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40G Overlay 10G DWDM Photonic Transmission Systems Using Advanced Modulation Formats

L.N. Binh

MONASH UNIVERSITY

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Le Nguyen Binh, BE(Hons), PhD (W.A.), C.Eng., MIEEE, MIET

Laboratory for Optical Communications and Applied Photonics,

Centre for Telecommunications and Information Engineering, Department of Electrical and Computer Systems Engineering,

Monash University, Clayton, Victoria 3168 AUSTRALIA

e-mail: le.nguyen.binh@eng.monash.edu.au

Summary

Advanced modulation techniques by manipulating the amplitude or phase of the optical carrier in either coherent or incoherent, via the different phase coding, fashions are attracting significant interests from the optical transmission systems and networks communities. Further more the signal formats such as return to zero (RZ), non-return-zero (NRZ) or carrier suppressed RZ or NRZ add also a new dimension to minimize the effects of nonlinearity on the pulse distortion. The combination of the modulation and pulse formats can be combined to achieve the best transmission performance.

This report presents:

- *An overview of the development of optical fiber communications in the last three decades and current spearheading directions of photonic transmission, the employment of advanced modulation formats.*
- *An fundamental understandings of the modulation formats, the structures of the transmitters and receivers. The experimental test bed is described.*
- *The experimental set up for transmission of modulation formatted signals, NRZ, RZ, CS-RZ, NRZ-DPSK, RZ-DPSK, CS_RZ DPSK etc over the optically amplified dispersion compensating channels. The dispersion tolerances of all modulation formats can be evaluated by using the transmission length of 1-4 km of SSMF and compared with back-to-back transmission.*
- *The system performance for all modulation formats of the transmission distance of 320 km and dispersion compensating set at 328 km equivalent length.*
- *The impact of the effects of the filtering of the photonic components such as the multiplexers and demultiplexers and optical filters at the receiver. Two types of optical filters: the thin film stack type and the array waveguide array grating.*
- *The measurement of the effects of either 10 G or 40 G on 40 G and 10 G channels respectively when transmitted simultaneously.*
- *Impacts of nonlinear effects on transmission performance of amplitude and phase difference modulation format.*

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1 INTRODUCTORY REMARKS

Increasing the data rates or basic bit rates is very critical for upgrading the transmission capacity of global telecommunication infrastructures. Over the last two decades we have been witnessed that the upgrading of the transmission rate from 2.5 Gb/s to 10 Gb/s and currently to 40 Gb/s then 160 Gb/s in the near future. The upgrading is essential to supply the information highways as demanded by the growing rate of the Internet. In certain routes of the telecommunication transmission sectors there needs to increase the transmission rates such that the upgraded channels can still be transmitted over the fiber channels without much altering the fundamental photonic structure of the system.

The long-haul transmission system has evolved, for 10 Gb/s and higher bit rates, with in-line photonic dispersion compensation and dispersion management to overcome the distortion of the lightwave signals. Simultaneously the attenuation of the signals via the transmission and compensating fibers, are optically equalized with in-line discrete and distributed optical amplification components such as the rare-earth doped fiber amplifiers[1], Raman and parametric fiber amplifiers [2] . Figure 1 shows the schematic diagram of a long haul transmission system in which lightwaves channels are multiplexed and transmitted in both directions. In-line optical amplification and dispersion compensation sub-systems are also included.

The next step of upgrading the transmission network would be logical if 40 Gb/s basic rates are employed as several basic electronic and photonic components are now matured and stable for field deployment. This rate can be employed using the multi-level modulation to increase the rate to 160 Gb/s or higher. Once the rate is increased but required minimum changes of photonic and electronic components of the transmission systems, the modulation technique should be developed in order to minimize the signal spectra so as to transmit the information channels without severe distortion[3].

The research works reported here present a number of advanced modulation techniques and the demonstration of the modulation, receiving and propagation of photonic signals over the transmission systems. The formats of non-return to zero (NRZ), return-to-zero (RZ) and carrier-suppressed (CS) NRZ and CS-RZ are used and associated with modulation formats such as amplitude and phase shift keying which are well-known in digital communication techniques. The challenge is that all these modulation formats are implemented in photonic domain.

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[1] R. Giles and T. Li, " Optical Amplifiers Transform Long Distance Lightwave telecommunications, Proc. IEEE, vol. 84, No. 6, 1996, pp. 870-883.

[2] R.A. Baumgartner and R.L. Byer "Optical Parametric Amplification" IEEE J. Quantum Electronics, Vol. QE-15, No. 6, June 1979, pp432-443.

[3] See papers presented and included in the Proceedings of the IEEE Workshop on Advanced Modulation Formats, San Francisco, USA Feb 2004.

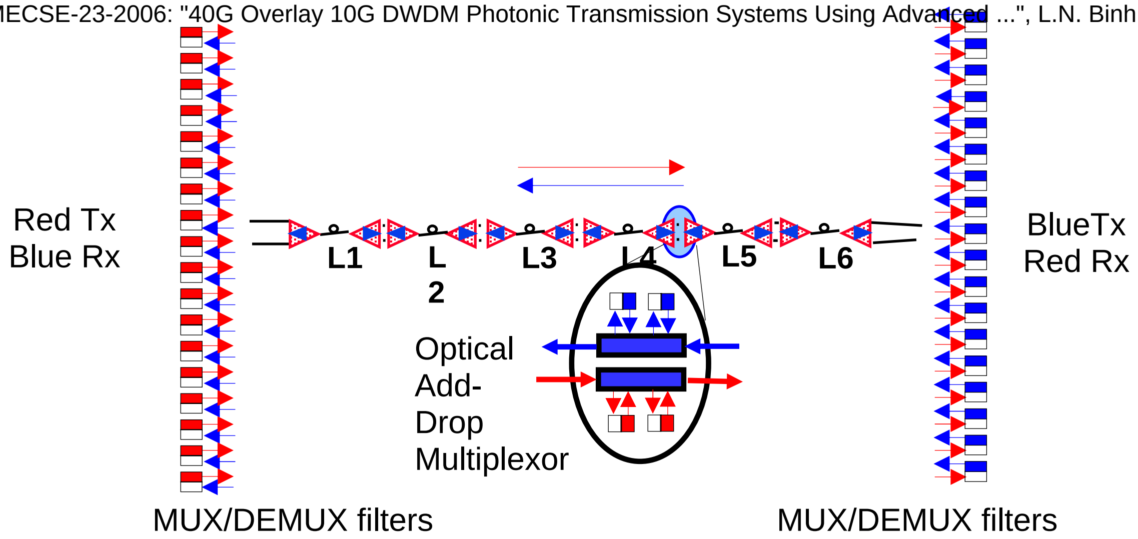

Figure 1 Schematic diagram of a long haul photonic transmission system. L = length of the transmission fiber, dispersion compensating fibers (DCF) hidden in the optical amplifiers denoted. Two optical amplifiers are used one as optical pre-amp and the other booster amplifiers. Photonic muxes and demuxes are array waveguide (AWG)

The report is thus organized as follows:

Section 2 gives an overview of the development of optical fiber communications in the last three decades and current spearheading directions of photonic transmission, the employment of advanced modulation formats is given. Section 3 gives the fundamental understandings of the modulation formats, the structures of the transmitters and receivers. The experimental test bed is described. Section 4 outlines the experimental set up for transmission of modulation formatted signals, NRZ, RZ, CS-RZ, NRZ-DPSK, RZ-DPSK, CS_RZ DPSK etc over the optically amplified dispersion compensating channels. Section 4 investigates the dispersion tolerances of all modulation formats, the transmission length of 1-4 km of SSMF is used for this purpose as compared with back-to-back transmission. Section 5 gives the system performance for all modulation formats of the transmission distance of 320 km and dispersion compensating set at 328 km equivalent length. Section 6 considers the effects of the filtering of the photonic components such as the mu and demux and optical filters at the receiver. Two types of optical filters: the thin film stack type and the array waveguide array grating. Section 7 then measures the effects of either 10 G or 40 G on 40 G and 10 G channels respectively when they are transmitted simultaneously.

The proposal of guiding of lightwaves in dielectric optical multi-layers[4] has started the intense search for low loss optical waveguides. Then for practical implementation, the circular waveguides, the optical fibers, in the 1970s have their attenuation factors reduced down to an acceptable and then reaching the theoretical limits of Raleigh scattering intrinsic loss of silica fiber. Single mode optical fibers[5] [6]were then developed in the late 1970 and the extensively employed in optical transmission system in the 1980. The bit rate at the time reaches to 140 Mb/s and then 565 Mb/s using intensity modulation and direct detection with in the pulse code modulation techniques for digital communications. The repeater distance reaches a maximum 40 Km with single mode optical fibers with a transmission loss of about 0.2 dB/km in the 1550nm spectral window. This limitation of the repeaterless distance is due to principal factors: (i) the optical loss and (ii) the dispersion of the single mode due to the spectral purity of the transmitted lightwave pulses.

System deployment was also extended further with a repeaterless span reaching 60 km with the applications of modulation techniques such as the amplitude and phase coherent communication method. Modulation methods such as the amplitude shift keying (ASK), phase shift keying (PSK) and differential PSK (DPSK), Continuous phase frequency shift keying (CPFSK) in association with the homodyne and heterodyne detection schemes. These modulation techniques offer a 3dB or 6dB improvement in the receiver sensitivity[7].

These two hurdles have been overcome by the significant development and invention of (i) in-line optical amplification[8] and (ii) the single mode DFB lasers and (iii) the dispersion management by dispersion compensating fibers and other discrete photonic components such the fiber Bragg gratings. AT the same time we have also witnessed the tremendous development of the external modulators reaching several 10s of GHz in the modulating 3dB bandwidth and photonic components such the array waveguide gratings for multiplexing and demultiplexing lightwaves channels[9] [10].

