Experiment 7

Name: Balasubramaniam M C
Roll: EE18B155

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Introduction:

This assignment deals with simulating a coherent detector used to detect QPSK data sent in at a given OSNR. We simulate for cases with and without-frequency offset between LO and transmitted signal ; phase noise due to combined linewidth in the lasers and fiber dispersion (either back to back or with fiber in the link). Frequency offset cancellation and chromatic dispersion compensation is also done on the received demodulated signal after which bit error rate and symbol decision is done.

The Coherent Detector Function:

First, we discuss the basic simulation of the coherent detector function with the 90 degree hybrid.
The photodetector parameters used were:

```
PD_bw = 12GHz - just above 10Gbaud baudrate to not add much noise
Rd = 0.5 A/W -Responsivity
RL = 50ohms -Typical load resistance
Fn = 1 -Noise figure-taken to be ideal
Stopband attenuation= 500dB
```

The responsivity of 0.5A/W was chosen as the typical photodetector responsivities available and also not so low enough to ruin the electrical SNR of the demodulated output. Stopband attenuation of 500dB is chosen so as to lower the effect of out of band frequencies in the photodetector which in reality shows an RC transfer function behaviour that decays as frequencies proceed to infinity, but since the 'lowpass' function doesn't give infinite attenuation at infinite frequencies, we choose a high stoppband attenuation. We try to keep the model restricted to what is similar for an photodetector accepting frequencies only upto it's bandwidth and nothing more.

The power chosen for the signal and LO were 1mW and 10mW. We don't want any modulation to be present in the variance of photodetector noise, also its better to operate close to the shot noise limit where we can change SNR using Ps(signal power). So, we use 10 times the power in the TX signal for the LO signal.

The Data parameters are:

```
Modulation Format: QPSK
```

```
Data type,rate: PRBS9 20Gbps
Baud rate: 10Gbaud
Samples per symbol: 4
fsampling: 40GHz
No. of symbols: 2^12
```

2^{12} symbols (QPSK) were transmitted at an sps (samples per symbol) of 4 using 2 PRBS9 bitstreams(each 10Gbps). 2^{12} symbols were enough for simulation purposes and generating enough symbols for the constellation. Likewise for the 'sps' value chosen, we also don't want unnecessarily high amplitude noise from PD, so we choose a low enough sampling frequency satisfying nyquist criterion.

The coherent detector function is mainly based on the 90 degree hybrid transfer function as shown in the code, after which we find the currents using the photodetector function and subtracting them. The currents obtained are plotted on a constellation diagram (after choosing one sample for each symbol slot) as shown in fig.1.

As we can see in fig.1 we obtain the normal expected QPSK constellation diagram with certain fluctuations in amplitude and phase. This is because the two photodetectors for I and Q both add noise with a given variance, hence showing slight variations in real, imaginary parts.

Ideal case with only an OSNR of 30dB:

In this section, we simulate using the LASER transfer functions, MZM at a 25Gbaud rate and OSNR 30dB. There's no freq. offset and phase noise involved.
The photodetector parameters are the same (for the same reasons stated earlier) except that the bandwidth is 26GHz now (fbaud being 25Gbaud).
The TX Laser power used is 0.1mW and LO laser power of 1mW (given).
The TX signal power is 10 times lower than LO because again, we want to operate in quantum limit for photodetector noise. The linewidth (combined) is 0Hz for no phase noise.
The MZM parameters are:

```
Vpi = 3V
V offset = 0.5V
Insertion loss = 0.3dB;
Extinction Ratio = 30dB;
```

IQ modulation is performed with two such MZMs. The low insertion loss is so that we don't lose a lot of power in the MZM with low enough input power already. The Extinction ratio is high enough (close to typical values) to give good enough destructive, constructive interference for 0,pi phases.

The Data parameters are the same except that the 'sps' used is 10 giving a 250GHz sampling frequency and we also have a 50Gbps datarate (due to fbaud being 25Gbaud). These are all given.
Now, white gaussian noise is added of given OSNR (scaled according to fsampling/Bref(12.5GHz)) to the signal and passed to the coherent detector.
Demodulation is done and we obtain I,Q currents. Symbol decision is done via thresholding and BER is calculated as per each bit flip error. The demodulated output is as shown in fig. 2 and I,Q transmitted and demodulated, decided symbols are as shown in fig. 3,4.

```
BER Calculated:0
```

Case with TX and LO laser linewidth of 10kHz:

In this section we take into account of phase noise from combined linewidth of TX and LO laser (10KHz). All the parameters used for the ideal case with OSNR 30dB and no phase noise are used here again(like PD bandwidth being 26GHz, Psig = 0.1mW , Rd of 0.5A/W etc.). The only difference here would be the phase noise due to linewidth. This can evolve with greater number of symbols simulated for and is a strong function of sampling frequency. However, both 'sps'(10-which is high enough) and total number of symbols(2^{12}) and even the linewidth ofcourse are just enough to not make the phase noise disturb the constellation a lot. We can see the constellation diagram of demodulated output in fig.5. We observe the 'smudge' due to phase noise from linewidth in the figure.

```
BER calculated:0
```

We observe that the BER calculated is also 0 because all symbols are still confined in their own quadrant. The time domain waveforms would also look similar to the earlier case (figs. 3,4) with no bit flip.

Case with combined LW of 10kHz and freq. offset 1GHz:

In this section, we additionally introduce a frequency offset of 1GHz between Tx, LO signals. In order to add a frequency offset, we introduce the phase via $exp(j2piw_{off} * nTs)$ at the 'nth' sample as shown in the code.
In order to detect this frequency offset, we take the fourier transform of the fourth power of demodulated IQ current obtained and find the frequency at which a maxima in the magnitude spectrum occurs (4*f_{off}).
Using this estimated offset, we can remove the offset conventionally as shown in the code.
Since we have a frequency offset here, the signal power becomes important here for it's estimation. So, ideally we'd want no other amplitude noise to disturb our estimate. The phase noise can cause a frequency spread, but the maxima will give us close to the right value. So, in order to achieve this, we'd want a good responsivity of the PD(0.5 A/W) and high enough Psig(0.1mW) to increase SNR. This shows to give a good constellation diagram after freq. offset cancellation as shown in fig. 7. Before freq. offset cancellation there is a circular spread due to rotation of the signal with time (fig.6). Frequency offset can be estimated from the maxima as shown in fig. 8. The frequency is negative because of inversion in f_{off} in the coherent detector (which is why we also take + sign for freq. off. correction).

```
BER without freq. offset correction(OSNR 30dB):0.50122
Freq. offset est. :0.99945GHz
BER with freq. offset correction(OSNR 30dB):0
```

All the symbols seem to still fit in each quadrant after the correction and hence we still get a low enough BER close to 0 even though there's a bigger spread compared to the phase noise case. Without the correction ofcourse the bit error rate is high (0.5) because all the symbols are seen to be rotating with time. The time domain waveforms after correction, again appear to be similar to figs. 3 and 4.

