Polarization Multiplexed Self-Homodyne Optical Communication System

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Abstract

The increased data traffic for the short-reach optical communication indicates the development of the system that has the capacity to fulfill the demands of the communication system. Several techniques are already developed to have improved results over the conventional communication system. Pulse amplitude modulation (PAM-4) is the very widely used link for optical communication, providing only a degree of freedom and terminating the improvement of the system. The system presented will use the higher-order modulation schemes like quadrature phase-shift keying (QPSK) and 16 level quadrature amplitude modulation (16-QAM) so as to increase the data rates of the system and the property of polarization multiplexing used in the presented system will give the advantage to the local oscillator (LO) less receiver. The polarization control using the constant modulus algorithm works efficiently at the receiver. This polarization multiplexed self-homodyne system gives better performance in terms of data rates and low power consumption.

Keywords: self-homodyne links, coherent optical communication, polarization multiplexing, local oscillator less receiver

1 Introduction

The demand for data traffic has increased [1] so does the need for the system to have high data rates and low power consumption properties. As the survey says the direct detection systems put the limit on the performance due to only one degree of freedom in intensity [2]. The PAM-4 link is a very widely used example of a direct detection system. This system is typically used for short-reach communication (<80km) with its simpler and power-efficient transmitter-receiver structure. In the direct detection system, the output decision variable depends on the intensity, and for the detection, photodetectors will be used. Depending upon the intensities the photodetector generates the output current. The use of a photodetector adds the noise to the system output and so do the amplifiers which collectively degrades the system sensitivity [3].

Another method to go for is coherent optical communication where the output decision variable depends on both the phase and intensity. Coherent communication also allows the use of higher-order modulation schemes likes quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) with different amplitude levels. The conventional coherent system requires carrier signal generation at the receiver in order to retrieve the information signal. The separate laser generates the carrier signal known as local oscillator (LO), a separate signal processing unit will be required for this generation. As the replica of the carrier will differ in some manner and the retrieval of the signal will be degraded [4]. There are two methods through which we can do coherent optical detection, dual-polarization coherent links, and coherent detection with digital signal processing (DSP). Where in a coherent system using dual-polarization links can have double the capacity because here both the polarization carries data. The multi-channel dual-polarization system demonstrated already with higher-order modulation techniques which results in better spectral efficiency. But the system requires highly complex circuitry to achieve the outcome. As the name suggests coherent detection with DSP will require the signal processing unit to get the desired output. The

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digital signal processing results in high power consumption which introduce again some additional hardware in the system.

Coherent communication systems are not so power-effective and cost-effective in comparison with direct detection system as it requires the LO and DSP for carrier signal generation [5]. Self-Homodyne (SH) links give a perfect balanced solution between the direct detection (DD) system and the conventional coherent system. Self-Homodyne links allow the transmission of the carrier signal with modulated signal through the same optical channel. Several methods are already demonstrated for self-homodyne links which include QPSK with inserted pilot symbols. Which uses return-to-zero (RZ) signal by converting the non-return-to-zero (NRZ) signal with the duty cycle of 50%. But due to the imperfection of the photodetector the intensities at the receiver ripples [6]. Some of the other methods like phase-modulated signals interleaved with reference light which uses NRZ signaling for the transmission of a carrier signal and time division multiplexing is done by a switch for transmission of the carrier signal and modulated signal through the same channel. The requirement of high-speed switches and high sensitivity to phase offset puts some limitations on system performance [7]. For the transmission of carrier signal along with the modulated signal polarization division multiplexing is the best-suited technique. Polarization of the transverse wave is the geometrical orientation of the oscillations. Light is an electromagnetic wave that consists of an electric field and magnetic field always perpendicular to each other, the term polarization in an electromagnetic wave is referred to the direction of an electric field. With the use of this technique, the system performance is demonstrated.

2 Theory

The co-transmission of the carrier signal with the modulated signal can be done in self-homodyne (S-H) links. The S-H links allow the transmission in two different polarization through the same optical channel. As because of the advantage of the transmission of carrier signal through an optical channel with modulated signal eliminates the use of DSP and local oscillator for carrier generation at the receiver. And provides a solution to the limitations of PAM-4 and conventional coherent optical communication systems.

The fig.1 shown is a polarization multiplexed signal. Polarization division multiplexing (PDM) is the best-suited method for transmitting two varied signals in two different polarizations through the same optical channel. For multiplexing of the signals carried on electromagnetic waves, which allows the transmission of two different signals using orthogonal polarizations over the same channel polarization multiplexing is used which is a physical level method for multiplexing. And is typically used for quadrature phase-shift keying and optical QAM.