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[4] K.C. Kao and G.A. Hockham, Proc. IEEE, vol. 113, 1966, pp. 1151. D. Marcuse "Theory of Dielectric Optical Waveguides", 2nd Ed., Academic Press, San Diego, 1991.
[5] A.W. Snyder " Understanding Single Mode Optical Fibers", Proc IEEE, ; M. Monerie ,IEEE J. Quantum Elect., vol. 18, 1082, pp.535; Elect Lett., vol. 18, 1982 , pp.642.
[6] L.B. Jeunhomme, " Single mode fiber optics", Marcel Dekker, N.Y. 1990.
[7] See chapters presented in S. Shamida, Ed. "Coherent Lightwave Communications Technology", Chapman and Hall London 1995.
[8] P.C. Becker, N.A. Olsson and J.R. Simpson "Erbium-doped Fibers Amplifiers", Academic Press, San Diego, 1999.
[9] A.P. Agrawal "Lightwave Technology" J. Wiley, N.J., 2004
[10] Proceeding of the IEEE workshop on Advanced Modulation Formats, San Francisco CA 2004. Section **FC Devices and Advanced Formats I ": "**FC1 Integrated Devices for Advanced Modulation Formats", "FC2 Single Sideband Demonstration using a Four Phase-Modulators Structure", "FC3 Performance of AMI-RZ and DCS-RZ Single-Sideband Signals in an 80% Spectral-Efficient
UDWDM Ultra-Long-Haul Transmission System", " FC4 Optical 8-DPSK and Receiver with Direct Detection and Multilevel Electrical Signals" Section **FD Devices and Advanced Formats II : "** FD1 Partial Response Modulation - From Concept to Implementation .

Modulation techniques are now reconsidered for ultra-high speed and high capacity photonic transmission systems[12] including (i) DPSK and DQPSK[13] (ii) Filtered modulation formats[14] (iii) CPFSK[15] [16]. These modulation format signals are detected, after the propagation and amplification, using the direct detection with a single detector or balanced detectors optical receiving structures. Thus the differential coding is normally preferred as the coherence of the lightwaves is not very critical as compared with the coherent detection. Besides the linewidth of the DFB lasers are narrow enough for these modulation schemes[17].

Therefore the principal objectives of the report are:

- To give an overview of the advanced modulation formats and associated coding techniques for long haul and high speed photonic transmission system;
- To describe in details the transmitting and receiving subsystems as well as the fiber propagation and dispersion compensating media and the optical amplifiers.
- To present the experimental set-up, measurement techniques and system performances
- To identify spearheading research and development directions and make some concluding remarks.

3 PHOTONIC TRANSMISSION TEST-BEDS

FD2 Performance of Maximum Likelihood Sequence Estimation with Different Modulation Formats", "FD3 Advantages of Frequency Shift Keying in 10-Gb/s Systems".

[11] See Proceeding of the IEEE workshop on Advanced Modulation Formats, San Francisco CA 2004. Section **ThD Networks and Systems "**ThD1 Performance of Advanced Modulation Formats in Spectrally Efficient Optical Networks", "ThD2 40-Gb/s Upgradability of 10-Gb/s Systems**"; section "FA Modulation Formats and Fiber Nonlinearities": "**FA1 Waveform Degradation by SPM in Carrier-Suppressed Optical SSB Transmission with NRZ and RZ Formats; " FA2 Application of Modulation Codes to Ghost Pulse Suppression.
FA3 Impact of Optical Modulation Formats on SPM-Induced Limitation in Dispersion-Managed Optical Systems . A Simplified Modeling; Section

[12] Proceeding of the IEEE workshop on Advanced Modulation Formats, San Francisco CA 2004. Section on **Ultra Long Haul Transmission: "** ThA1 Chirped Return-to-Zero Formats for Ultra Long-Haul Fiber Communications" , "ThA2 Transmission of RZ-DQPSK over 6500 km with 0.66 bit/s/Hz Spectral Efficiency"

[13] Proceeding of the IEEE workshop on Advanced Modulation Formats, San Francisco CA 2004.Section **ThB Differential Quadrature Phase Shift Keying : "**ThB1 Highly Spectral Efficient Transmission with CSRZ-DQPSK"; "ThB2 Comparison of Different DQPSK Transmitters with NRZ and RZ Impulse Shaping", "ThB3 Comparison of Six Different RZ-DQPSK Transmitter Set-Ups Regarding their Tolerance towards Fiber impairments in 8x40Gb/s WDM Systems" , "ThB4 Generation of Arbitrary Quadrature-Amplitude Modulated Signals using a Single Dual-Drive Modulator"; Section **ThC Differential Binary Phase Shift Keying : "**ThC1 Differential Phase Shift Keying for 10-Gb/s and 40-Gb/s Systems" , "ThC2 BER Depending Tolerances of DPSK Balanced Receiver at 43Gb/s", "ThC3 Suppression of Stimulated Brillouin Scattering by using RZ-DPSK Format in Long-Span Unrepeatered Transmission System" , "ThC4 Performance of DPSK Signals with Nonlinear Phase Noise for Systems with Small Number of Fiber Spans".

[14] Proceeding of the IEEE workshop on Advanced Modulation Formats, San Francisco CA 2004.Section **on "FB Optically Filtered Modulation Formats" : "**FB1 Optically Filtered Modulation Formats and Their Transmission Performance" , "FB2 Spectral Reshaping by Narrow Optical Filtering toward High Information Spectral Density 40Gbit/s Transmission", "FB3 Spectral Mode Splitting - Concepts and Applications"

[15] S.P. Majumder and M.S. Alam, "Performance Analysis and simulation of optical direct detection FSK and DPSK systems", IEEE Publication.

[16] M.M. Matalgah, and R.M. Radaydeh," Hybrid Frequency-Polarization Shift-Keying Modulation for Optical Transmission", J. LIGHTW.. TECH., VOL. 23, NO.. 3, March 2005, pp1152-1163.

[17] S. Savory and A. Hadjifotiou, "Laser Linewidth Requirements for Optical DQPSK Systems", IEEE Photonic Tech Lett., Vol. 16, No.. 3, March 2004, pp. 930-933.

Figure 2 shows the schematic diagram of a photonic communications employing advanced modulation formats. The transmitters would consist of a narrow linewidth laser source to generate lightwaves of wavelength conformed to the ITU grid. These lightwaves are combined and then modulated. This form is for laboratory experiments only. In practice each laser source would be modulated by an external modulation sub-system. Figure 3 shows the structure of a 40G transmitter in which two LiNbO3 optical interferometric modulators[18] (MZIM) are used. The MZIM can bee a single or dual drive type. We will demonstrate in a later section the formulation of these devices for generation of novel phase shift keying lightwave signals.

The first MZIM is used to generate the periodic pulse trains or pulse carver. This is useful to generate the RZ format and suppression of the lightwave carriers if necessary. Thus if a RZ and CS is required then the MZIM is biased at the minimum transmission point, that is there are two lightwave carriers both are shifted by pi phase shift with respect to each other, hence suppression of the carrier as seen by the fiber, the transmission media. This is very important when the dispersion compensating fibers are used whose cores are much smaller than that of the transmission fibers, hence sensitive to nonlinear induced phase effects. A structure of a packaged MZIM and its operating characteristics are given in Figure 4. The second MZIM is used to switch on and off the pulse train and hence generate a random data sequence with or without the carrier suppression. In the case that a NRZ format is required, then the pulse carver is biased at the maximum transmission point. On the other hand the MZIM can be biased at the quadrature point ($V_{pi/2}$) so as to preserve the linearity f the modulator.

The transmission is obvious and consists of the ingle fibers of either the standard SMF ITU-G.652 or non-zero dispersion shifted fibers (NZ-DSF) ITU – G.655. The dispersion and distortion of the lightwave signals are usually compensated by dispersion compensating fibers (DCF). As indicated in Figure 2 the DCFs are normally accompanied by two discrete optical amplifiers, the Erbium-doped optical amplifiers (EDFA), one is for pre-amplification to compensate the attenuation of the transmission span, the other is a booster amplifier for boosting the optical power of the channels to an acceptable, below the nonlinear limit level.

The optical amplification can be implemented with in-line EDFAs or discrete and distributed Raman amplifiers. We assume in this work that the amplifiers are operating in the saturation mode.

The receiving sub-system would take on: (i) single detector direct detection optical receiver (ii) the balanced detector receiving structure. For the later case the structure is well known that is it consists of single photo-detector followed by electronic pre-amplifier and a main amplifier and an equalizer depending on whether the

[18] LN Binh "Lithium Niobate optical modulators", Int. Conf on Material and Technology Symposium M: Material and Devices, Singapore July 2005; Journal of Crystal Growth, January 2006, to appear.

amplifier is a trans-impedance of a high-impedance structure. The structure of a balanced optical receiver is shown in Figure 5. Figure 6 shows a pair of parallel DPSK balanced receiver with pi/4 phase shifting in each arm to form a DQPSK balanced receiver structure. Although this structure is not experimentally demonstrated, this type of receiver is employed in our SIMULINK model and is given here for future reference. A photonic Mach-Zehnder delay interferometer is used to delay one bit or two bit periods depending whether the PSK modulation is two or multi-level. Hence this interferometer acts as an optical phase comparator. Due to some fabrication imperfection the delay path would be tuned by a thermal electrode and driven y a DC voltage.