Case with combined LW of 10kHz, freq. off. 1GHz and Fiber dispersion :

Now, we add a fiber to the link and simulate the system for different OSNR values. This case isn't much different from the previous one except that there is fiber dispersion which is compensated for anyway. We are ignoring attenuation in fiber here. With the same OSNR of 30dB, paramters of Rd (responsivity) , load resistance , PD bandwidth , total number of symbols, 'sps', etc are all the same as earlier because fiber dispersion doesn't change any of them since it doesn't affect magnitude in anyway and although the phase is shifted around, it's compensated for later anyway. In order to compare for different OSNR values, we can tune Rd, Psig in such a way as to give good enough electrical Photodiode SNR and just enough to see the differences in performance for three cases.

The fiber dispersion is implemented using the Non-linear shcrodinger equation changing the phase of the FFT of the signal. In chromatic dispersion compensation, we do the exact same thing with parameters of 'D', 'lamda' and length of fiber (80km), but with the opposite sign in the phase added. Correction is done upto 2nd order (with the 'beta2' term). An 'Rd' of 0.5A/W, and Psig of 0.1mW is just enough for giving a good constellation for the 30dB OSNR case. We use the same 'Rd' and Psig for all cases and it provides a decent unbiased variation in BER, constellation diagram output.

OSNR 30dB:

The result is as shown in fig. 9. As we can see due to high enough OSNR, the additional RIN noise from laser isn't high enough to move symbol points to the opposite quadrant. This case is similar to the previous one without fiber since dispersion compensation is almost exact. The spread is mostly due to phase spread by the freq. estimation offset error.

```
Freq. offset est. :0.99945GHz
BER with freq. offset and chromatic disp. correction(OSNR 30dB) :0.0036621
```

Hence, the BER also is low.

OSNR 20dB:

The result is as shown in fig. 10. Here, we can see considerable amplitude spread compared to last case due to source amplitude noise. This increases BER and moves some symbols to the opposite quadrant.

```
Freq. offset est. :0.99945GHz
BER with freq. offset and chromatic disp. correction (OSNR 20dB) :0.0061035
```

OSNR 10dB:

The resultant constellation diagram is as shown in fig. 11. In this case, the amplitude spread is a lot compared to phase spread so that more symbols go to the opposite quadrant due to lower OSNR and hence, the BER is also much higher

```
Freq. offset est. :0.99945GHz
BER with freq. offset and chromatic disp. correction (OSNR 10dB) :0.1272
```

As we can see from the time domain waveforms (in-phase and Q-phase) in figs. 12,13, there are considerable errors in bits giving a higher BER.

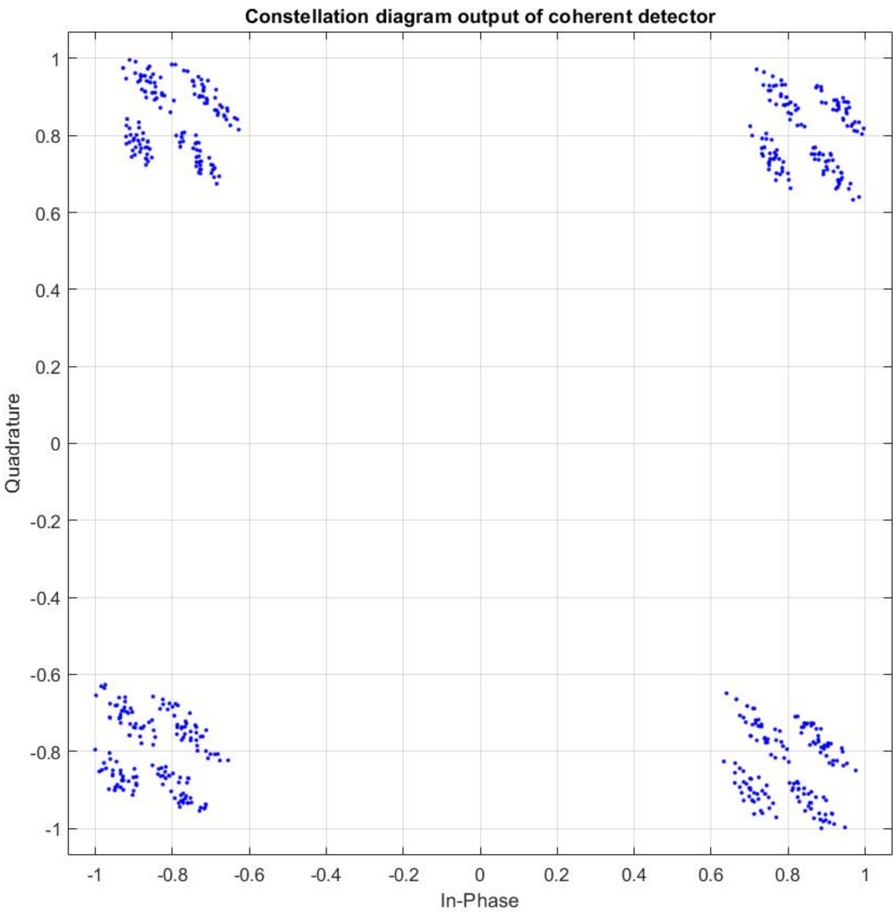

Figure 1: Constellation diagram for demodulated I,Q currents for QPSK 10Gbaud transmission after test simulation of coherent photodetector.

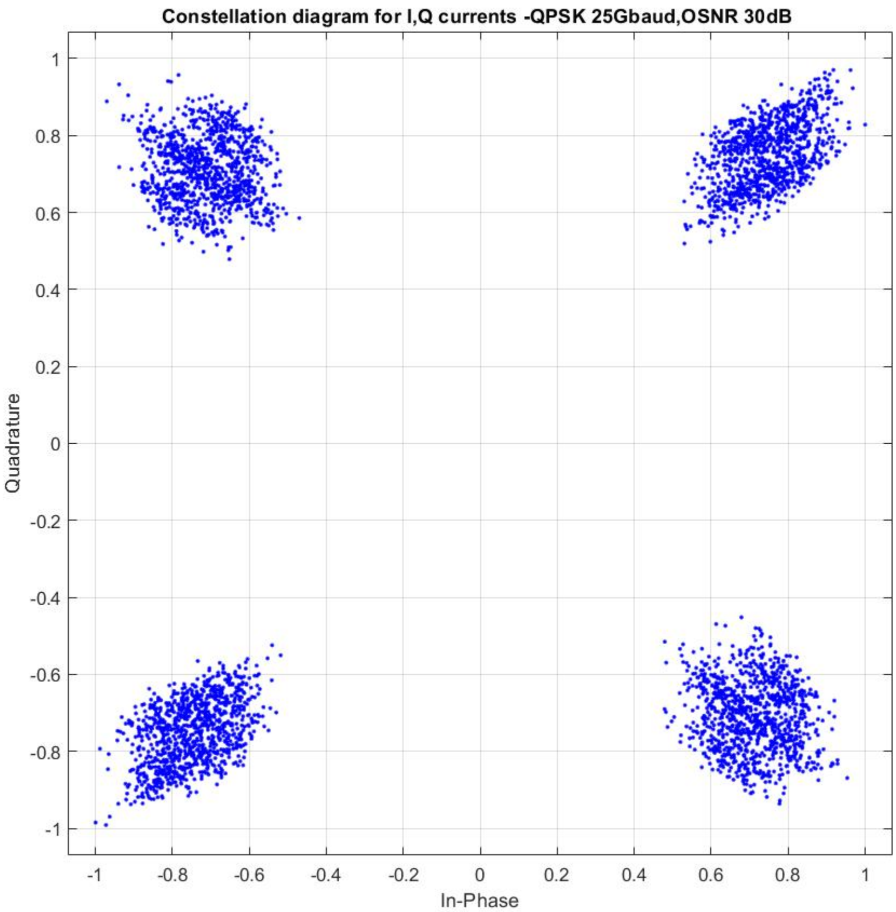

Figure 2: Constellation diagram for demodulated I,Q currents for QPSK 25Gbaud with no freq. offset, phase noise and OSNR= 30dB.

