Optics Communications 294 (2013) 134–138

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Bit-rate transparent DPSK demodulation scheme based on injection locking FP-LD

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A R T I C L E I N F O

Article history:
Received 15 October 2012
Received in revised form
31 December 2012
Accepted 3 January 2013
Available online 19 January 2013

Keywords:
Phase modulation
Fabry–Perot laser diode
Polarization selective devices

A B S T R A C T

We propose and demonstrate a bit-rate transparent differential phase shift-keying (DPSK) demodulation scheme based on injection locking multiple-quantum-well (MQW) strained InGaAsP FP-LD. By utilizing frequency deviation generated by phase modulation and unstable injection locking state with Fabry–Perot laser diode (FP-LD), DPSK to polarization shift-keying (PolSK) and PolSK to intensity modulation (IM) format conversions are realized. We analyze bit error rate (BER) performance of this demodulation scheme. Experimental results show that different longitude modes, bit rates and seeding power have influences on demodulation performance. We achieve error free DPSK signal demodulation under various bit rates of 10 Gbit/s, 5 Gbit/s, 2.5 Gbit/s and 1.25 Gbit/s with the same demodulation setting.

1. Introduction

Compared with intensity modulation formats, differential phase shift-keying (DPSK) signal has better nonlinear and polarization mode dispersion tolerance. So realizations of DPSK signal modulation/demodulation and DPSK format conversions are always the research focuses [1–4]. The traditional DPSK signal demodulation scheme is to split data into two paths with one path having one bit period delay generated by a Mach–Zehnder delay interferometer (MZDI). In the receiving process, besides single port detection with a photodetector (PD), a balance detector can offer 3 dB receiver sensitivity improvement [5]. However, the cost of MZDI is too high and a thermoelectric cooler (TEC) must be integrated in this device to compensate temperature drift [6]. Until now, there are many reports about novel DPSK demodulation schemes, including using discriminator filter [7], and structured fiber Bragg grating (FBG) which has similar optical spectrum to that of MZDI [8], also with the help of birefringent fiber [9]. These schemes support only fixed bit rate demodulation. Though researchers have designed variable bit rate DPSK signal demodulation schemes, systematic parameters must be adjusted along with the signal bit rate. In other words, these schemes are not bit-rate transparent. For example, while using stimulated-Brillouin-scattering based DPSK demodulation scheme [10], bit rate variable demodulation can be realized through properly adjusting the pump power. When using wavelength selective switch (WSS) to realize this function [11], the passband of a WSS has to be reprogrammed. A cascaded four-wave mixing (FWM) effect has been utilized in DPSK signal demodulation [12], but the wavelength of pump light must be tuned to introduce a proper delay time.

A cost-effective and easily achievable DPSK demodulation scheme meets the requirement of future optical network [13,14]. This scheme must support bit rate transparent demodulation function and multi-channel demodulation function [15]. Previously, injecting locking with a dual side emitting distributed feedback laser diode (DFB-LD) to realize DPSK signal demodulation has been reported [16,17]. This method supports bit rate transparent DPSK demodulation, but dual side emitting DFB-LD has special structure and small wavelength tuning range, which hinders supporting DPSK demodulation with a wide wavelength range. In this paper, we use a Fabry–Perot laser diode (FP-LD) with multiple-quantum-well (MQW) structure made by InGaAsP material to realize bit rate transparent DPSK signal demodulation. When transverse electric (TE) polarization DPSK signal serves as the seeding light, an unstable injection locking state of FP-LD excites transverse magnetic (TM) polarization mode. DPSK signal format is converted to polarization shift-keying (PolSK) signal format. Then after a polarization beam splitter (PBS), we extract intensity modulated (IM) data from PolSK signal to accomplish DPSK demodulation. Additionally, utilizing multimode output characteristic of FP-LD, we can realize DPSK signal demodulation with different wavelengths individually. In this experiment, we analyze the influences of demodulation performance under various longitude modes, bit rates and seeding power to validate this novel DPSK demodulation scheme.