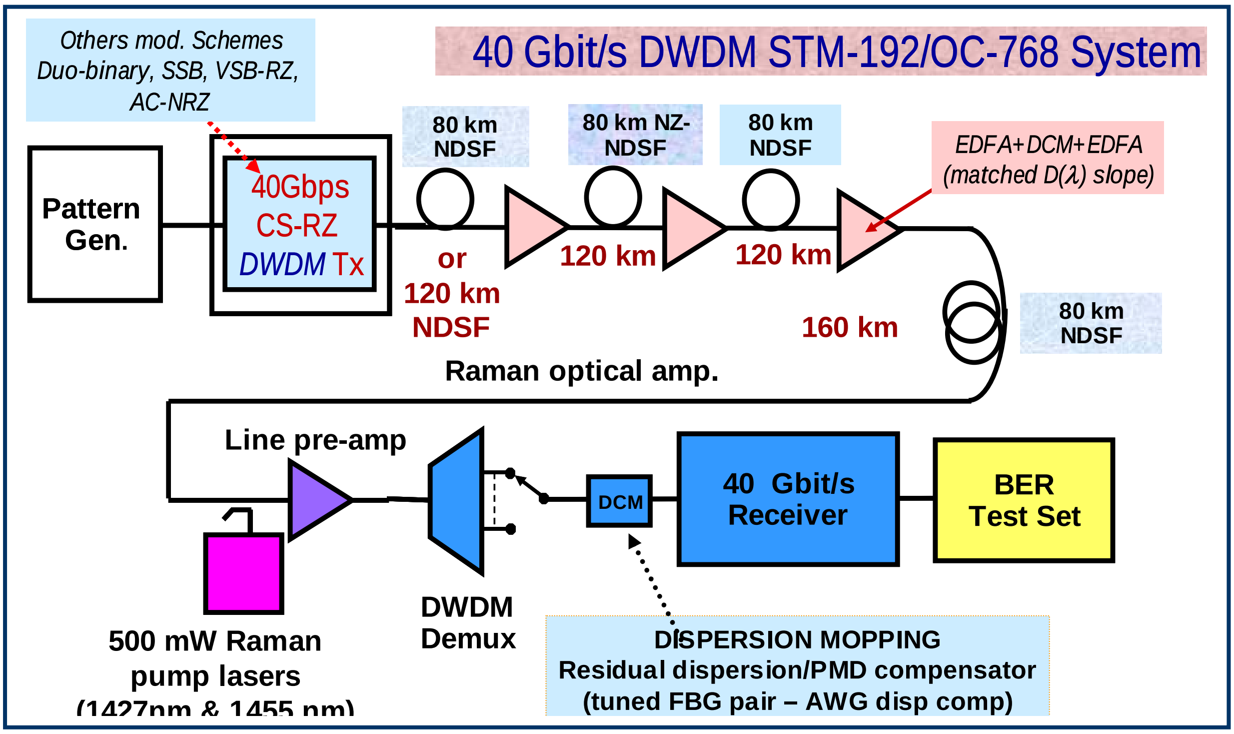


Figure 2 Schematic diagram of a 40G DWDM photonic communication system employing advanced modulation formats.

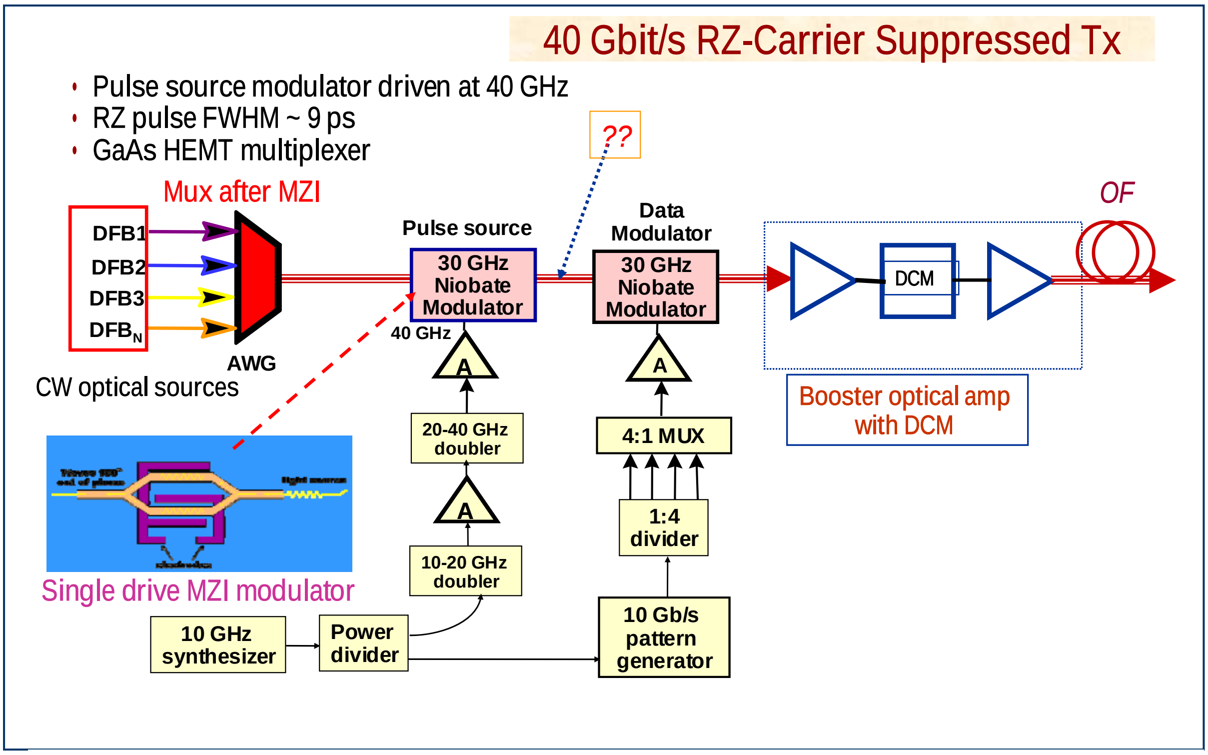


Figure 3 Structure of external modulation for generation of advanced modulation format lightwave signals.

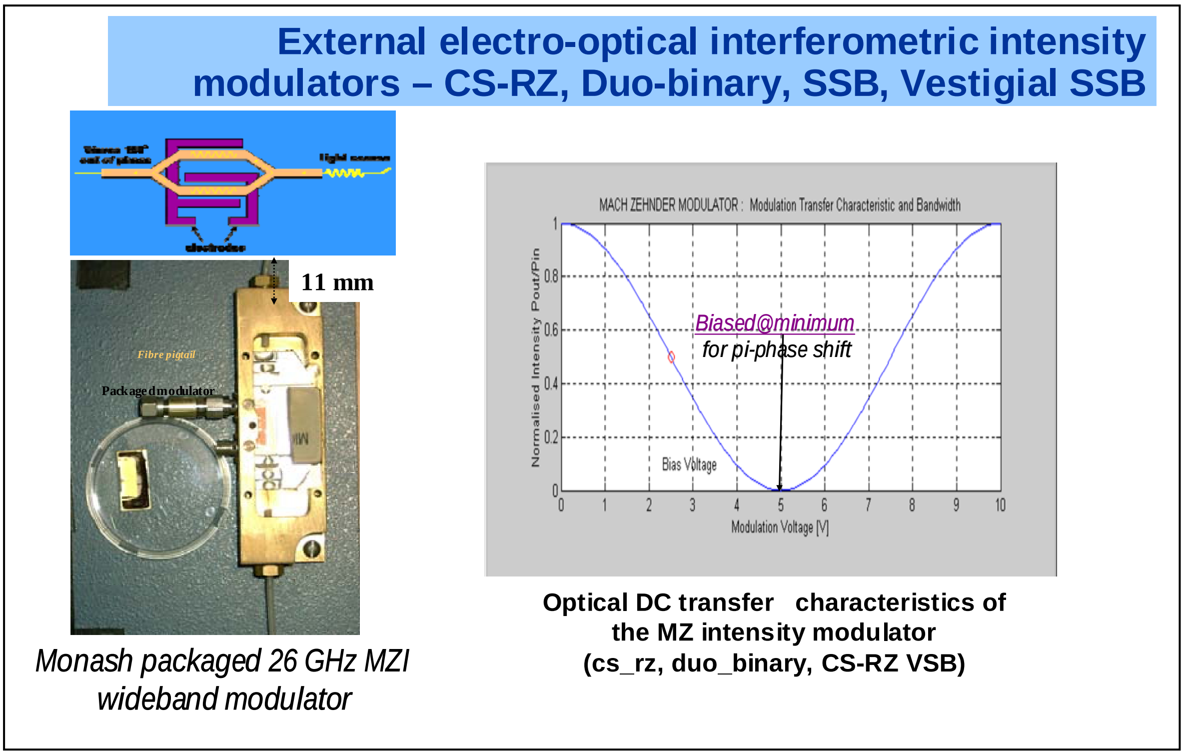


Figure 4 MZIM structure, packaged device and operating characteristics – the transfer curve.