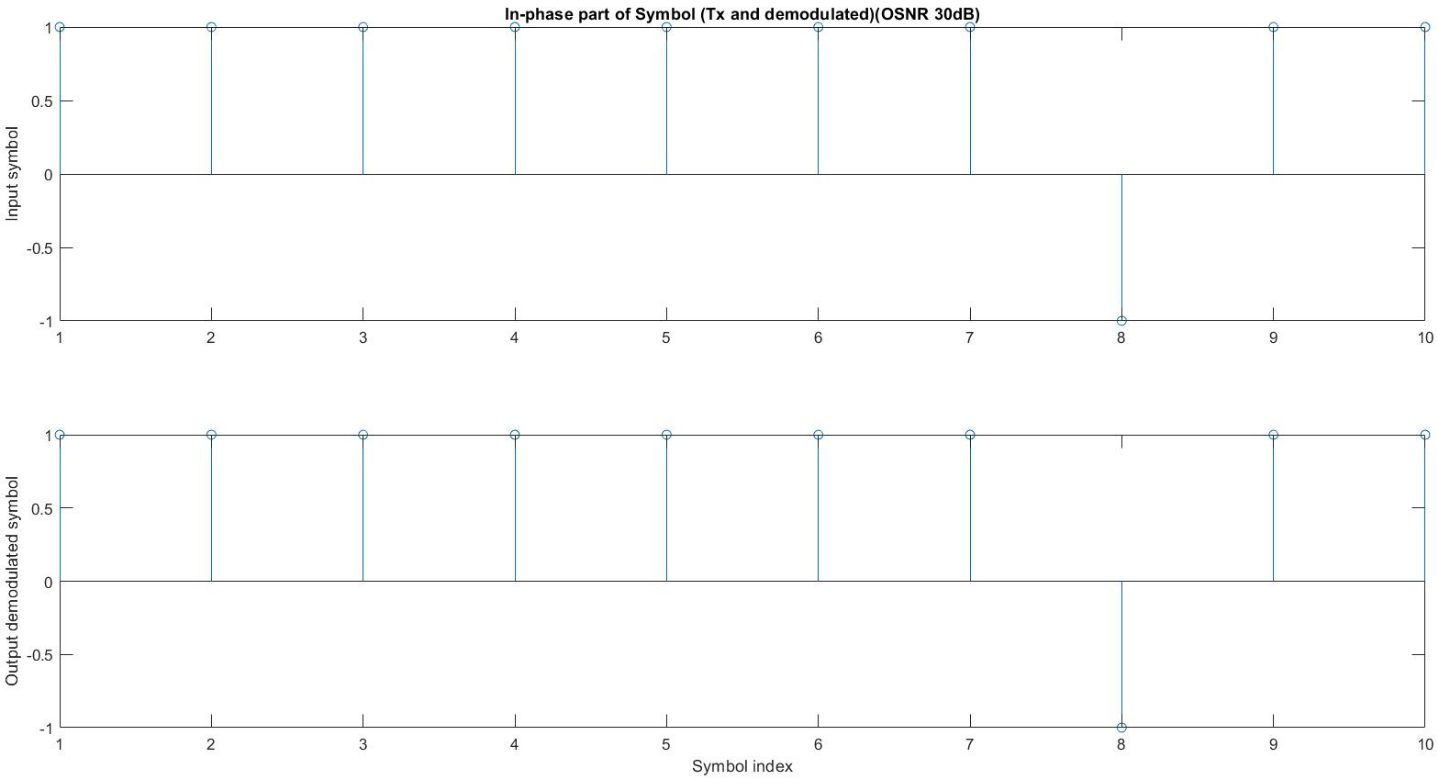

Figure 3: In-phase time domain waveform for demodulated symbols with QPSK 25Gbaud with no freq. offset, phase noise and OSNR= 30dB.