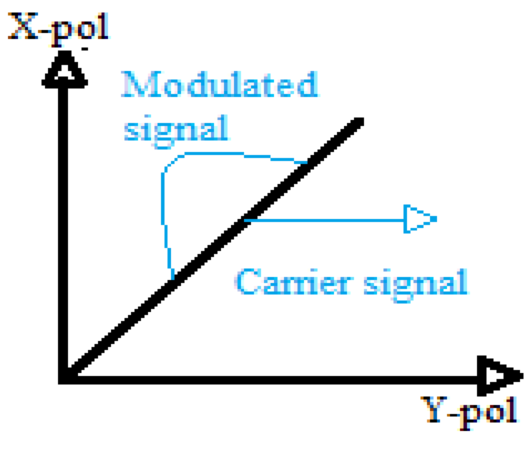

Fig. 1. Polarization Multiplexed signal

There will be signals on both polarization, the modulated signal will be on X-polarization whereas the carrier signal will on Y-polarization. The polarization multiplexed self-homodyne (PM-SH) optical communication system using PDM provides all the advantages of the conventional coherent optical communication system with lower optics and signal processing units [8].

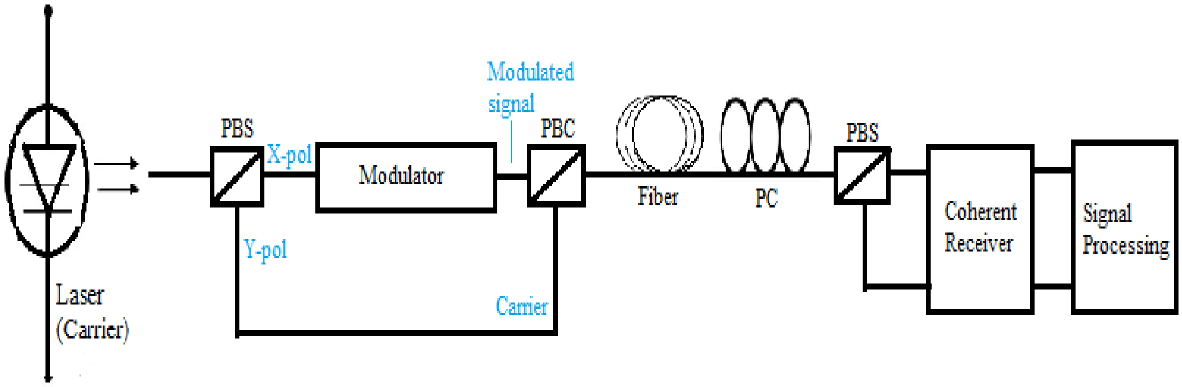

Fig. 2. Polarization Multiplexed Self-Homodyne system

The basic block diagram for the polarization multiplexed self-homodyne system is, as shown above, includes optical components like polarization beam splitter (PBS), polarization beam combiner (PBC), and polarization controller (PC). The PBS separates out the two orthogonal polarizations of the wave coming from the optical laser. Then by using a Mach-Zehnder-modulator (MZM) the signal on X-polarization is modulated. And the other one is used just as it is. By the use of PBC, the polarizations are combined then transmitted through the same optical channel. For recovery of the signal, the state of polarization should be the same as the transmitter so PC is used to get back the states and with the DSP circuitry at the receiver, the signal is reconstructed. As an effective solution for reducing the bit error rate at the receiver adaptive polarization controller is used.

3 Proposed Method

As to overcome the limitations like only one degree of freedom does not allow the system to adapt higher order modulation schemes in PAM-4 links of an optical communication system and high power consumption of the system due to the need of local oscillator for the generation of a carrier signal in conventional coherent systems, the system which eliminates both drawbacks by allowing the use of higher-order modulation techniques with SH links to transmit the carrier information with the same optical channel is determined. Quadrature amplitude modulation (QAM) and quadrature phase-shift keying (QPSK) becomes the very first choice for coherent optical communication.

The polarization multiplexed self-homodyne optical communication system uses the QPSK modulation techniques and 16-QAM technique to increase the data rates. The Fig. 3 shows the polarization multiplexed self-homodyne optical communication system with SH links. The laser is used to generate the optical carrier signal. As to transmit both the carrier signal along with the modulated signal in two different polarization through the same channel, the polarization needs to be separate.