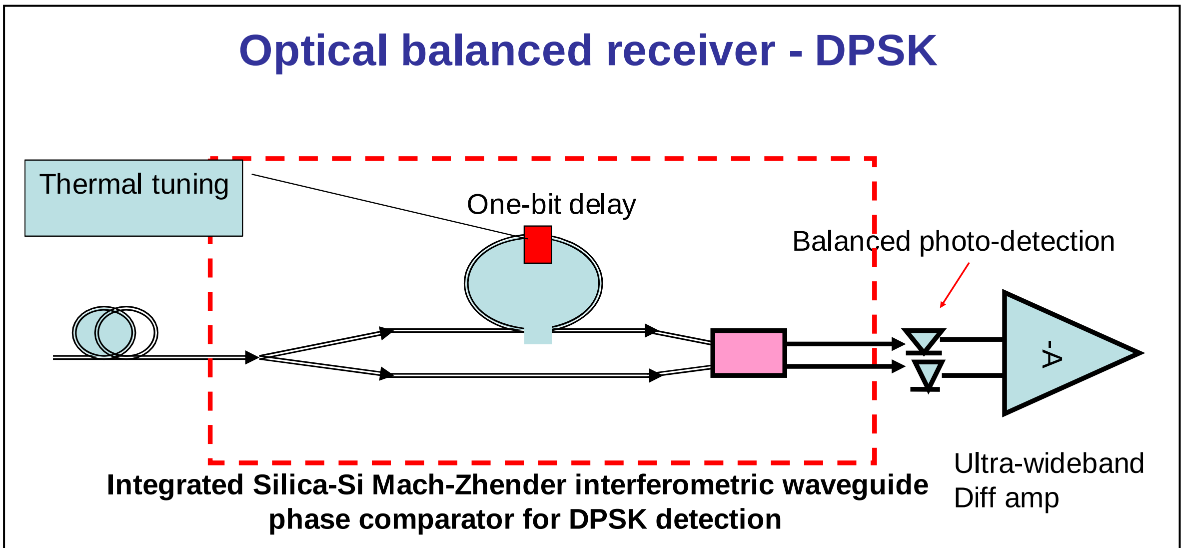


Figure 5 Structure of a balanced optical receiver consisting of a photonic Mach Zehnder delay interferometer acting as a phase comparator and detected by two photodetectors connected back to back then a single input electronic pre-amplifier or fed to a differential electronic amplifier.

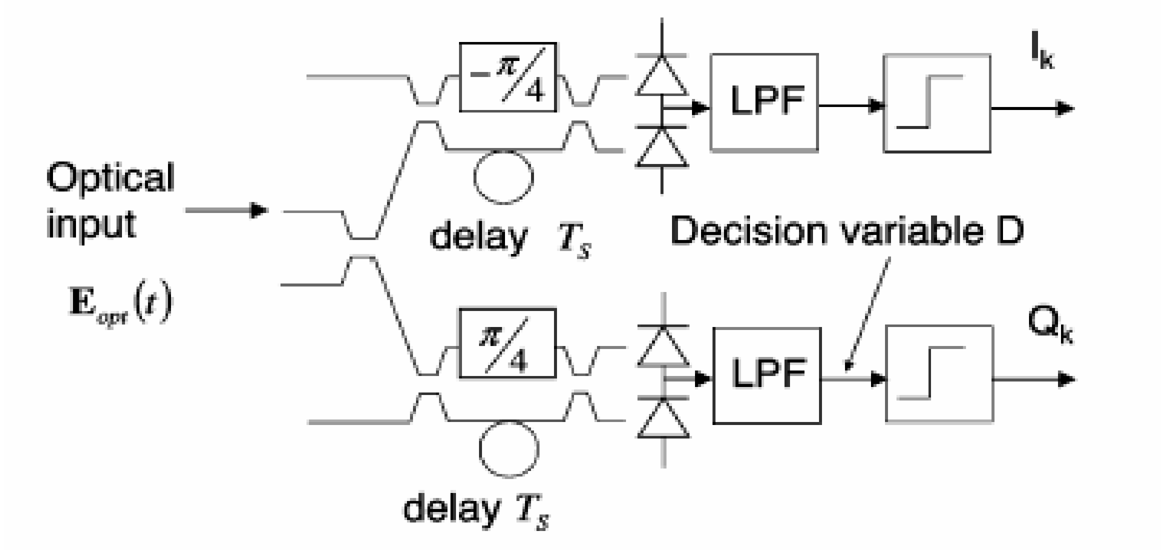


Figure 6 Balanced receiver structure for phase difference modulation format. Note it is a parallel structure of two DPSK balanced receiver with additional phase shifting of pi/4

4 MODULATION FORMATS AND TRANSMISSION SYSTEMS

Our experimental set up is shown in Figure 7. The photonic components are tabulated in *Table 1*. The set up is used to investigate the back-to-back transmission ensuring an error free transmission prior to conduct experiments of the transmission over optical fibers. The length of the fiber is varied between 1 to 4 km length of Standard SMF (SSMF) with a dispersion factor of 17 ps/(nm.km). The transmitter can be set for different modulation formats such as RZ-ASK[19], NRZ-ASK, CS-RZ ASK, NRZ-DPSK, RZ-DPSK and CS-RZ DPSK formats.

[19] The term amplitude shift keying (ASK) is used to distinguish it with the ON-OFF Keying (OOK) which usually used to indicate the intensity modulation direct detection scheme. While non-coherent is still used in this work the term ASK is used as the linewidth of the laser source is required to be narrow to minimize the dispersion effect.

Photonic sub-systems	Description	Remarks
Laser source	Tunable laser set at 1551.72 nm for centred wavelength (lamda 5) and 1548.51 nm for lamda 1 – 1560 nm for lamda 16.	
Multiplexer and demultiplexer	NEL-AWG = frequency spacing 100G 3 dB BW of 0.5 nm. Circulating property so spectrum would appear cyclic (note the spectrum) - note of the channel input and out put – e.g input at port 5 of Lamda 5 then output at port 8. Input Lamda 1 at port 1 then output at port 8 (Lamda 1). This demux is a NEL array waveguide product. The AWG has a circulant property and thus can be used as cascade filters.	
Photonic transmitters (Tx) for different modulation format generation	The Tx can be set at CSRZ-DPSK or RZ- DPSK, no DQPSK format facility is available.	A pair of external modulators of MZIM single drive . SHF model 5003
Clock Recovery Module	Clock recovery using 6 dB splitter	SHF module
Optical receiver	Balanced receiver used when DPSK format is used. Otherwise Discovery Semiconductor Lab Buddy DS-10H is employed. A MZD inteferometer with thermal tuning of the delay path included.	Tuning of MZ phase decoder at the Rx is necessary when lamda channels are changed
In-line optical amplifiers	EDFA 1 driven at 178 mW pump power (saturation mode). EDFA2 driven at 197 mW (saturation mode).	All EDFAs are driven in the saturation mode
Other components	Optical attenuator is used to vary the optical power input at the receiver for setting the operating condition in the linear or nonlinear region. About 5 dBm is required to set the onset level of nonlinear operation. Optical attenuator is inserted in front of the receiver to ensure no damage of the photodetector.	
PRBS	Bit pattern generator SHF-BPG 44	
Error Analyser	SHF model EA-44	
“cheated clock”	Direct synchronization of the sync signals to the error analyzer. If no “ cheated clock” is indicated then a clock recovery moddule is used for synchronization and sampling of the received data sequence.	

Table 1 Photonic components and operating characteristics

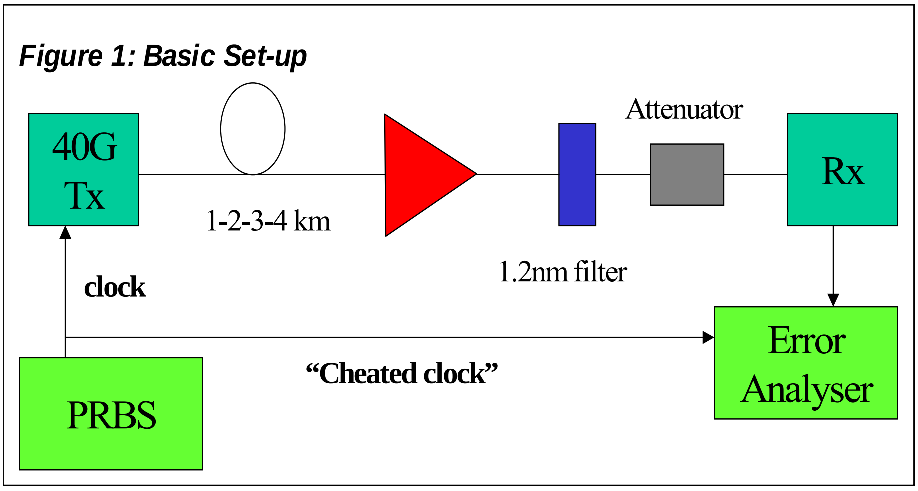


Figure 7 Schematic diagram of the experimental set-up for measurement of the dispersion tolerance of modulation formats.

4.1 Optical Spectra of Modulation Format Lightwave Signals

The optical spectra are captured on the Photonetics optical spectrum analyzer (OSA) via an EDFA and the 1.2nm filter. Figure 8 and Figure 9 show the spectra of the channels under different modulation formats. **Error! Reference source not found.** to Figure 11 display these spectra at the output of optical filters. Clearly the CS-RZ format shows a moderate optical spectra with most of the signal energy contained in the signal. Unlike that of the NRZ and RZ formats there are carrier energy about 3- 6 dB above the signal level. Thus the CS-RZ would offer better performance in term of the BER and receiver sensitivity. Furthermore if the phase modulation is associated with this CS-RZ formats, the constant amplitude of the scheme would offer another dimension of improvement of the receiver sensitivity and more tolerant to the dispersion.