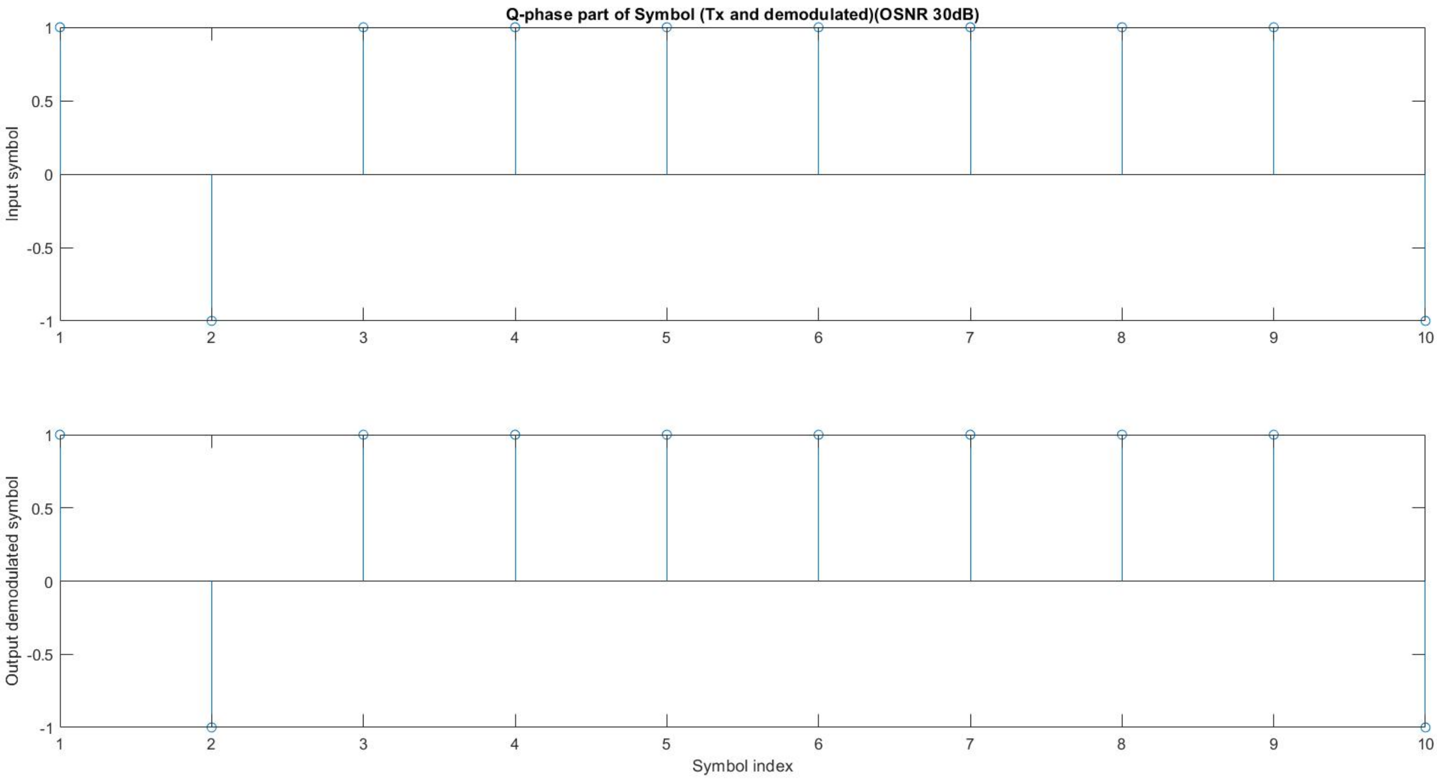

Figure 4: Q-phase time domain waveform for demodulated symbols with QPSK 25Gbaud with no freq. offset, phase noise and OSNR= 30dB.

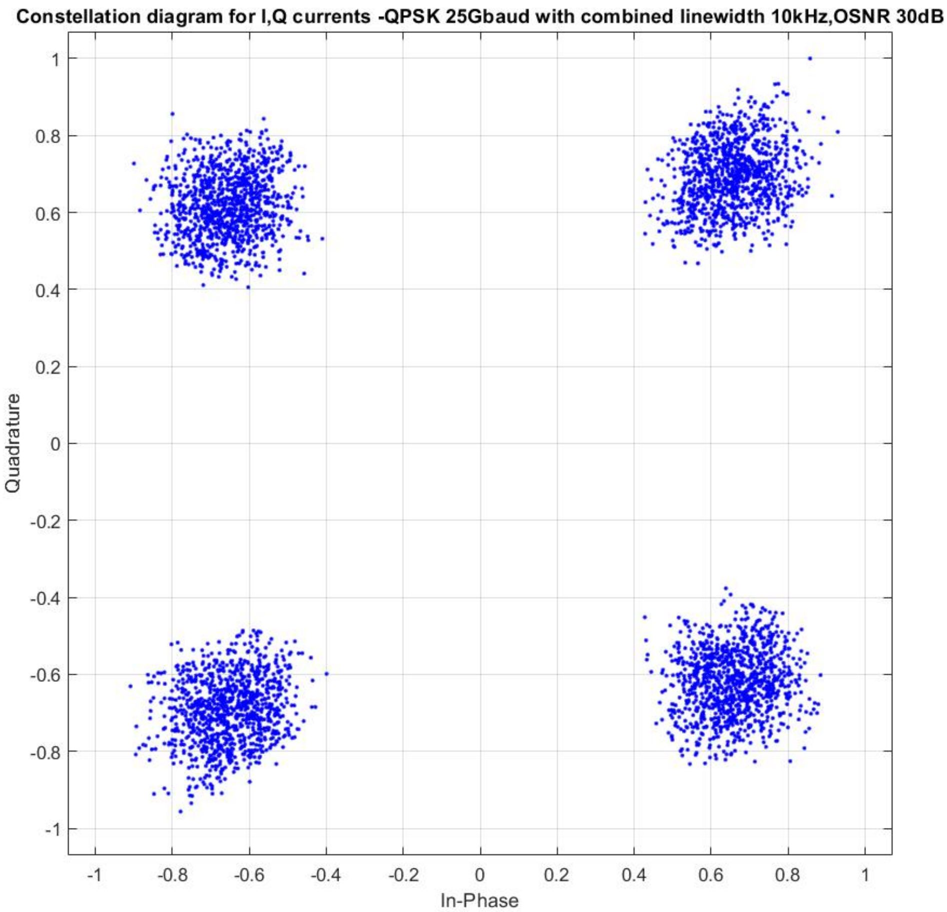

Figure 5: Constellation diagram for demodulated I,Q currents for QPSK 25Gbaud, combined LW 10kHz, with no freq. offset and OSNR= 30dB.

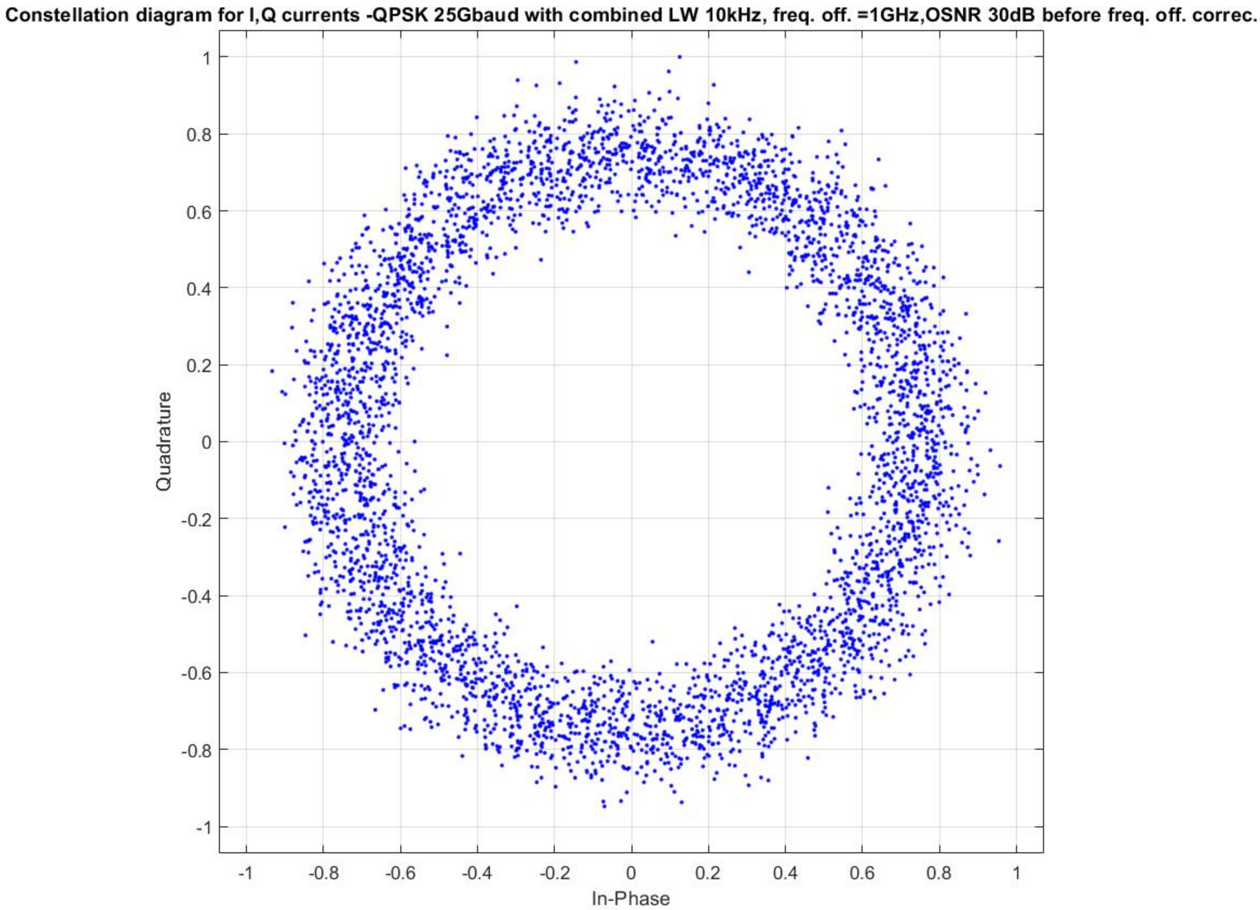

Figure 6: Constellation diagram before freq. offset correction for demodulated I,Q currents for QPSK 25Gbaud, combined LW 10kHz, with freq. offset 1GHz and OSNR= 30dB.