2. Systematic principle

The principle of DPSK signal demodulation based on injection locking of FP-LD is shown in Fig. 1. In free running state, MQW

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http://dx.doi.org/10.1016/j.optcom.2013.01.001

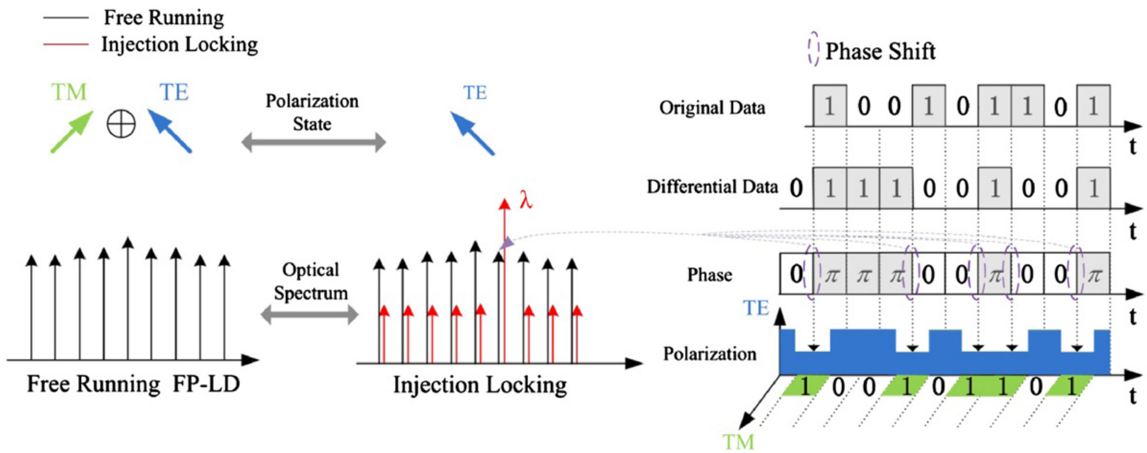

Fig. 1. Systematic principle.

InGaAs FP-LD has multimode optical spectrum, which consists of both TE and TM mode polarization states. When the external seeding light is in TE mode, FP-LD has stable TE polarization locking state. After differential coding, the rising/falling time of differential intensity data lasts for a certain time Δt in every "0"–"1" or "1"–"0" intensity transition. When a phase modulator (PM) is driven by the differential intensity data, a phase shift corresponding to rising/falling time of Δt induces a frequency deviation Δf. When this DPSK signal is used as the seeding light, an unstable injection locking state is attained in every phase shift due to the frequency deviation. Because FP-LD has TE mode polarization state in line with the seeding light, it returns to the free running state in every unstable injection locking moment and the output light contains both TE and TM mode polarization states. So each phase shift corresponds to TM mode exciting. In the end, a PBS splits TM light for intensity detection. In this way, DPSK demodulation is achieved through DPSK to PolSK and PolSK to IM format conversions.

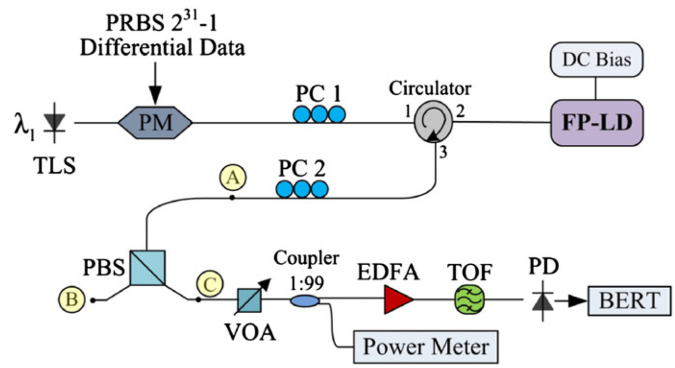

Fig. 2. Experimental setup. TLS: tunable laser source; PM: phase modulator; PC: polarization controller; FP-LD: Fabry–Perot laser diode; PBS: polarization beam splitter; EDFA: erbium-doped fiber amplifier; TOF: tunable optical filter; VOA: variable optical attenuator; PD: photodetector; BERT: bit error rate tester.