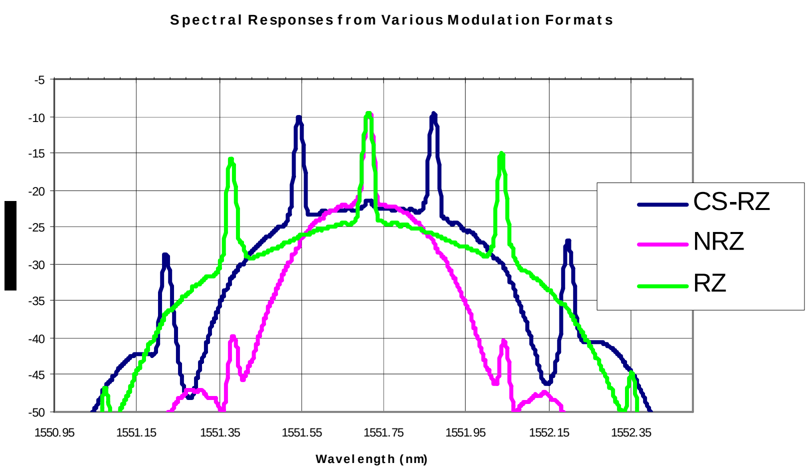


Figure 8 Optical spectra of CS-RZ ASK, NRZ-ASK and RZ-ASK – base rate 40 G

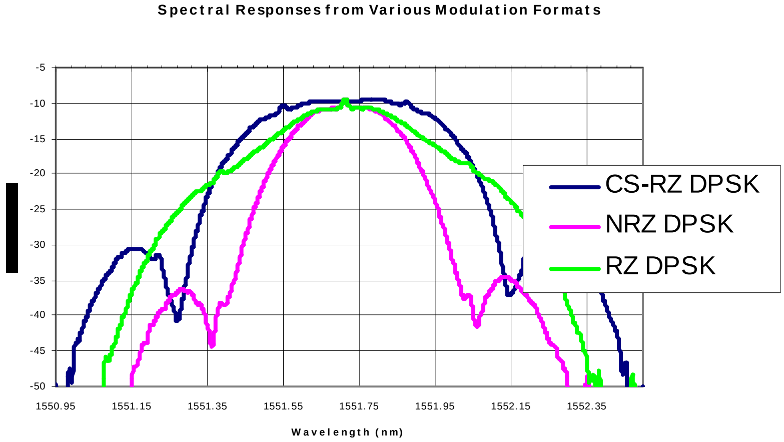
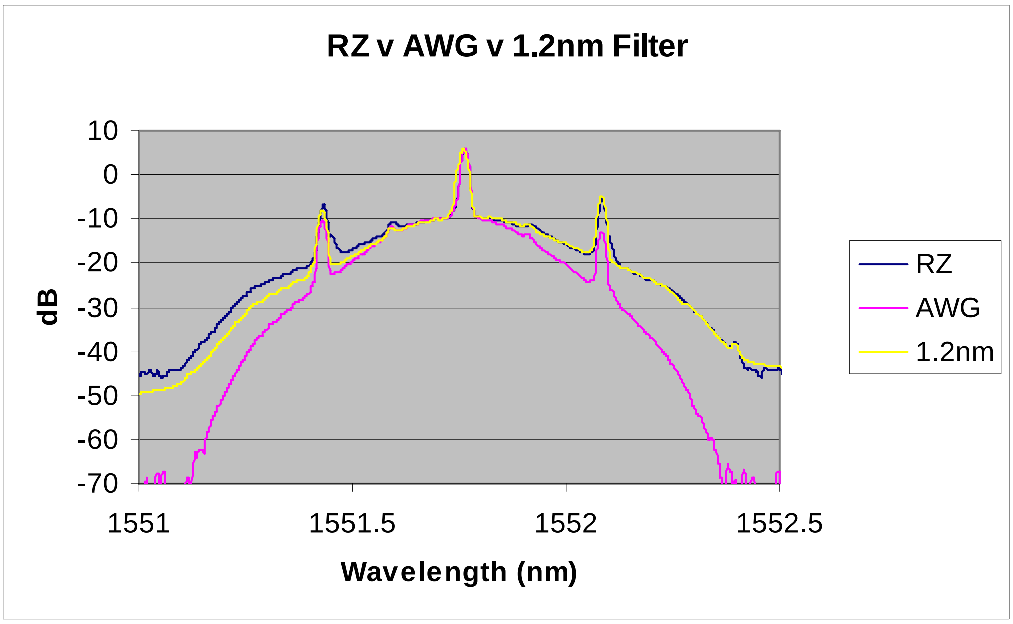


Figure 9 Optical spectra of CS-RZ DPSK, NRZ DPSK and Rz DPSK – base rate 40 G

Spectra taken on Photonetics OSA of standard RZ modulation (a) exiting Tx (b) via 0.5nm AWG, (c) via 1.2nm tunable filter :



Error! Reference source not found. *shows the optical spectra of the lightwave signals of different modulation formats after passing through the AWG multiplexer or deemultiplexer. The AWG noticeably narrow spectrum would reduce the sidelobe power spectral density. Although the 1.2nm filter is slightly off its center centre (hence the unbalanced look). It is observe that the filtered spectrum is unaffected. For the case of the AWG its passband is narrow (0.5 nm passband). We observe some reduction of the spectra and hence signal distortion would be expected.*

As above for NRZ-ASK and CS-RZ- ASK the 1.2nm filter does not significantly affect the lightwave signal spectra. However as discussed for the AWG, the spectra sidelobes are reduced. Figure 10 and Figure 11 show the optical spectra of the modulation formatted signals at the output of the optical filters.

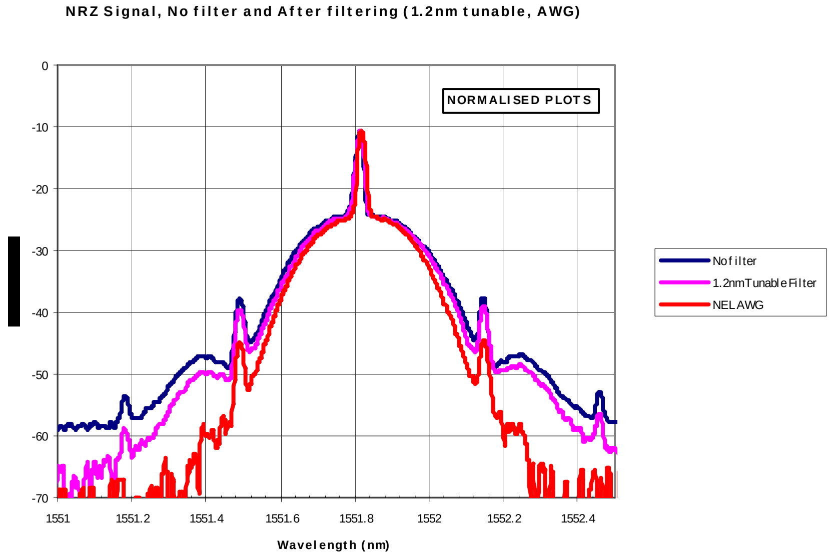


Figure 10 Optical spectra of NRZ-ASK base rate 40 G after the optical filters – thin film 1.2 nm and NEL AWG 0.5 nm passband and no filter.- minimum effect on the spectrum.

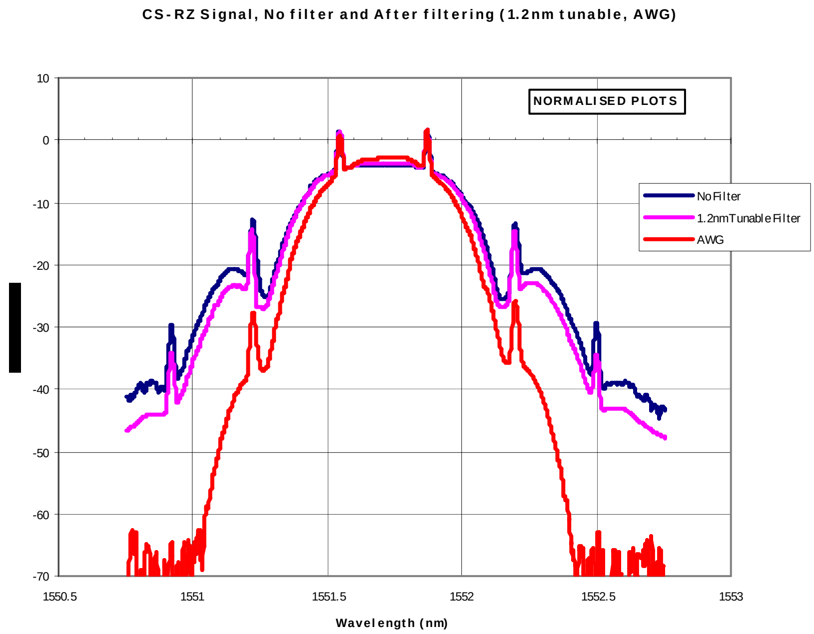


Figure 11 Optical spectra of CS-RZ – base rate 40 G after optical filters thin film and AWG types.

4.2 Eye diagrams of the 40G transmitted waveforms

These were captured on Agilent 50 GHz plug-in at the output of the electronic amplifier followed the balanced receiver or the DS-10 single diode detector. Transmission fiber length: 0, 1, 2, 3, or 4km SSMF to evaluate the effects of dispersion and thus dispersion tolerance.

