), (3.66E-14) and (4.69E-16) for channel (1), channel (2), channel (3) and channel (4) with acceptance BER. Whereas, Fig. 4 is the explaining the result of BER over a different distance of FMF based on an 850 nm wavelength. Similar to Figure 3, we started from 3 km (1.84E-41), (1.03E-31), (1.67E-20) and (1.28E-32) for channel (1), channel (2), channel (3) and channel (4) to 9 km (1.13E-08), (4.69E-08), (8.75E-09) and (9.55E-08) for channel (1), channel (2), channel (3) and channel (4) with acceptance BER.

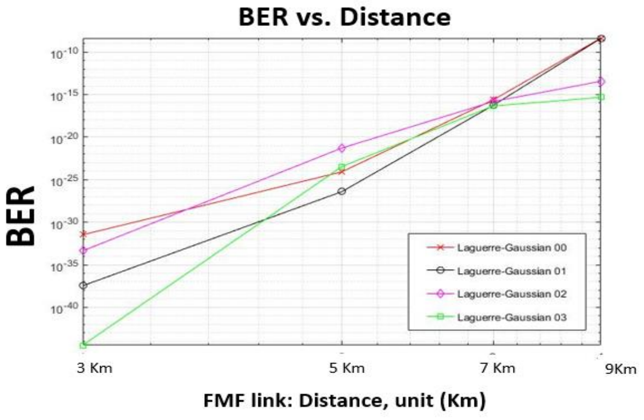


Fig. 3. BER of four LG modes for the wavelength 1550 nm.

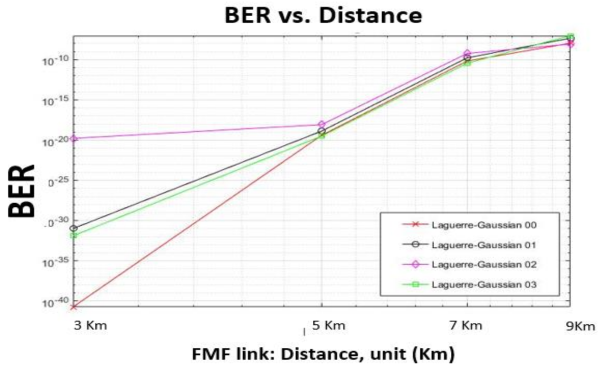


Fig. 4. BER of four LG modes for the wavelength 850 nm.

Figure 5, describes BER over a different distance of FMF based on a 780 nm wavelength. The comparison is started from 3 km (4.41E-13), (4.00E-29), (3.23E-20) and (3.12E-29) for channel (1), channel (2), channel (3) and channel (4) to 9 km (1.30E-07), (1.50E-06), (1.28E-07) and (1.25E-06) for channel (1), channel (2), channel (3) and channel (4) with acceptance BER.

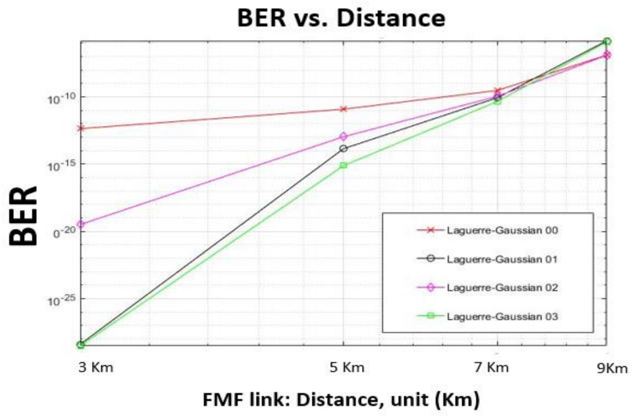


Fig. 5. BER of four LG modes for the wavelength 780 nm.

Figure 6, shows the comparison of the different wavelengths such as 1550 nm, 870 nm and 780 nm based on BER through different distance starting from (3 - 9 km). The results of BER of 1550 nm, 850 nm and 780 nm wavelengths in the distance 3 km are (3.44E-32), (1.84E-41) and (4.41E-13). In the distance 5 km the results are (8.36E-25), (4.10E-20) and (1.23E-11) for wavelengths 1550 nm, 850 nm and 780 nm. Moreover, in the distance 7 km results of BER of 1550 nm, 850 nm, and 780 nm wavelengths are (2.43E-16), (6.76E-11) and (3.07E-10). All the performance results are acceptable for distance (3 – 7 km). The outcome of BER in (9 km) (which is the maximum distance) is (4.30E-09) of 1550 nm wavelength is acceptable BER than the other wavelength ((1.13E-08) of 850 nm and (1.30E-07) of 1550 nm). Furthermore, the wavelength of 1550 nm produces higher power with less attenuation in the transmission. Additionally, it provides the best distance with less BER compared to 780 nm and 850 nm wavelengths.