3. Experimental setup and results analysis

Fig. 2 shows the experimental setup diagram of the proposed bit-rate transparent DPSK demodulation system. Signal demodulation and format conversion are realized by an MQW InGaAs FP-LD. A continuous wave (CW) λ light is generated by a tunable laser source (TLS) with a maximal output power of 14 dBm. Pseudo random binary sequence (PRBS) differential data with word length of 2^{31}–1 and various bit rates are modulated on this wavelength through a PM to generate DPSK signal. Then the DPSK light is served as seeding light, whose polarization state is adjusted to TE mode through a polarization controller (PC1). In the injection locking process, a prerequisite requirement for the stable locking state is that the wavelength of seeding light must align with that of one longitude mode of the FP-LD. The locking light output is from the 3rd port of optical circulator. In this case, the optical spectrum of FP-LD is very similar to that of a single mode laser and the side mode suppression ratio (SMSR) can reach 50 dB. Before passing through a PBS, we adjust the polarization state of PC2 in order to split the fundamental TE and TM modes. After PBS, signal is attenuated by a variable optical attenuator (VOA) with one 1:99 optical coupler connected behind. An optical power meter is connected to the 1% output port of coupler. Then the received signal is pre-amplified by an erbium-doped fiber amplifier (EDFA), and the main mode of amplified signal is filtered out by a tunable optical filter (TOF). We use a 10-GHz bandwidth photodiode (PD) to receive the optical signal for bit error rate (BER) measurement. In Fig. 2, we set three points for eye diagrams and time domain waveforms measurement. Point A is set before PBS and it is utilized to observe PolSK signal which is un-split by PBS. Points B and C are located behind PBS. We observed TE and TM polarization signals at these two points, correspondingly, after completing PC2 adjustment. The bias current of FP-LD is set to 54 mA and we use 1550.4 nm longitude mode in injection locking. Eye diagrams and time domain waveforms at points A–C are shown in Fig. 3. In Fig. 3(a), PolSK signal has indistinct eye diagram and slight fluctuations in time domain waveform. This is due to the mixing of TE and TM polarization lights before passing through the PBS. Fig. 3(b) shows the eye diagram and waveform of the split TM mode signal. The eye diagram is clearly open and we can get a distinct waveform. Signal of point C is used for comparison. In Fig. 3(c), signal of TE polarization state has larger amplitude than that of the TM mode signal. The time domain waveform of TE mode is the inverse code of the TM polarization waveform. It can be explained that every phase shift induces TM mode exciting and the power of TE polarization state has a certain loss in the corresponding bit. When there is no phase shift, FP-LD can maintain TE mode light output. In addition, considering that FP-LD has larger TE mode gain than that of TM mode, the amplitude of TE mode signal is greater than that of the TM mode signal.

The FP-LD used in this experiment has high polarization selective feature and wide wavelength tuning range. Through changing the bias current, the output spectrum can cover optical wavelength from 1530 nm to 1565 nm. Fig. 4 shows the BER