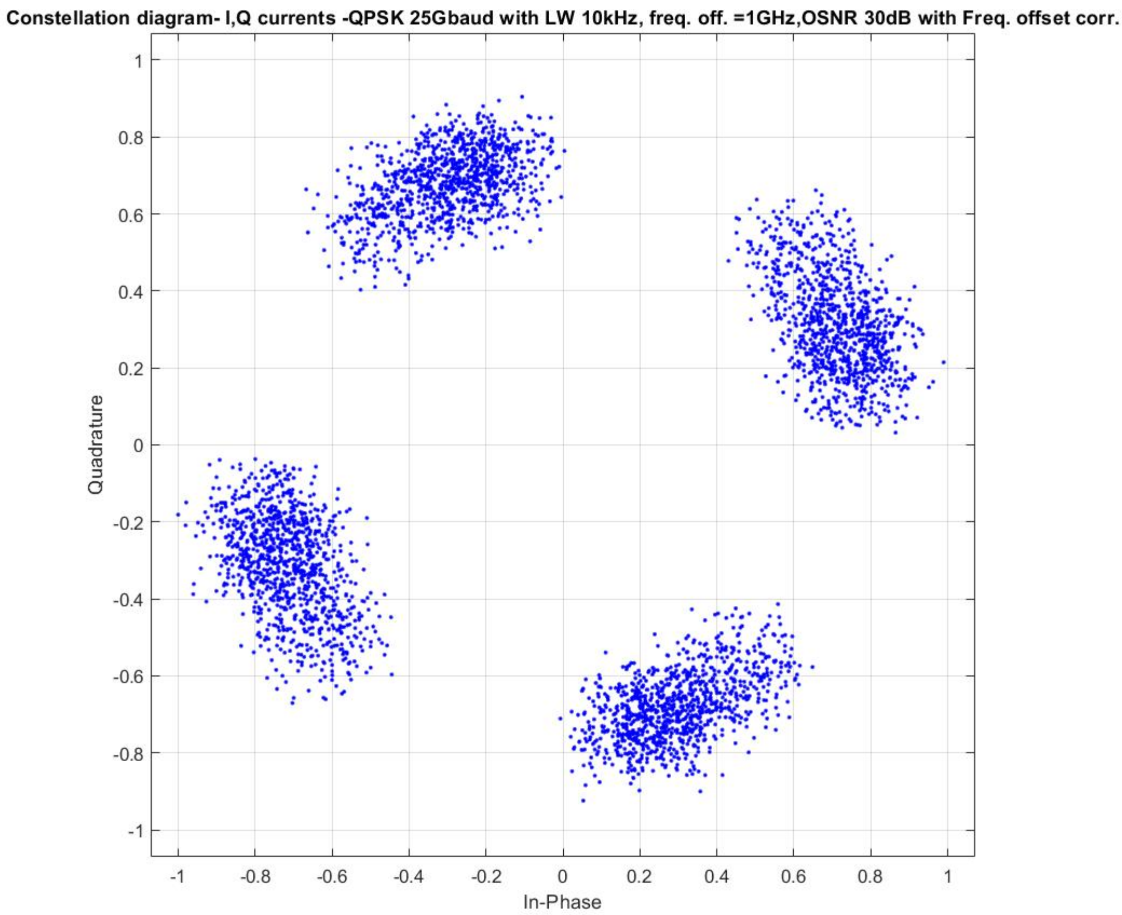

Figure 7: Constellation diagram after freq. offset correction for demodulated I,Q currents for QPSK 25Gbaud, combined LW 10kHz, with freq. offset 1GHz and OSNR= 30dB.