For the separation of orthogonal polarization, an optical component called polarization beam splitter (PBS) is used. Basically, the PBS is a mirror or a specific kind of prism. The beams after splitting in X and Y polarizations need mot to have the same optical power.

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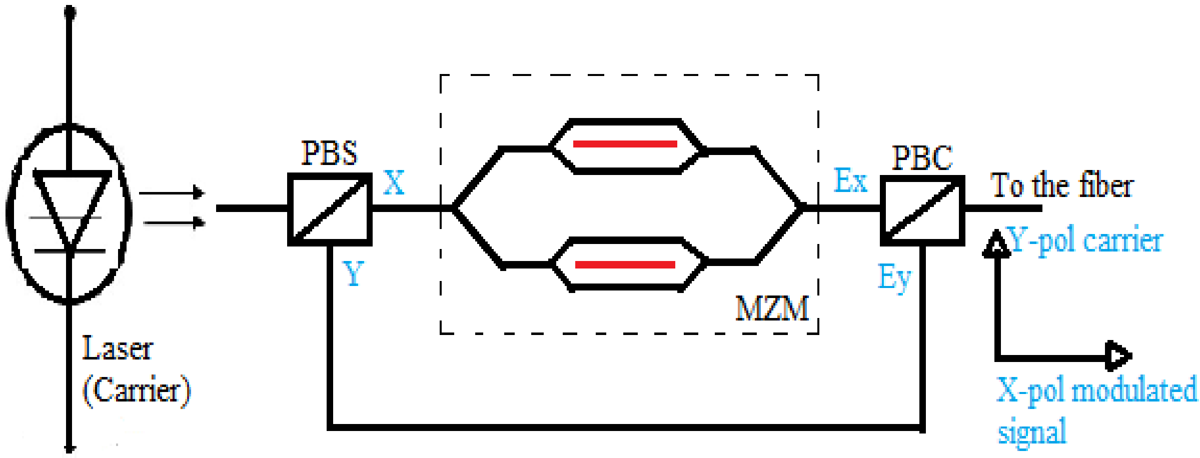

Fig. 3. Transmitter block diagram of polarization multiplexed self-homodyne system

On the X polarization, the modulation will be done by using the Mach-Zehnder modulator (MZM). The fig. 4 shows the mach-zehnder modulator. MZM follows the interferometric structure designed with the material having a strong electro-optic effect. Optical path lengths changes when input arms are given an electric field resulting in phase modulation. Intensity modulation can be obtained by combining two different arms with different phase modulation.

The QPSK modulation is a digital modulation technique that transmits the data by changing the phase of a carrier signal. QPSK with four phases and for constellation points can encode 2 bits per symbol. Two different data streams are given as input to MZM to get the QPSK modulated signal. The output equation for the QPSK MZM is [9]:

$$Vout = Ein\left[\cos\left(\pi\frac{Vi(t)}{V\pi}\right) + j\cos\left(\pi\frac{Vq(t)}{V\pi}\right)\right] \qquad (1)$$

Where Vi(t) and Vq(t) are voltages corresponding to input data signals and Vπ is characteristics voltage. The supply of bias voltage should be continuous for adequate functioning of MZM's.

Similarly, for 16-QAM the output equation will be the same. The only difference is to use PAM-4 signal as an input to the MZM to get 16-QAM output. The four binary data streams need to be converted into multilevel data streams before giving them to the input of the IQ modulator for adding phase information. The need to go for 16-QAM is to have a system with a higher-order modulation scheme that gives the data rates better than the conventionally used PAM-4 links. 16-QAM is a digital modulation scheme which has 16 constellation points and transmits 4 bits per symbol.

The signal in Y polarization is used for transmission of carrier phase information with the modulated signal. After the modulation now both the polarizations need to be combined to travel through the same optical channel. For the combining processes, a polarization beam combiner is used. Polarization division multiplexing is used for transmitting the signal from two different polarization through a single channel.