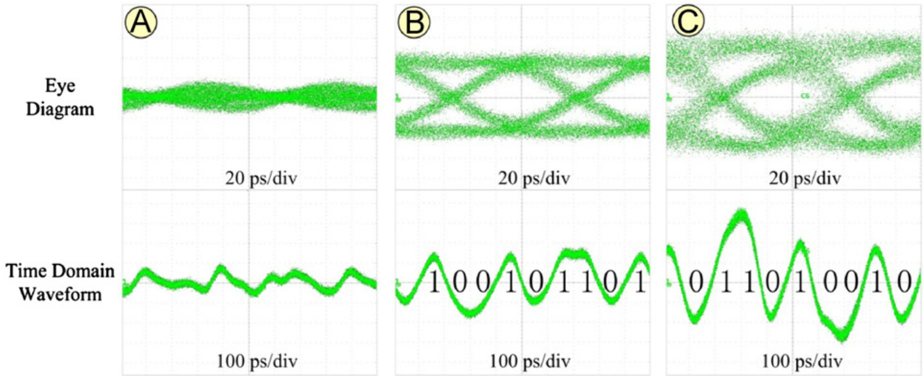

Fig. 3. Eye diagrams and time domain waveforms at A, B, C observing points.(a) port A before PBS; (b) port B after PBS; and (c) port C after PBS.

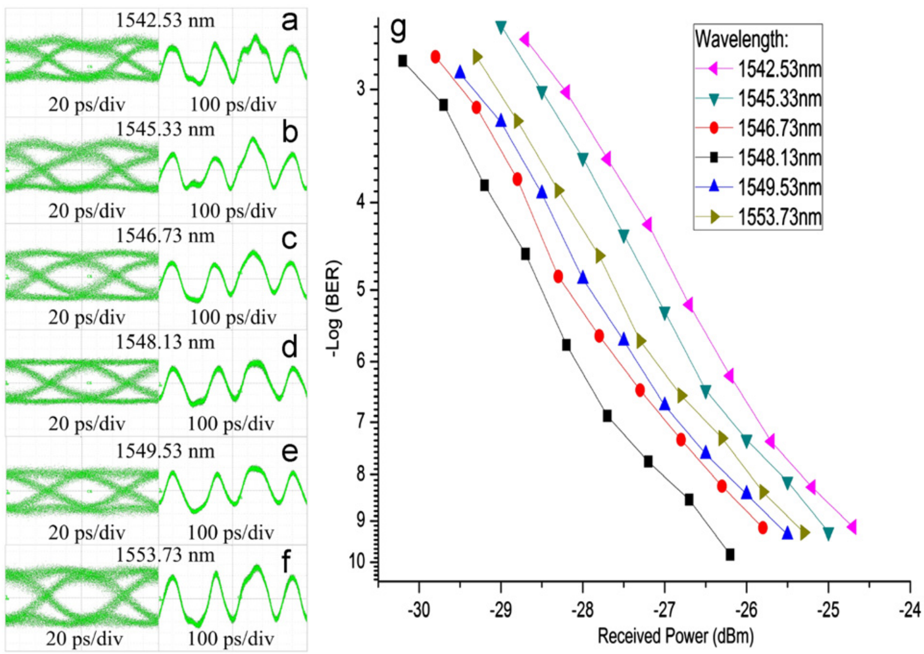

Fig. 4. Eye diagrams, time domain waveforms and BER performance under different longitude modes at 10 Gb/s: (a) 1542.53 nm; (b) 1545.33 nm; (c) 1546.73 nm; (d) 1548.13 nm; (e) 1549.53 nm; (f) 1553.73 nm; and (g) BER measurement of different longitude modes.

performance with corresponding eye diagrams and time domain waveforms under different longitude modes. The bias current is set at 48 mA and the main longitude modes of FP-LD are located around 1548 nm. We select six longitude modes of 1542.53 nm, 1545.33 nm, 1546.73 nm, 1548.13 nm, 1549.53 nm and 1553.73 nm for injection locking DPSK demodulation at 10 Gb/s. Through comparing these data and pictures, we can find that the central mode of 1548.13 nm has the best demodulation performance with clear eye diagram and waveform as depicted in Fig. 4(d). Fig. 4(a) and (b) manifests DPSK demodulation performance at short wavelength longitude modes of 1542.53 nm and 1545.33 nm, respectively. There is some intensity fluctuation in the eye diagrams and waveforms. Compared with the central mode at 1548.13 nm, the receiver sensitivity has 1.2 dB degradation. Considering the long wavelength modes at 1549.53 nm and 1553.73 nm, the demodulation signal has less intensity fluctuation and the performance is better than that of short wavelength modes as depicted in Fig. 4(e)–(g). The power penalty is less than 1 dB in contrast to the 1548.13 nm central mode. FP-LD has larger gain effect in long wavelength region and therefore better injection locking performance compared with the short wavelength side.