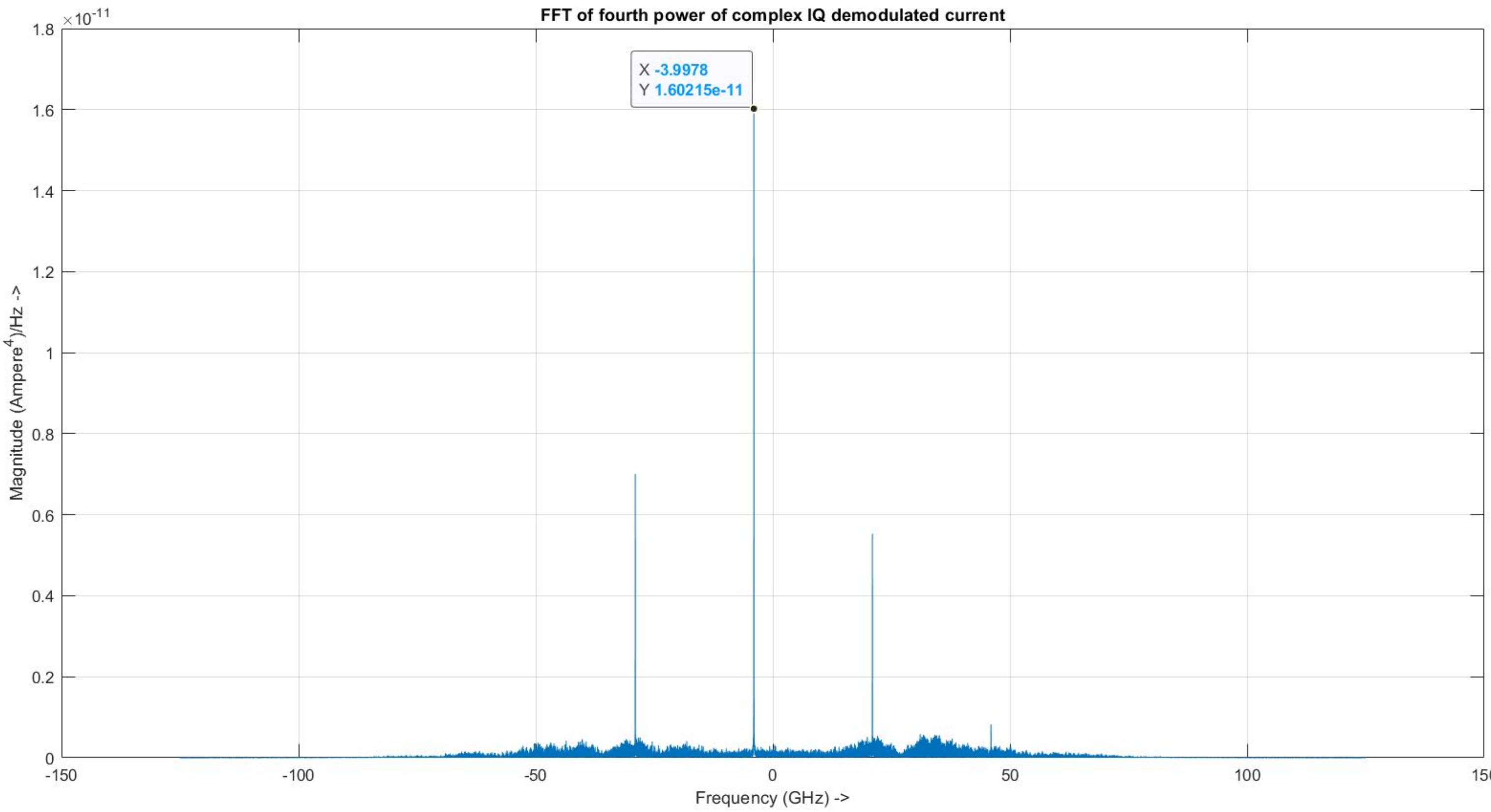

Figure 8: Plot of Magnitude of FFT of 4th power of IQ demod. currents to estimate freq. offset. The spike at $4 * f_{off}$ can be seen in the fig.

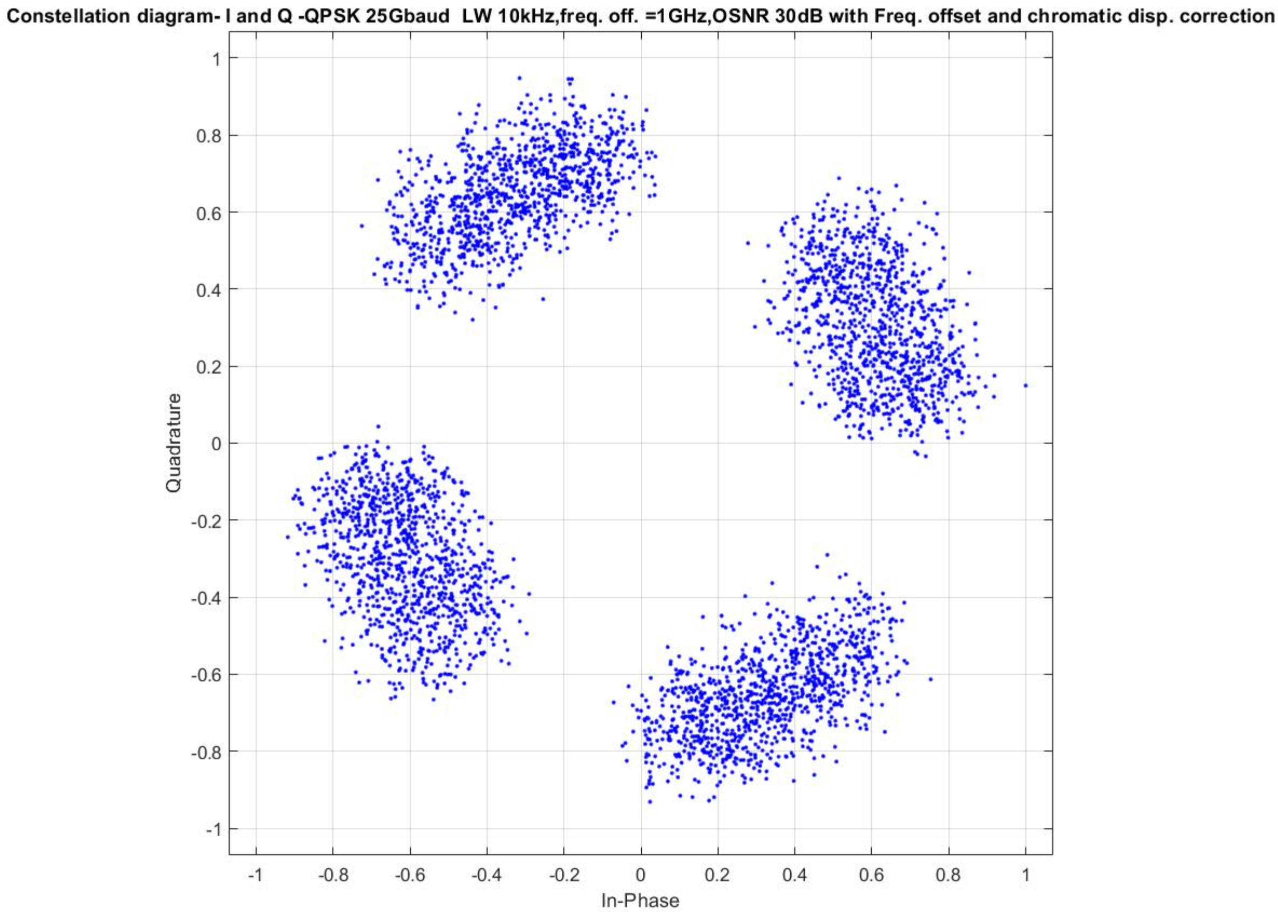

Figure 9: Constellation diagram after freq. offset, chromatic dispersion correction for demodulated I,Q currents for QPSK 25Gbaud, combined LW 10kHz, with freq. offset 1GHz and OSNR= 30dB passing through an 80km fiber with D = 17ps/nm-km.