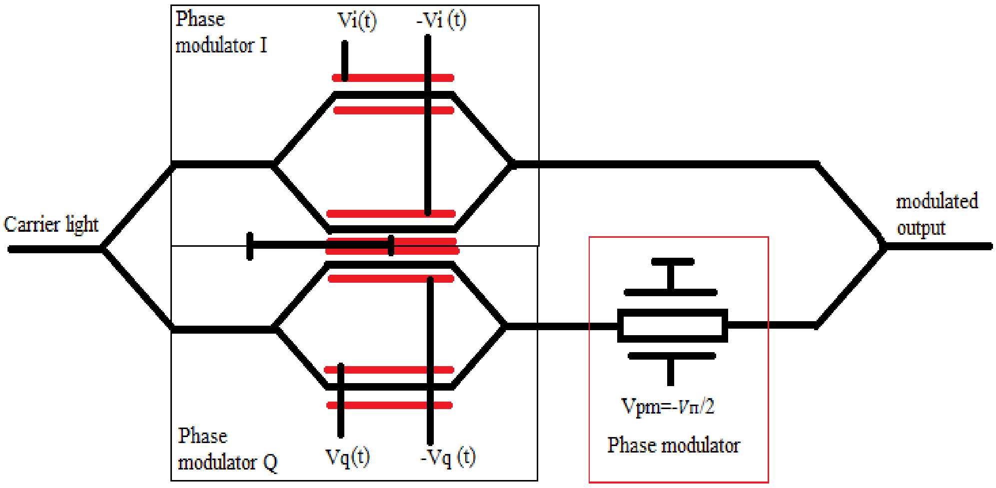

Fig. 4. Mach-Zehnder Modulator (MZM)

The component in X-pol is Ex and Y-pol is Ey then the polarization multiplexed signal can be written as:

$$P = \begin{bmatrix} Ex \\ Ey \end{bmatrix} \tag{2}$$

The polarization multiplexed signal is transmitted through the optical channel. The optical channel impairments will affect the signal and the state of polarization will change. As mixing of polarization is observed due to polarization impairments the system is based on polarization diversity. In mathematical terms, the polarization diversity effect can be represented by the Jones matrix [10]. Jones matrix is written as:

$$T = \begin{bmatrix} \alpha e^{j\o} & -\beta \\ \beta & \alpha e^{-j\o} \end{bmatrix} \tag{3}$$

Where α and β are the power splitting ratio between two orthogonal polarization and ø is the phase difference between a component of X-pol (Ex) and Y-pol (Ey). These parameters will cause the mixing of polarization in the channel. The signals after traveling through the optical fiber can be expressed as:

$$\begin{bmatrix} E'x \\ E'y \end{bmatrix} = TP$$

$$R = \begin{bmatrix} E'x \\ E'y \end{bmatrix} = \begin{bmatrix} \alpha e^{j\o} Ex - \beta Ey \\ \beta Ex + \alpha e^{-j\o} Ey \end{bmatrix} \tag{4}$$

Where E'x and E'y are the received components with mixed polarizations.

The state of polarization at the receiver should be the same as the transmitter to demodulate the information signal. The change in state polarization causes the mixing of the modulated signal and carrier signal. Separation of the carrier signal and modulated signal is an essential task to perform before demodulation. For this separation, we need to have the same state of polarization as of transmitter. For this, a particular unit called a polarization controller needs to be used in the system. Now the separation of the carrier signal and modulating signal can be done by using the constant modulus algorithm as a polarization de-multiplexing technique or by performing polarization control in the optical domain. In this paper, the polarization de-multiplexing using constant modulus algorithm is done for separation of modulated signal and carrier signal.

For performing the polarization demultiplexing the received signal vector will multiply with the J matrix. The general form of the equation is:

$$\begin{bmatrix} E"x \\ E"y \end{bmatrix} = J \begin{bmatrix} E'x \\ E'y \end{bmatrix} = JT \begin{bmatrix} Ex \\ Ey \end{bmatrix} \tag{5}$$

For better performance of this polarization demultiplexer, matrix J needs to have some updates. The constant modulus algorithm (CMA) based error minimization technique is used to control the matrix J.

The constant modulus algorithm does not require any training symbols from the transmitter for further processing, therefore CMA is called a blind equalizer. The bandwidth of the system can be saved and also the validity and reliability of the system can be improved by the use of blind equalization [11]. Fig. shows the constant modulus algorithm for the polarization control.