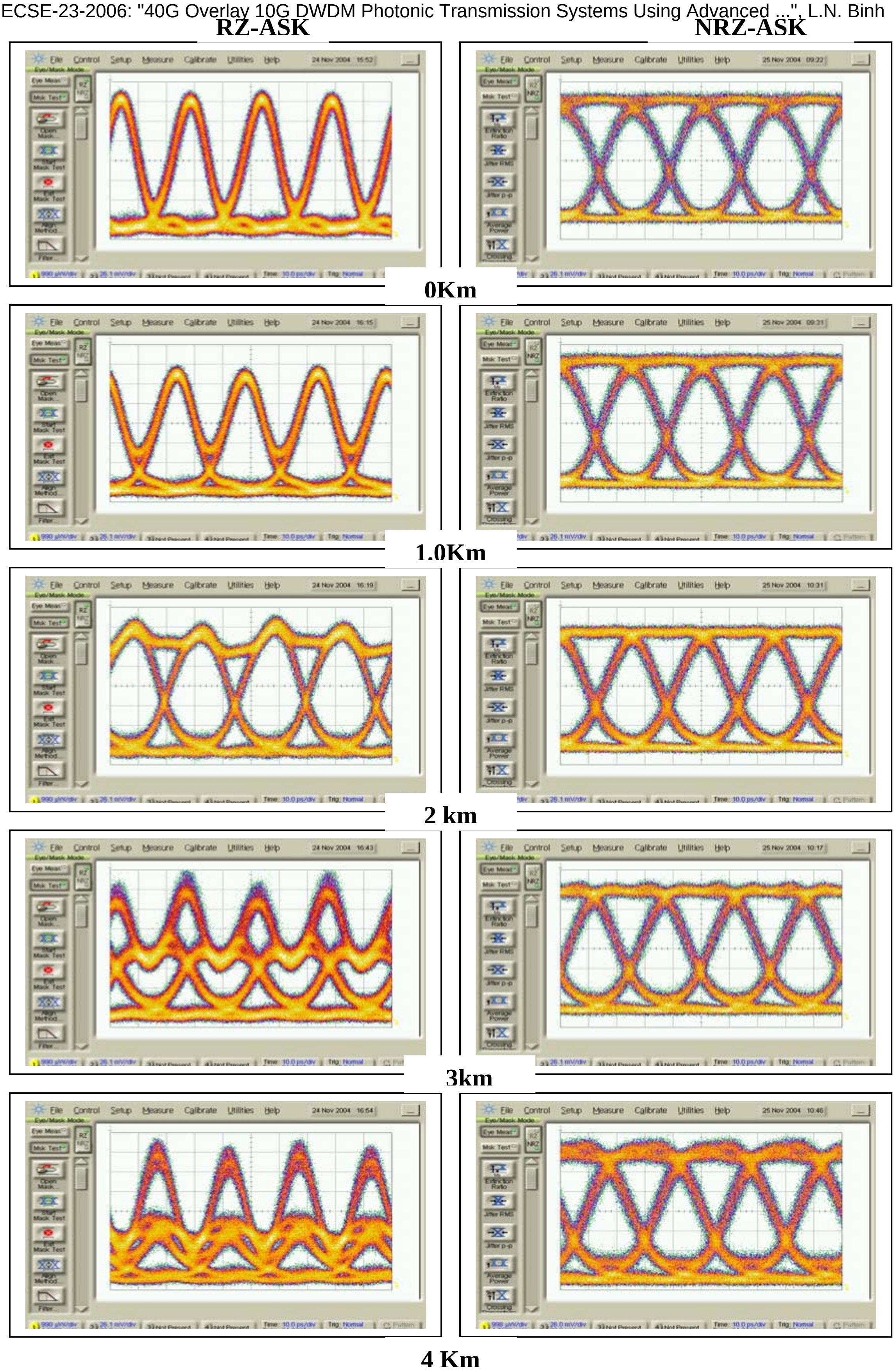


Figure 12 Samples of eye diagrams of ASK modulation formats – SSMF length is a parameter.

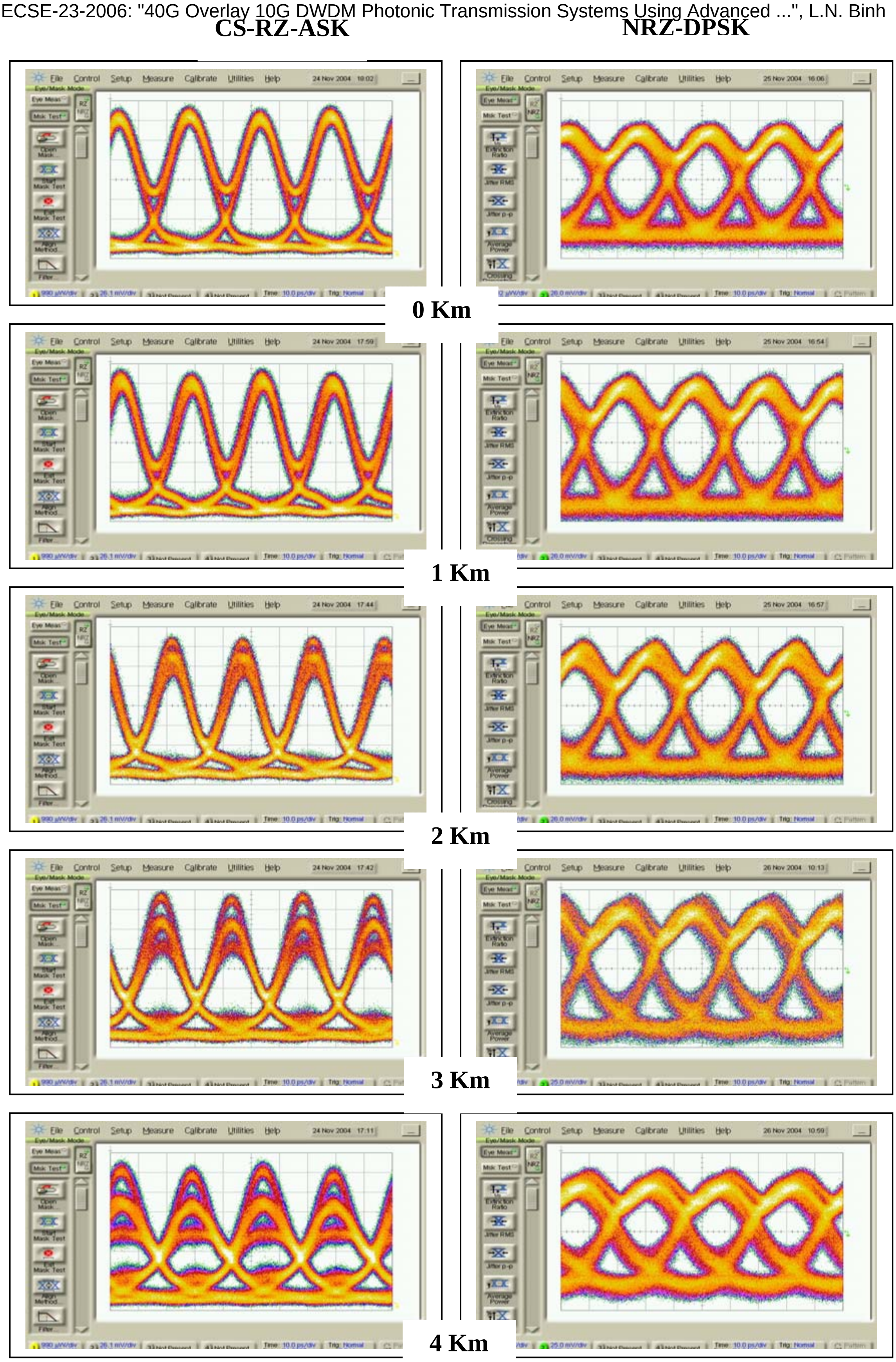


Figure 13 Samples of eye diagrams of phase difference NRZ-DPSK and CSRZ ASK modulation formats – SSMF length is a parameter.