The demodulation performance of injection locking FP-LD under different bit rates is shown in Fig. 5. In the bit-rate transparent experiment, we select 10 Gb/s, 5 Gb/s, 2.5 Gb/s and 1.25 Gb/s as four different bit rates. For comparison, 10 Gb/s and 5 Gb/s DPSK demodulation performance based on MZDI is also analyzed. Bias current of FP-LD is 53.7 mA and central mode of 1550.4 nm is selected for demodulating DPSK signal. As the data rate generated by pulse pattern generator (PPG) is changed, the whole system supports bit rate variable DPSK demodulation with no need to change any system parameter. Thus bit rate transparent DPSK demodulation is achieved. From signal eye diagrams and time domain waveforms in Fig. 5(a)–(d), we can find that the demodulated signal has larger eye and pulse width with gradual reduction of the bit rate. Fig. 5(e) shows BER performance under different bit rates. When the data rate is 10 Gb/s, we can achieve nearly the same receiver sensitivity compared with the MZDI and the receiver sensitivity is about −26.5 dBm. 5 Gb/s bit rate corresponds to steeper rising/falling time and therefore widely open eye diagram. Receiver sensitivity can reach −28.7 dBm. When we use the MZDI, receiver sensitivity is improved to about 0.4 dB. One prominent merit of our scheme is that high sensitivity DPSK demodulation can be realized at low bit rate. The sensitivity

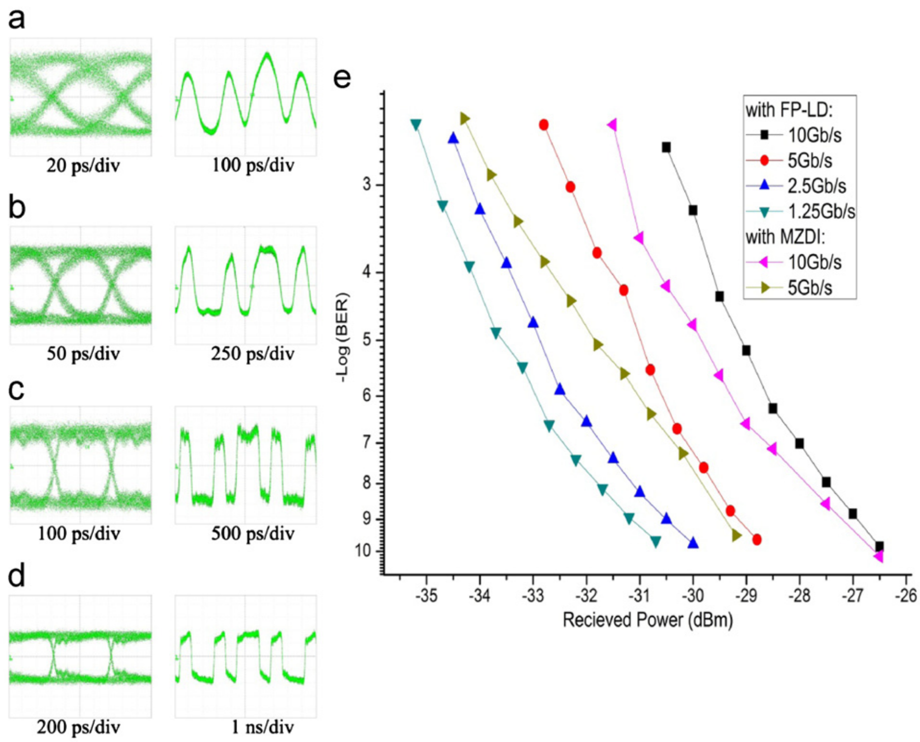

Fig. 5. Eye diagrams, time domain waveforms and BER performance under various bit rates:(a) 10 Gb/s; (b) 5 Gb/s; (c) 2.5 Gb/s; (d) 1.25 Gb/s; and (e) BER measurement of different bit rates.