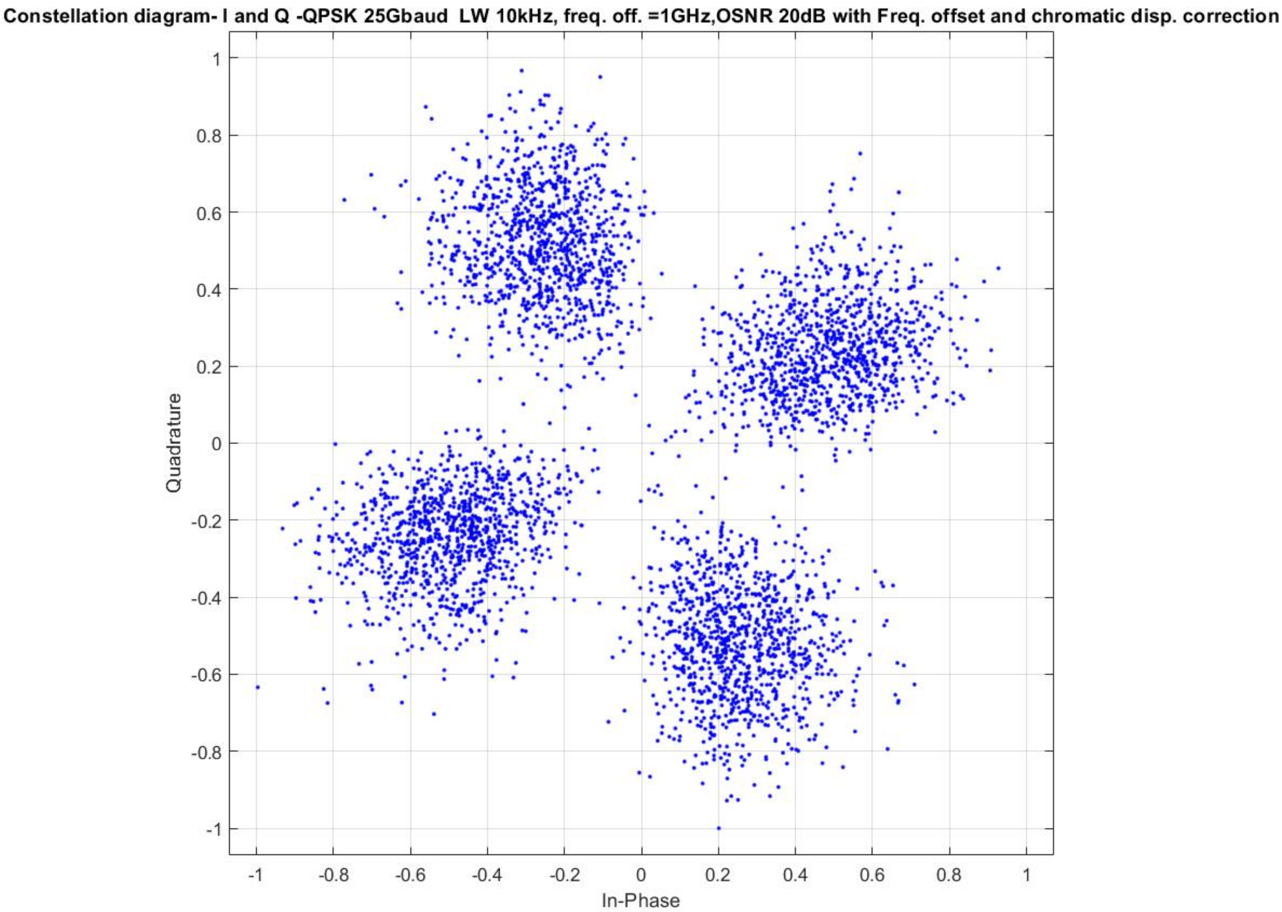

Figure 10: Constellation diagram after freq. offset, chromatic dispersion correction for demodulated I,Q currents for QPSK 25Gbaud, combined LW 10kHz, with freq. offset 1GHz and OSNR= 20dB passing through an 80km fiber with D = 17ps/nm-km.

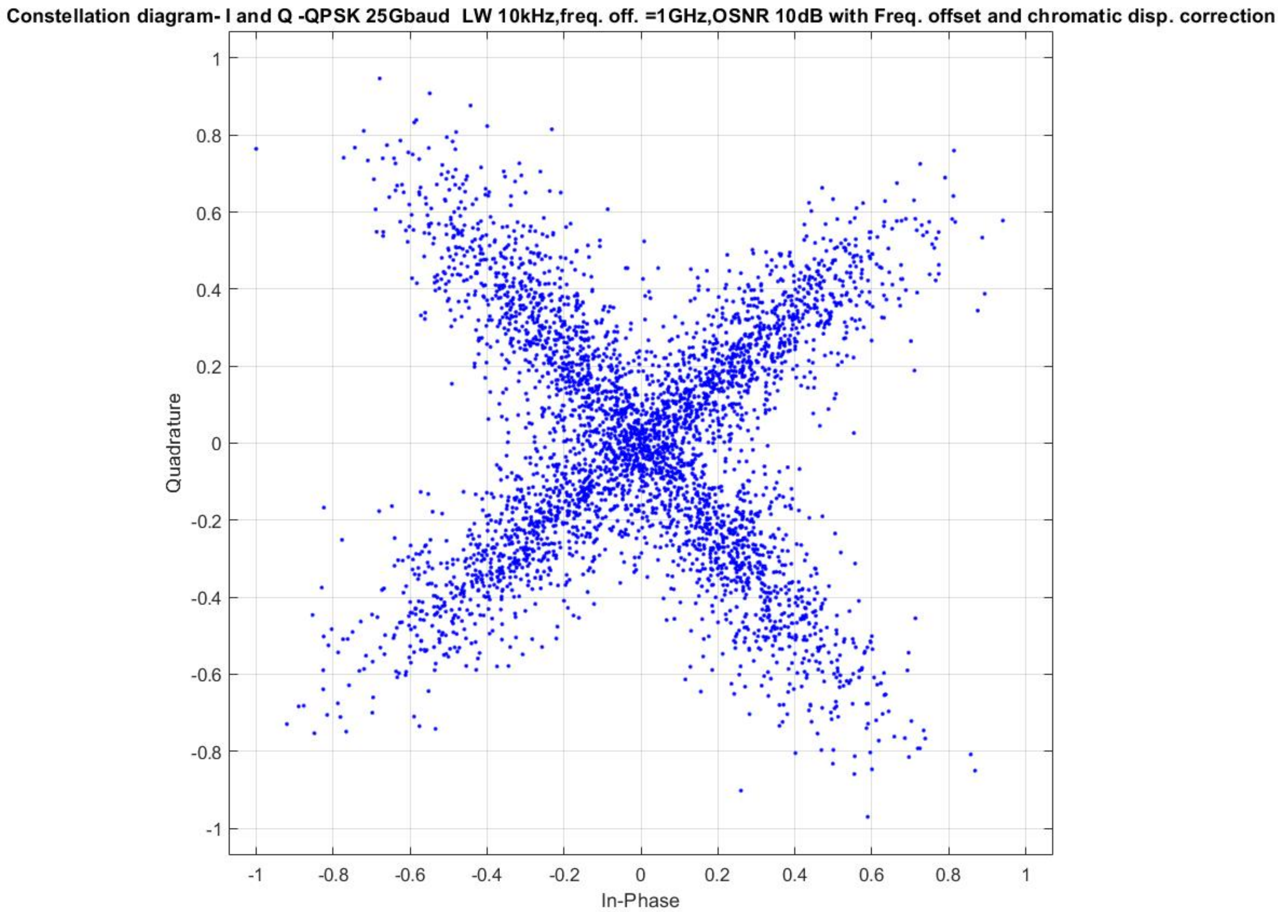

Figure 11: Constellation diagram after freq. offset, chromatic dispersion correction for demodulated I,Q currents for QPSK 25Gbaud, combined LW 10kHz, with freq. offset 1GHz and OSNR= 10dB passing through an 80km fiber with D = 17ps/nm-km.