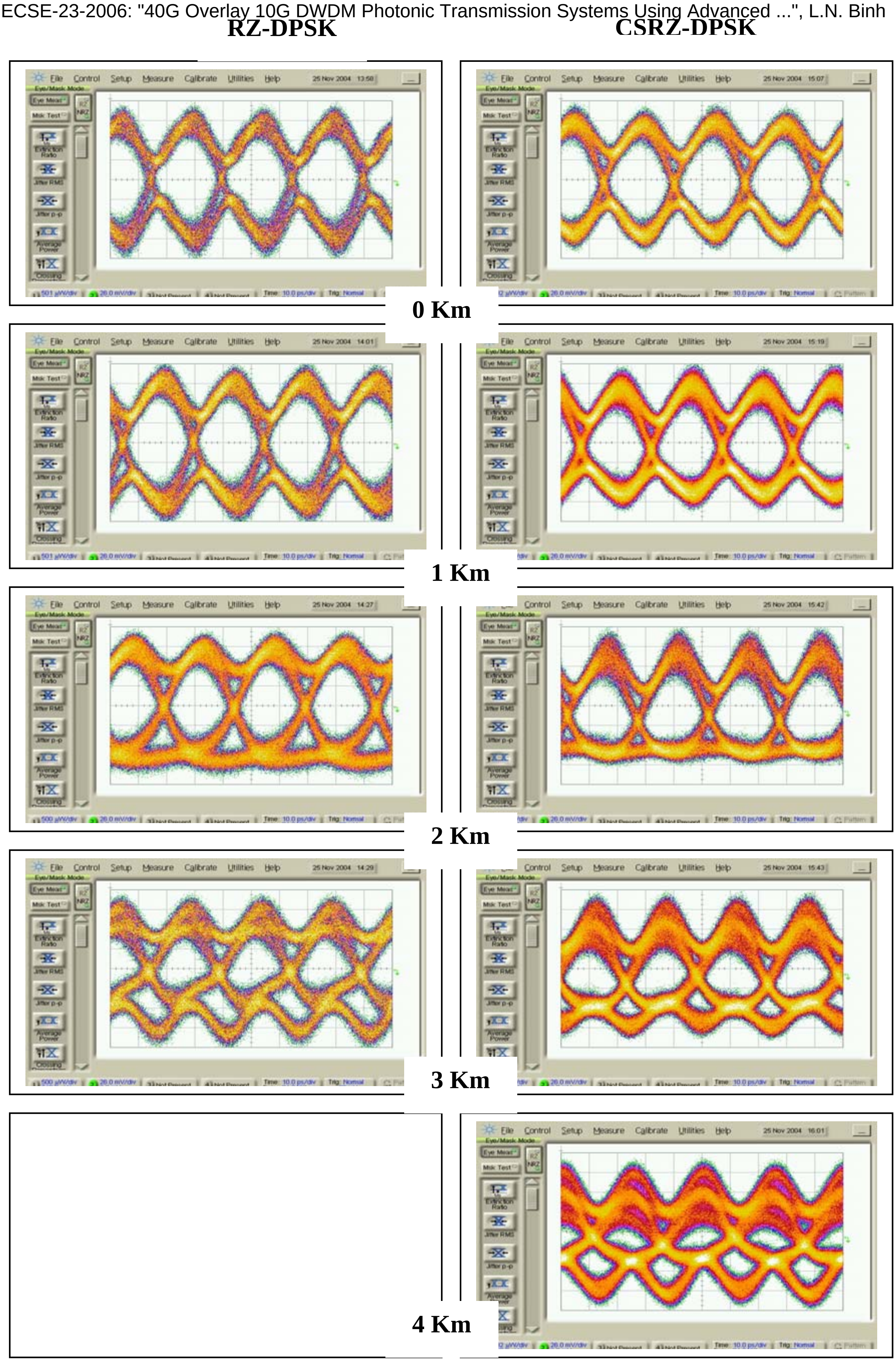


Figure 14 Samples of eye diagrams of phase difference modulation formats – SSMF length is a parameter.

5 DISPERSION TOLERANCE OF DIFFERENT MODULATION FORMATS

40G sent via SMF first them amp and then 1.2nm filter to ensure no nonlinearities. Used "cheated clock" i.e. directly from PRBS generator to Error Analyser for non-DPSK fornats as we had to use a "LAB BUDDY" 45GHz Rx with in-built amp directly onto Error Analyser without an external electrical amplifier as it would distort the detected eye diagram. This means that the optical power is not sufficiently high to drive clock extractor.

5.1 NRZ-ASK

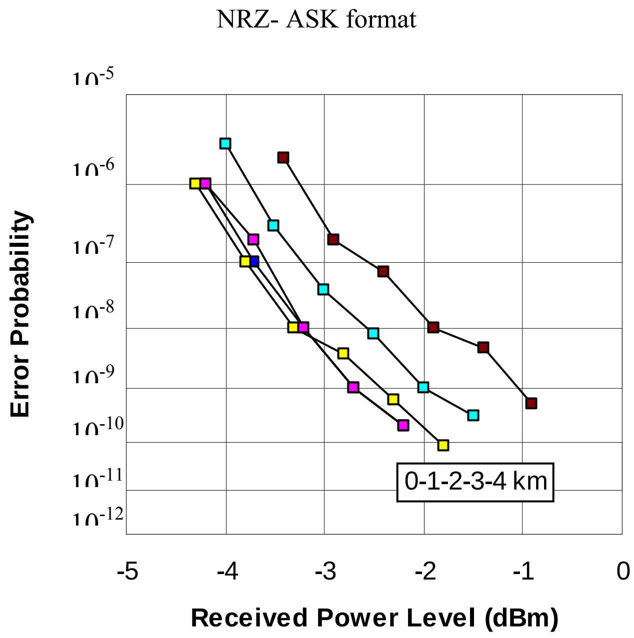


Figure 15 BER versus receiver sensitivity (-10dB) for NRZ format transmission back to back (0km) and 1-4 km of SSMF.

5.2 NRZ DPSK

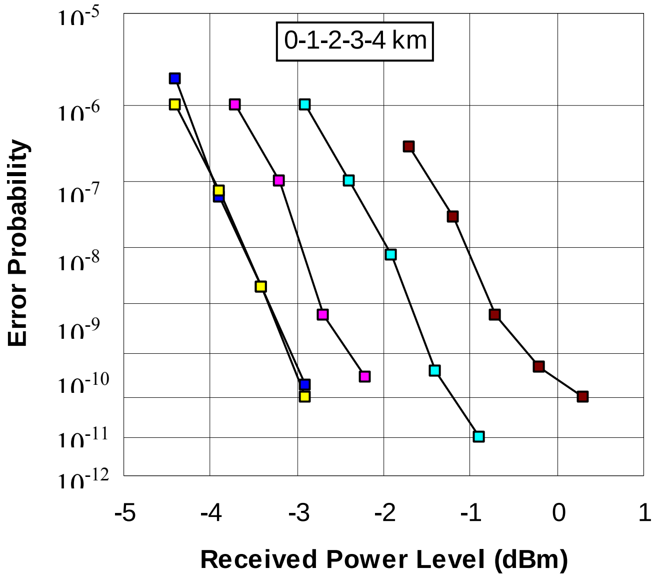


Figure 16 BER versus receiver power obtained for NRZ – DPSK format with back-to-back (0km) and 1-4 m SSMF.

5.3 RZ Format

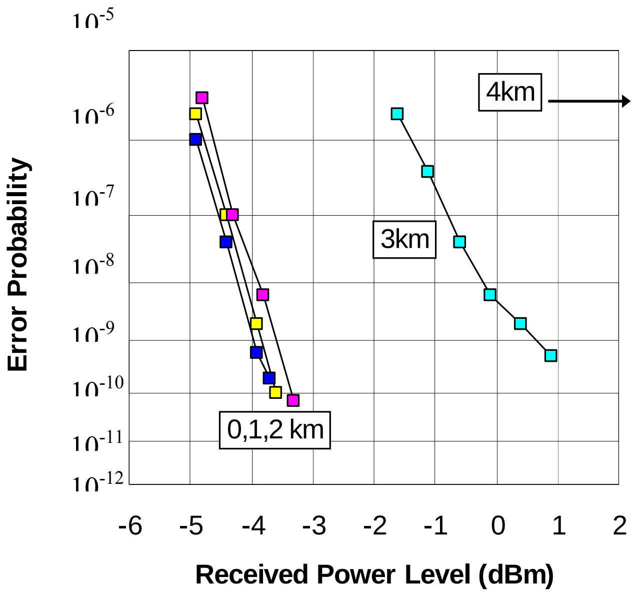


Figure 17 BER versus Rx sensitivity (-10dB) – modulation format RZ ASK

5.4 CS-RZ

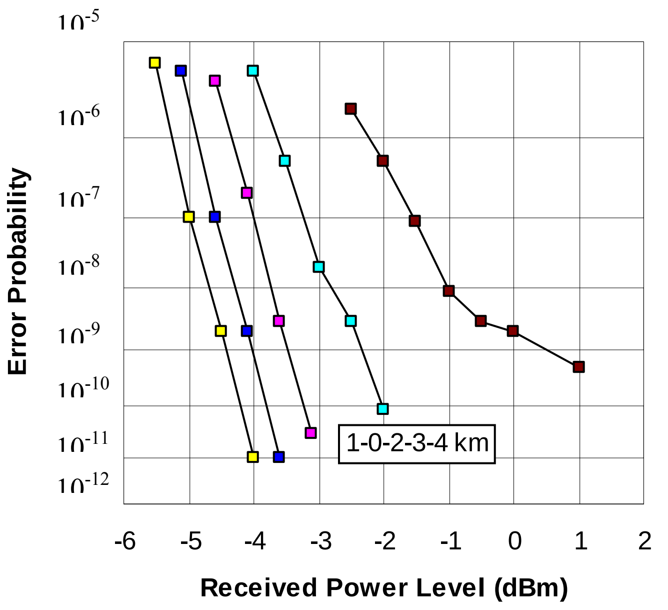


Figure 18 BER versus Rx sensitivity (-10dB) – modulation format CS_RZ ASK. Yellow dots are for back-to-back.

5.5 RZ-DPSK

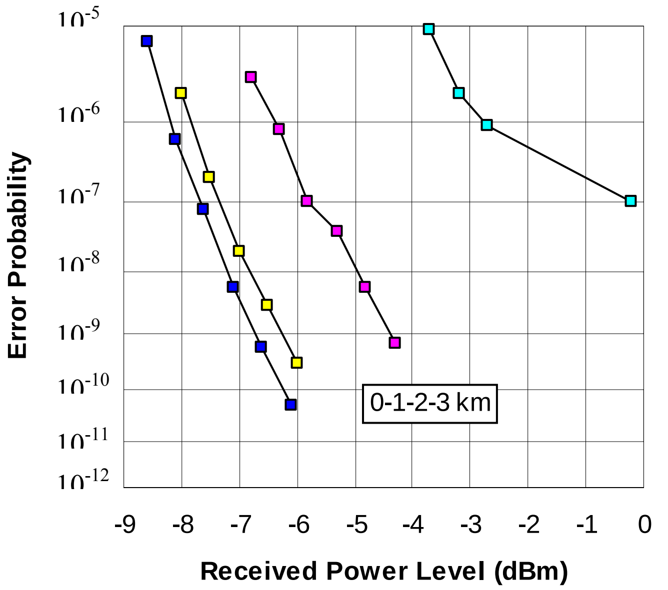


Figure 19 BER versus receiver sensitivity (-10dB) power obtained for RZ – DPSK format with back-to-back (0km) and 1-4 m SSMF.