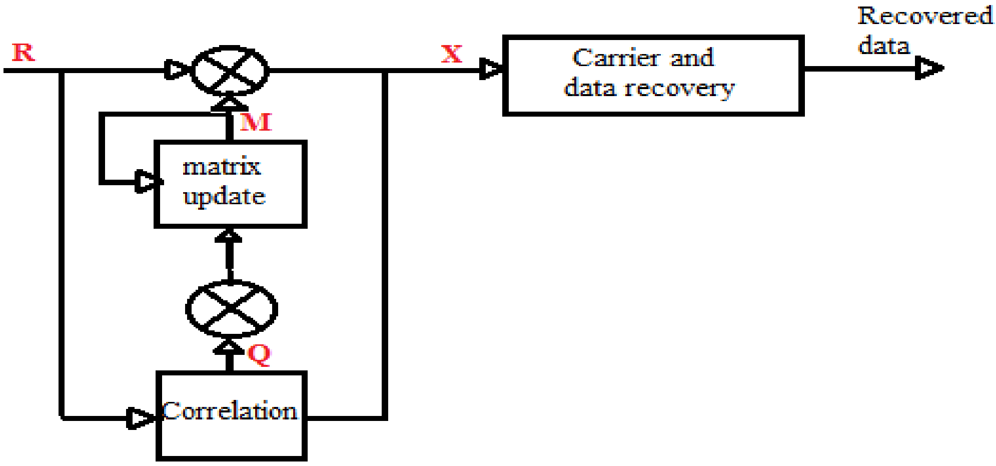

Fig. 5. Constant Modulus Algorithm at the receiver

Where R is the mixed received signal, M is the matrix that will be modified by the algorithm, Q is the correlation matrix for the received signal and obtained signal after processing. This correlation matrix Q is used for matrix updation to have error reduction. The matrix updation equation is given by:

$$Mnew = Mold + gQ \qquad (6)$$

Where g is the adjustable gain factor. The updation of M matrix components can be given as:

$$Mxx[n+1] = Mxx[n] + \mu[1 - |E''x[n]|^2]E''x[n]E'x[n]$$
$$Mxy[n+1] = Mxy[n] + \mu[1 - |E''x[n]|^2]E''x[n]E'y[n]$$
$$Myx[n+1] = Myx[n] + \mu[1 - |E''y[n]|^2]E''y[n]E'x[n]$$
$$Myy[n+1] = Myy[n] + \mu[1 - |E''y[n]|^2]E''y[n]E'y[n]$$

Where Mxy and Myx are the components representing cross-polarization effects, μ is the step size parameter and M[n] is the matrix coefficient at nth symbol period. The updation of matrix M will be done after every symbol interval. As CMA is a blind algorithm the phase error is not considered [12].

After the separation of the carrier signal and modulated signal now again at the receiver, we need to separate the two orthogonal polarizations with the use of a polarization beam splitter. Here now in X polarization we have the modulated signal now the demodulation will be done on this signal to get the original information. The receiver block diagram is as shown in Fig..

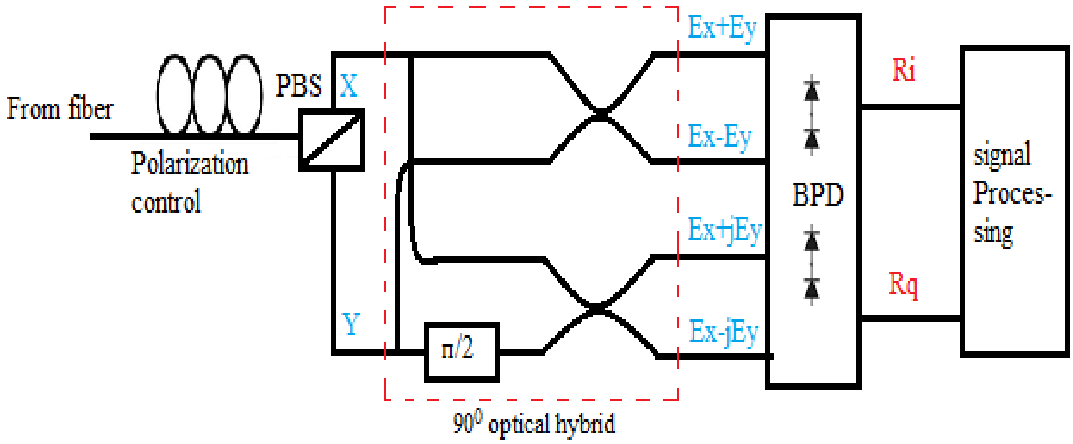

Fig. 6. Receiver block diagram of polarization multiplexed self-homodyne system

After the polarization controller, the orthogonal polarizations are separated and given to 90^0 optical hybrid. An optical hybrid is used to provides the output signal with some phase shift. An optical hybrid combines the signal in both polarization to generate the in-phase and quadrature-phase components.