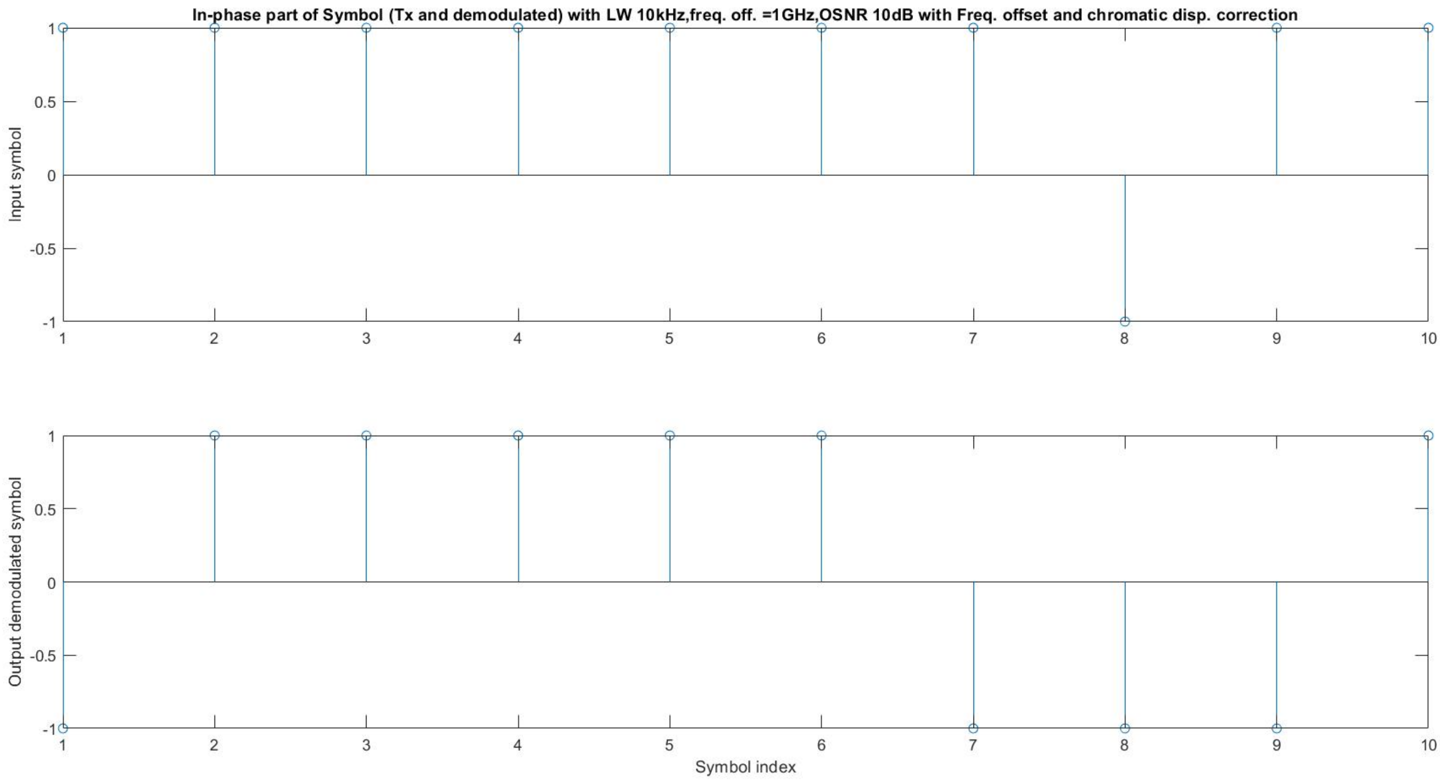

Figure 12: I-phase time domain waveform for demodulated symbols with QPSK 25Gbaud with freq. offset 1GHz , LW 10KHz, OSNR= 10dB after passing through fiber of length 80km (D = 17ps/nm-km) after all the compensations.

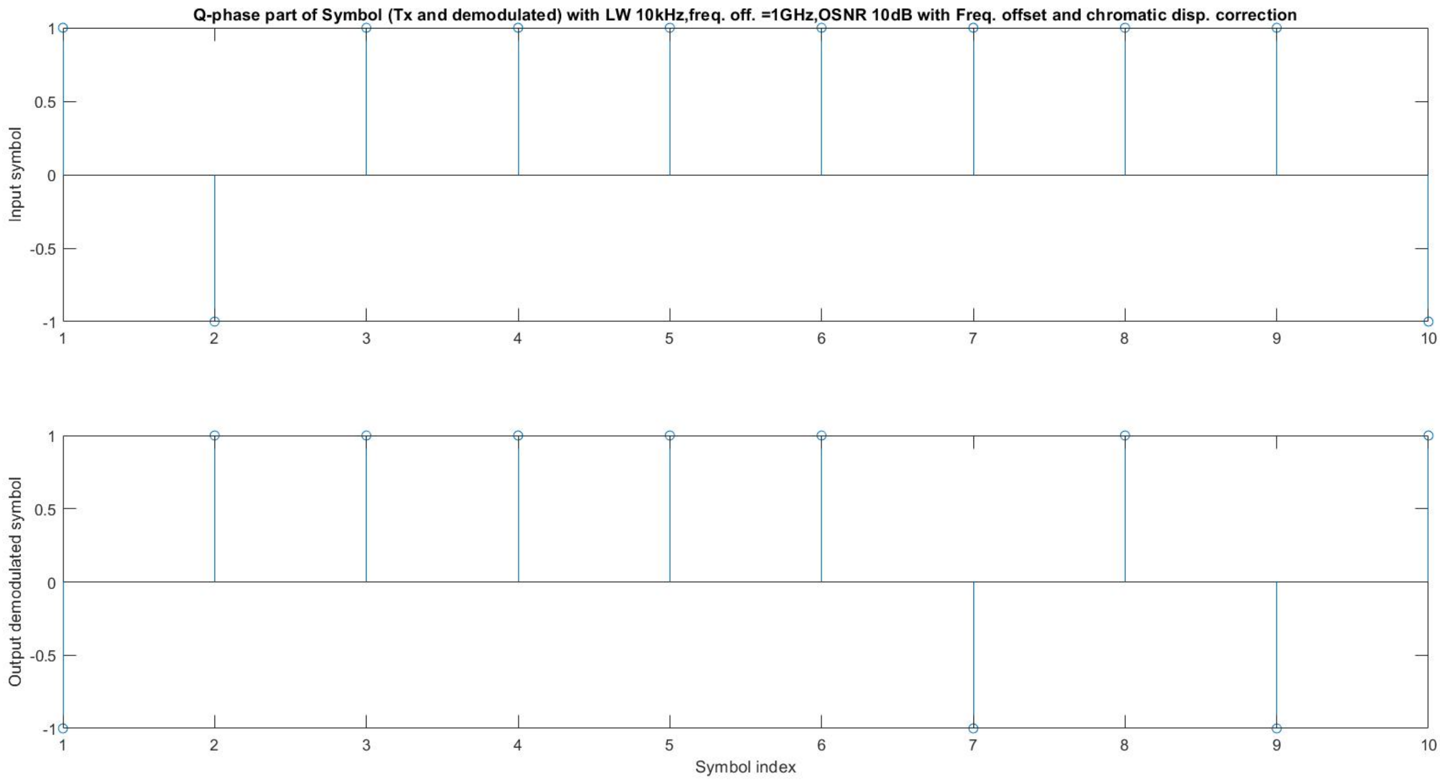

Figure 13: Q-phase time domain waveform for demodulated symbols with QPSK 25Gbaud with freq. offset 1GHz , LW 10KHz, OSNR= 10dB after passing through fiber of length 80km (D = 17ps/nm-km) after all the compensations.