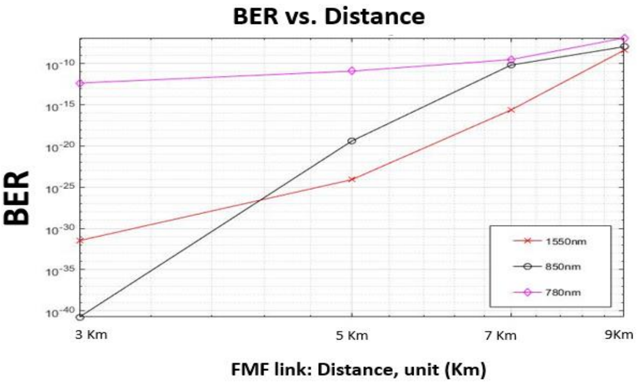
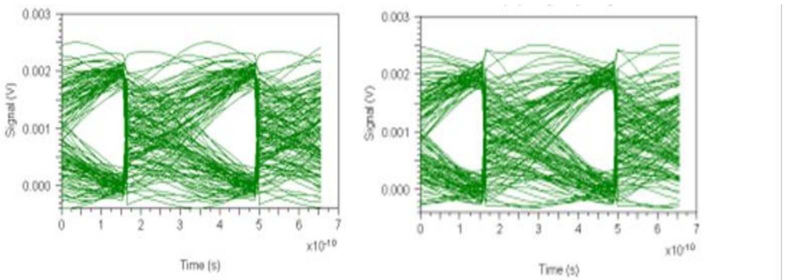
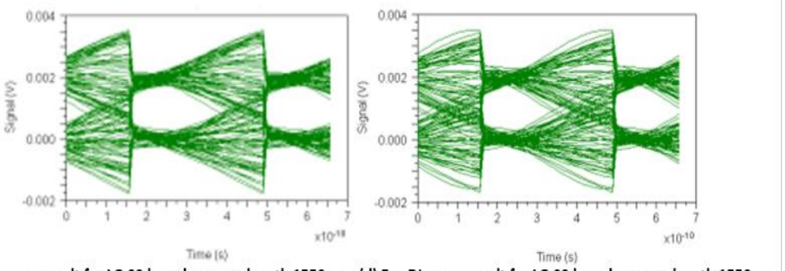


Fig. 6. BER of the wavelengths 1550 nm, 870 nm and 780 nm.

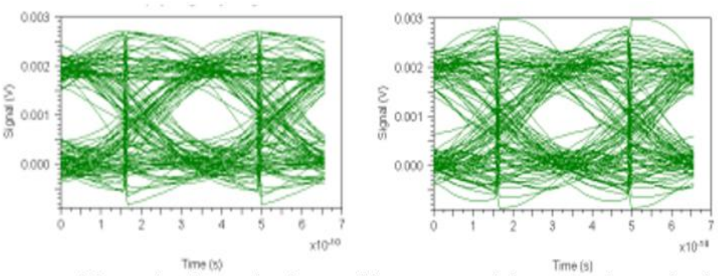


(a) Eye Diagram result for LG 00 based on wavelength 1550nm (b) Eye Diagram result for LG 01 based on wavelength 1550nm

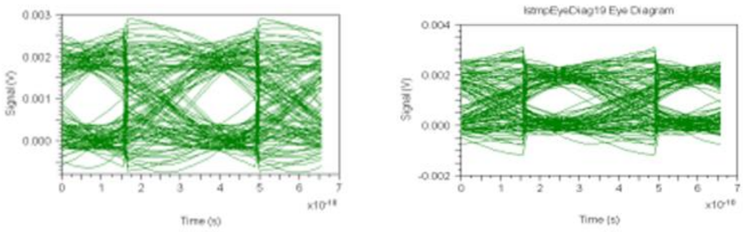


(c) Eye Diagram result for LG 02 based on wavelength 1550nm (d) Eye Diagram result for LG 03 based on wavelength 1550nm

Fig. 7. Eye Diagram result of four LG modes for the wavelength 1550 nm.



(a) Eye Diagram result for LG 00 based on wavelength 780nm (b) Eye Diagram result for LG 01 based on wavelength 780nm



(c) Eye Diagram result for LG 02 based on wavelength 780nm (d) Eye Diagram result for LG 03 based on wavelength 780nm

Fig. 8. Eye Diagram result of four LG modes for the wavelength 780 nm.

The other performance for this study is eye diagram as seen in Fig. (7 and 8). Specifically, Fig 7 shows eye diagram result of four LG mode based on 1550 nm wavelength. Fig 8 illustrates the eye diagram result of four LG mode based on 859 nm wavelength. Lastly, Fig 9 depicts the eye diagram result of four LG mode based on a 780 nm wavelength. Thus, below are an illustration of the eye diagram of four LG modes after propagation over FMF based on SDM with DFE. The eye openings for all channels in 1550 nm wavelength compared to 780 nm and 850 nm wavelength.

IV. CONCLUSION AND FUTURE WORK

In this paper, we studied the compensation of nonlinear distortions in optical communication systems based on different wavelength propagations over FMF. Extensive Simulation has been conducted, and the results show improvements through the BER, Eye diagram, and bandwidth after using DFE of four channels. The four channels are carrying LG 00, LG 01, LG 02 and LG 03 modes (Each carries 3 Gbits of data). All these channels are applied using the SDM system. The output of the proposed system equalized at the receiver with a DFE equalizer to enhance the bit error rate performance. The comparison of the proposed channels showed that wavelength of 1550 nm produced higher power with less attenuation in the transmission in term of distance. Additionally, this wavelength produced the best distance with less BER compared to 780 nm and 850 nm wavelengths.

Future work involves the ability to apply another optimization scheme Bees Algorithm [38-41] in SDM to compensate nonlinear distortion. Additionally, different equalization schemes can be tried to improve the signal quality in terms of nonlinearity reduction.

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