Balanced photodetectors are used to generate the equivalent electrical signals and fed with the outputs of optical hybrid. In the coherent receiver, the balanced photodetectors give an advantage over receiver sensitivity. The output currents of an optical hybrid with photodetectors can be given as:

$$\begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{pmatrix} \approx \begin{pmatrix} [E_x + E_y][E_x + E_y]^* \\ [E_x - E_y][E_x - E_y]^* \\ [E_x + jE_y][E_x + jE_y]^* \\ [E_x - jE_y][E_x - jE_y]^* \end{pmatrix}$$

Where the X-pol signal representing the complex value modulated signal and the Y-pol signal representing the complexed value carrier signal can be written as:

$$Ex = Ase^{j(wct+\theta m)} \quad (7)$$

$$Ey = Aloe^{jwct} \quad (8)$$

Where θ_m is the angle value having phase information in accordance with the transmitted QPSK modulated signal, wc is the frequency of carrier signal, A_s is modulated signal amplitude and A_{lo} is carrier magnitude. The modulated signal amplitude will always be smaller than the carrier signal amplitude due to all of the insertion losses ($A_s << A_{lo}$). The quadrature and in-phase components of the received signal can be given as:

$$Ri = I1 - I2 = 4 * Alo * As * cos\theta m \quad (9)$$

$$Rq = I3 - I4 = 4 * Alo * As * sin\theta m \quad (10)$$

From the above equation we can get the phase value information.

4 Experimental Results

The experiment has done on the software MATLAB by considering the equations and theory mentioned earlier.

For the polarization diversity effect the power splitting ratio is considered as 2:3. The results for polarization multiplexed self-homodyne system for QPSK is as shown in Fig. 7.