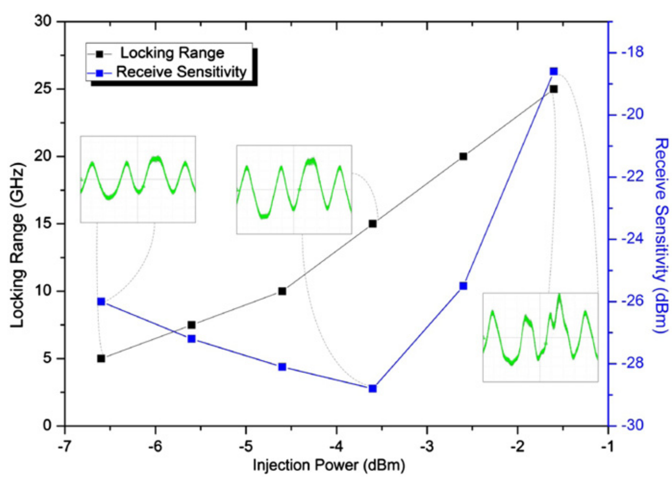

Fig. 6. Locking range and receiver sensitivity versus different injection powers.

of 1.25 Gb/s signal is about 4 dB higher than that of 10 Gb/s bit rate. Inter-symbol interference (ISI) is minimized, because of sharp edge pulse and open width of eye diagram. This is due to the rising and falling time of FP-LD. In simulation, a fast rising/falling time can support 40 Gb/s error free DPSK demodulation, but the commercial product which we use has slow rising/falling time and the corresponding bit rate is about 10 Gb/s.

In the experiment, we change the power of seeding light and maintain the DPSK signal bit rate at 10 Gb/s. A relationship of the receiver sensitivity and locking range of FP-LD versus the injection signal power is given in Fig. 6. With increasing seeding power, the stable locking range of FP-LD becomes larger. The initial seeding power is −6.6 dBm, which has 5 GHz stable locking range. When the seeding power is increased to −1.6 dBm, the locking range can extend to nearly 25 GHz. However the receiver sensitivity is firstly improved and then becomes worse with the increase of the seeding power because on increasing seeding power, the power of TE mode code which generated by injection locking FP-LD and TM mode inverse code which generated by unstable locking state both have a certain enhancement. As the power of TM mode code increases, the receiver sensitivity is improved. When seeding power is −3.6 dBm, we can get the optimal receiver sensitivity −29 dBm and the sensitivity is 2.4 dB better than that when seeding power is −6.6 dBm. With further increase of seeding power, the locking range of FP-LD is enlarged. This will influence unstable locking state of FP-LD and induce intensity fluctuation of TM mode inverse code. So after raising seeding power to a certain level, worsens receiver sensitivity. The sensitivity at −1.6 dBm seeding power is about 7.5 dB, worse than that of −2.6 dBm seeding power.

4. Conclusion

We realize a bit rate transparent and wavelength tunable DPSK demodulation scheme based on injection locking FP-LD. This scheme utilizes an unstable injection locking state of FP-LD and frequency deviation generated by PM to attain polarization conversion in every phase shift. When various bit rates DPSK signal is demodulated, no system parameter needs to be readjusted. The experiment results demonstrate that main modes of FP-LD have better demodulation performance than those of other longitude modes and an optimal seeding power is attained.

Acknowledgment

The work was jointly supported by the National "973" Project of China (Nos. 2010CB328205, 2010CB328204 and 2012CB315602), the National Nature Science Fund of China (Nos. 60972032, 61090393 and 60825103) and the National "863" Hi-tech Project of China.

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