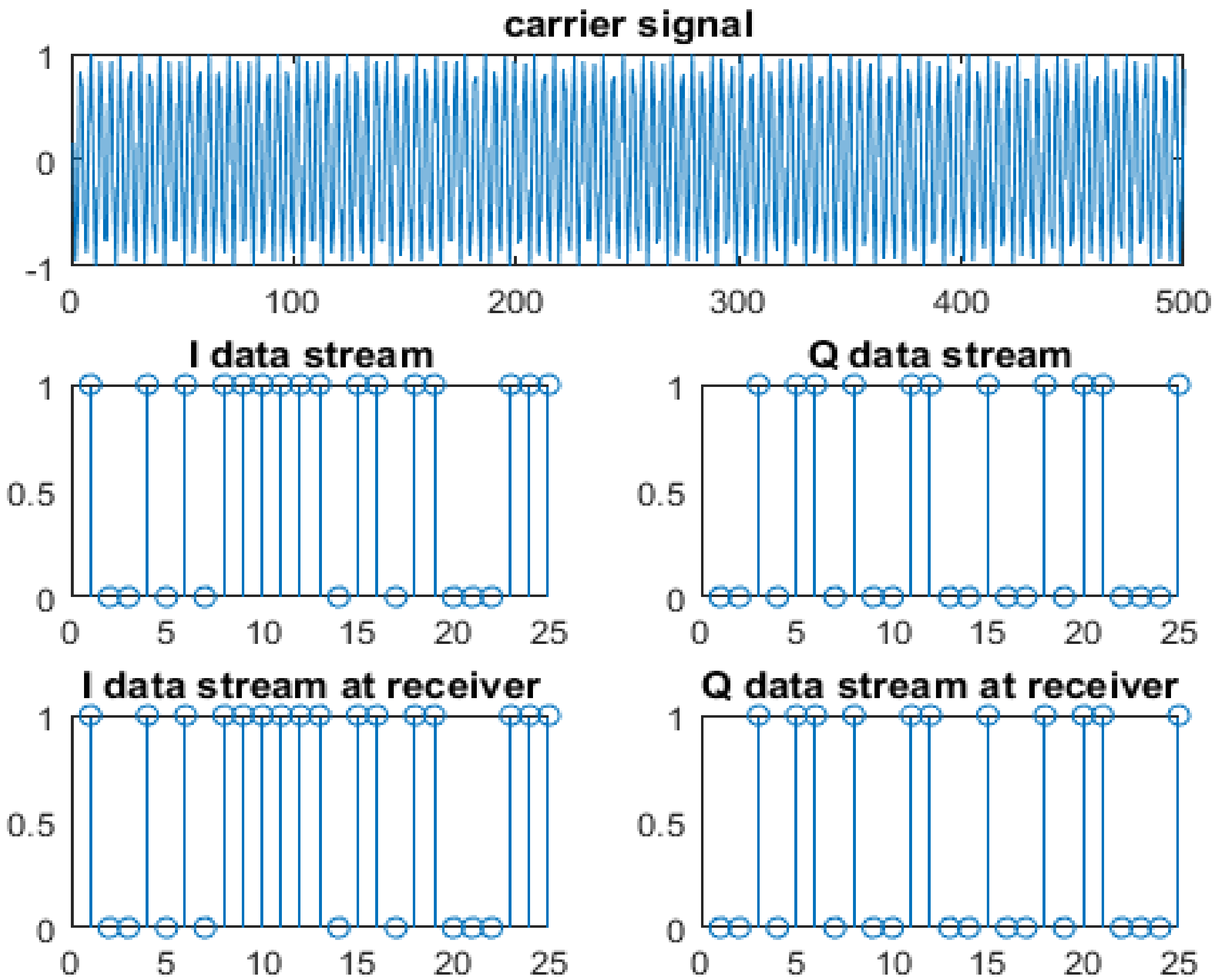

Fig. 7. Output of the polarization multiplexed self-homodyne system using QPSK modulator. The system has used the constant modulus algorithm of error minimization for polarization control.

Similarly, the results of polarization multiplexed self-homodyne system using 16-QAM modulator is also shown after that in Fig. 8.

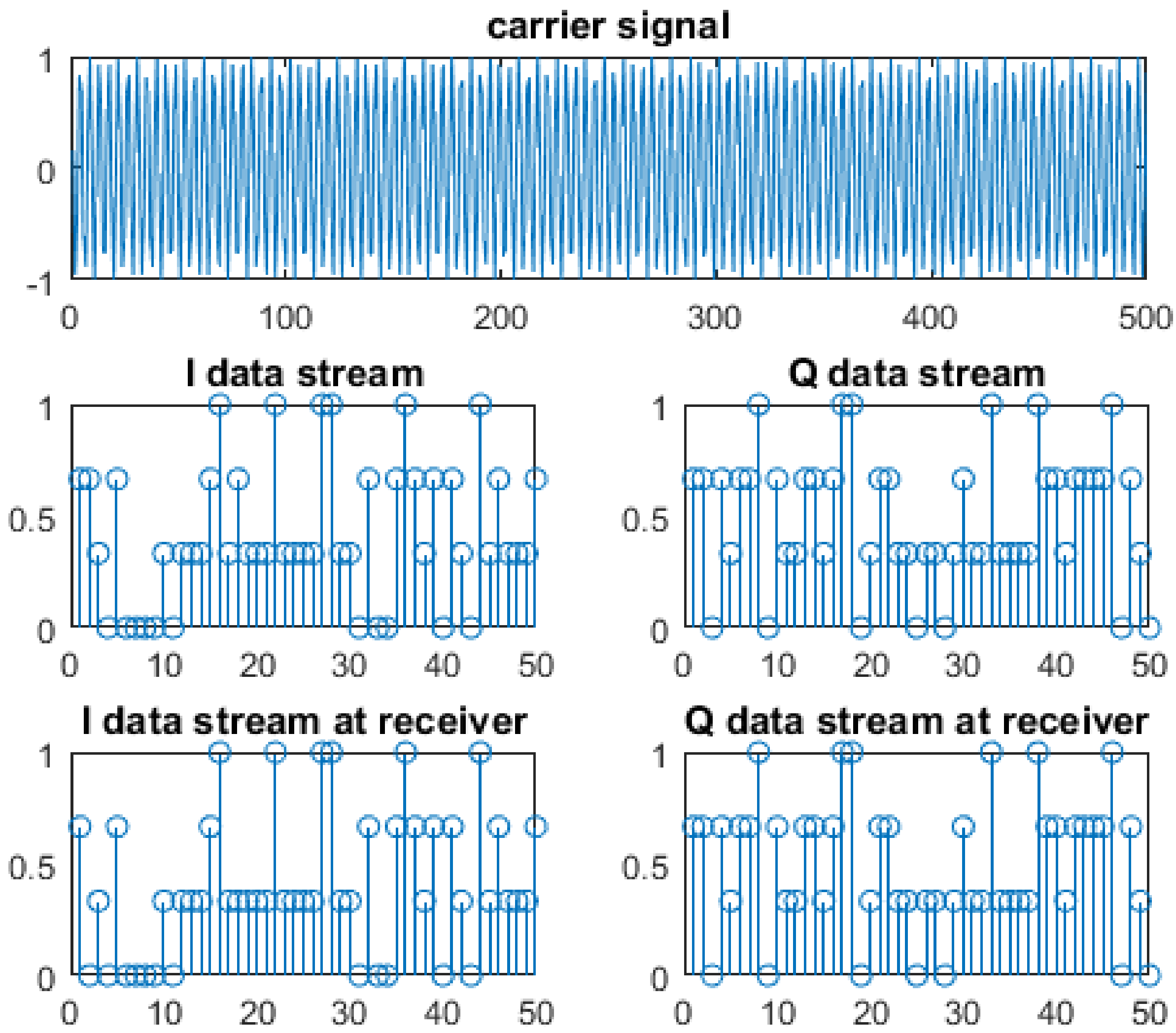

Fig. 8. Output of the polarization multiplexed self-homodyne system using 16-QAM modulator. The system has used the constant modulus algorithm of error minimization for polarization control.

5 Conclusion

The polarization multiplexed self-homodyne system using QPSK and 16-QAM modulation techniques is demonstrated. The use of polarization multiplexing eliminates the use of a local oscillator at the receiver. The use of a constant modulus algorithm for polarization control corrects the state of polarization of signal to a great extent that at the receiver the original information signal can be reconstructed. The system uses higher-order modulation schemes thus gives better data rates than existing systems. Polarization multiplexing add the low power consumption property to the advantages of the system.

References

[1] "Cisco Visual Networking Index: Forecast and Trends, 2017 - 2022," White paper Cisco, Document ID: 1551296909190103, 27 Feb 2019.

[2] M. Chagnon, "Direct-detection technologies for intra-and inter-data center optical links," in Optical Fiber Communications Conference and Exhibition (OFC), p. W1F.4, March 2019.

[3] G. Keiser, "Optical Fiber Communications," Second edition, McGraw-Hill Education (India) Pvt Limited, 2008.

[4] K. Kikuchi, T. Okoshi, M. Nagamatsu, and N. Henmi, "Degradation of bit-error rate in coherent optical communications due to spectral spread of the transmitter and the local oscillator," Journal of Lightwave Technology, vol. 2, no. 6, pp. 1024–1033, December 1984.

[5] Forestieri, M. Secondini, F. Fresi, G. Meloni, L. Poti, and F. Cavaliere, "Extending the Reach of Optical Interconnects with DSP-

Free Direct-Detection," Journal of Lightwave Technology (JLT), vol. 35, no. 3174-3181, pp. 1–1, August 2017.

[6] G. W. Lu, M. Nakamura, Y. Kamio, and T. Miyazaki, "40-Gb/s QPSK with Inserted Pilot Symbols using Self-homodyne Detection," in Optical Fiber Communication and the National Fiber Optic Engineers Conference (OFC/NFOEC), p. OMP4, March 2007.

[7] Y. Okamura and M. Hanawa, "All-Optical Generation of Optical BPSK/QPSK Signals Interleaved With Reference Light," IEEE Photonics Technology Letters (PTL), vol. 24, no. 20, pp. 1789–1791, Oct 2012.

[8] R. Kamran, S. Naaz, S. Goyal and S. Gupta, "High-Capacity Coherent DCIs Using Pol-Muxed Carrier and LO-Less Receiver," in Journal of Lightwave Technology, vol. 38, no. 13, pp. 3461-3468, July 2020.

[9] L. Zhao, H. Shankar, and A. Nachum, "40G QPSK and DQPSK Modulation," White paper Inphi Corporation, April 2014.

[10] K. Kikuchi, "Polarization-demultiplexing algorithm in the digital coherent receiver," 2008 Digest of the IEEE/LEOS Summer Topical Meetings, pp. 101–102, July 2008.

[11] L. Liu, Z. Tao, W. Yan, S. Oda, T. Hoshida and J. C. Rasmussen, "Initial tap setup of constant modulus algorithm for polarization de-multiplexing in optical coherent receivers," 2009 Conference on Optical Fiber Communication, San Diego, CA, USA, 2009, pp. 1-3, 2009.

[12] Wei Rao, Kang-min Yuan, Ye-cai Guo and Chao Yang, "A simple Constant Modulus Algorithm for blind equalization suitable for 16-QAM signal," 2008 9th International Conference on Signal Processing, Beijing, China, pp. 1963-1966, 2008