5.6 CS RZ-DPSK

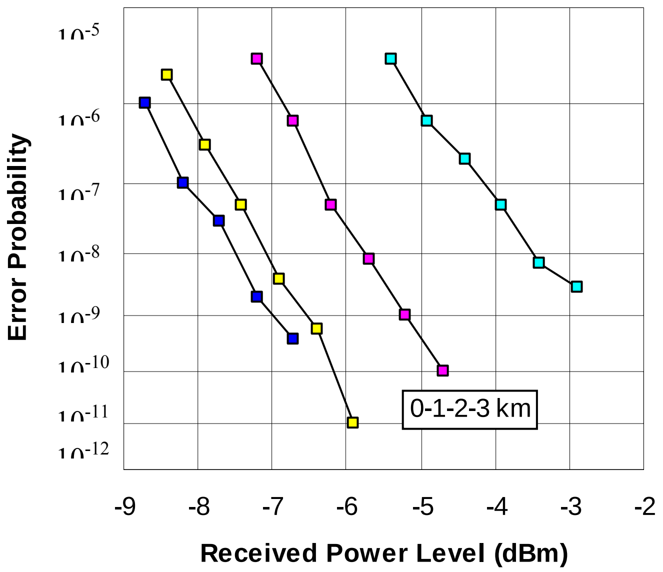


Figure 20 BER versus receiver sensitivity (-10dB) power obtained for CS-RZ – DPSK format with back-to-back (0km) and 1-4 m SSMF. . Note the ~3-4dB improvement of the RZ type DPSK's over ASK formats.

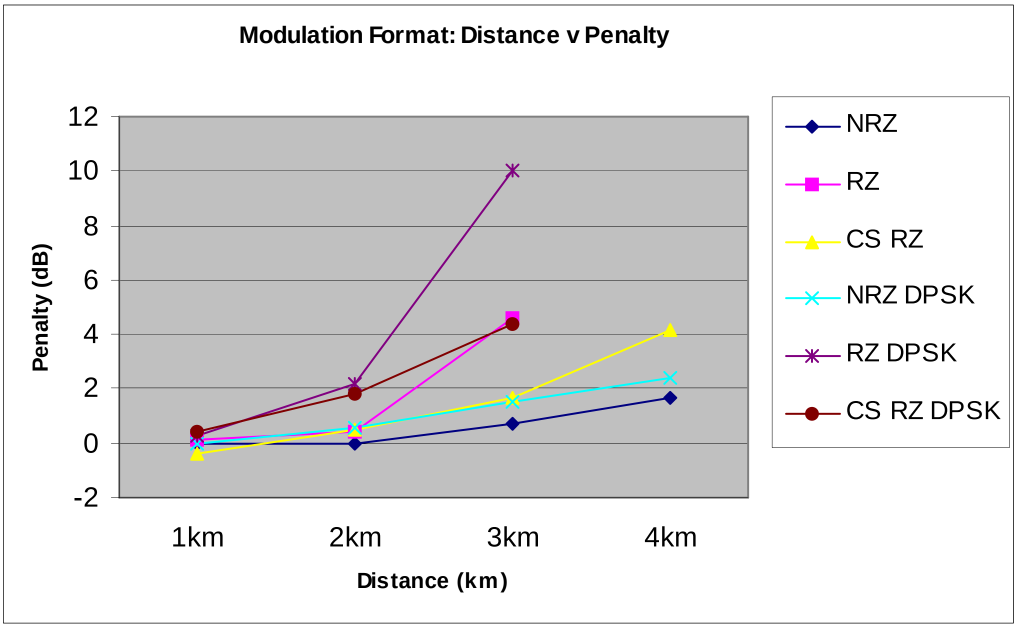


Figure 21 Power penalty as a function of the transmission distance for various modulation formats

6 40 GB/S TRANSMISSION: LONG HAUL TRANSMISSION 50 KM AND 320 KM OPTICAL TRANSMISSION – EFFECTS ON MODULATION FORMATS

6.1 Transmission over 50 Km dispersion compensated span

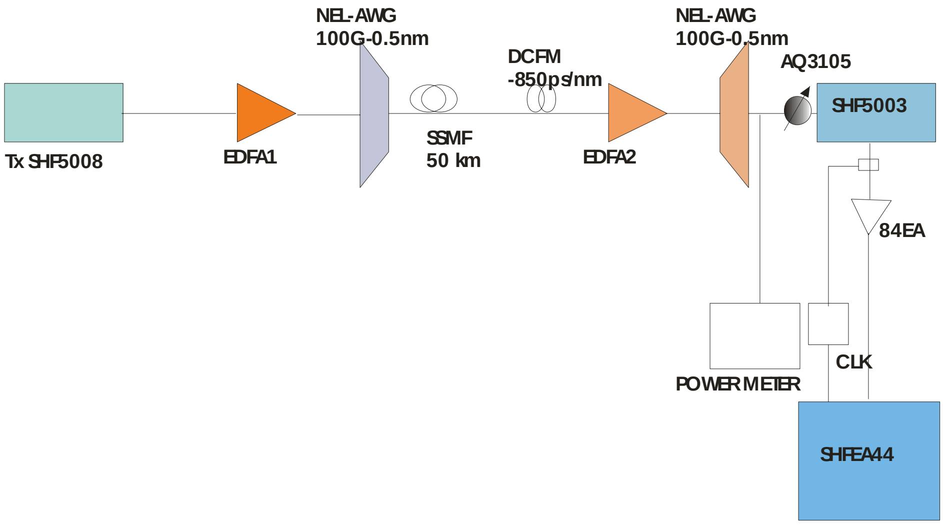


Figure 22 Dispersion managed 50 km SSMF +DCFM transmission system set-up

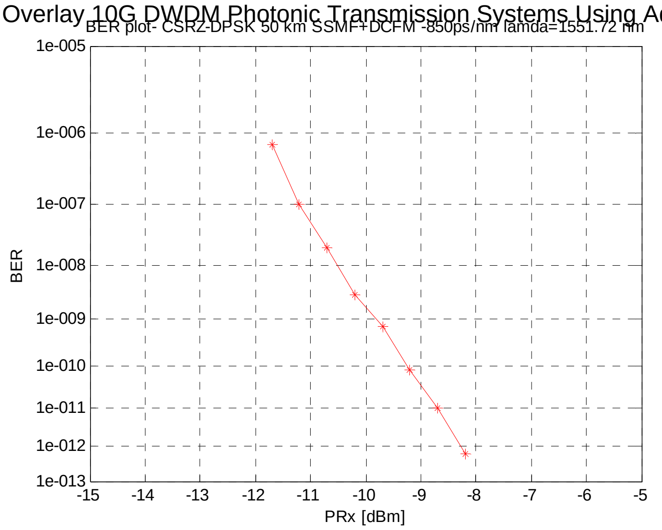


Figure 23: Receiver sensitivity of the CSRZ-DPSK modulation format. Transmission distance= 50 km SSMF + Sumitomo DCFM (-850 ps/nm @1550nm) – source wavelength lamda 5 = 1551.72 nm CSRZ-DPSK transmission after 50 km SSMF and DCFM (-850 ps/nm at 1550 nm).

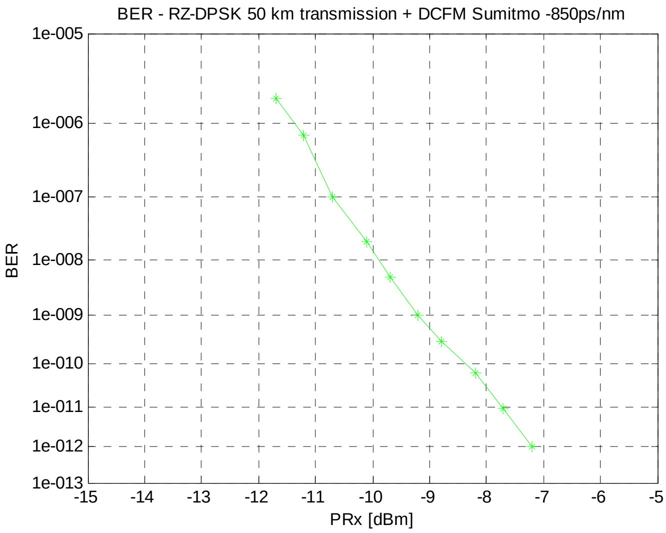


Figure 24 Optical transmission over 50 km of SSMF + DCFM (total dispersion -850 ps/nm); Modulation format = RZ –DPSK, Eye diagram captured at -10.7 dBm at the power meter (1:10 FC port). Note: full clock recovery used for sampling the EA 44E. Centre wavelength (lamda 5) = 1551.72 nm.

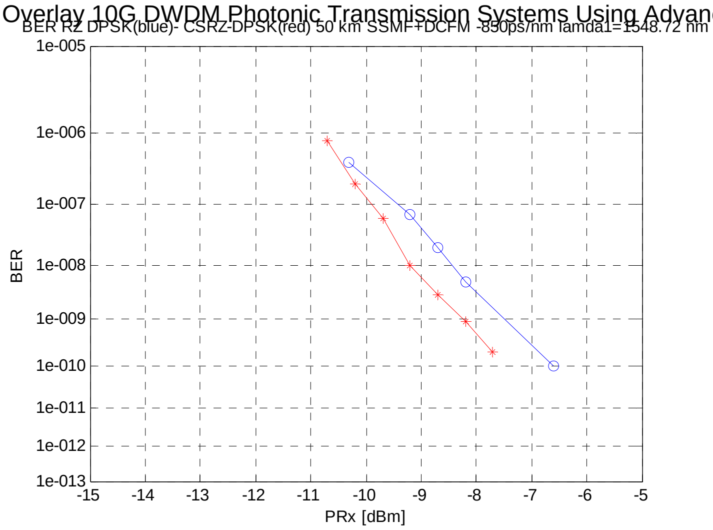


Figure 25: RZ-DPSK (blue) and CSRZ-DPSK (red) modulation format transmission distance= 50 km SSMF + Sumitomo DCFM (-850 ps/nm @1550nm) – source wavelength (Lamda 1)= 1548.51 nm. MUX and DEMUX NEL-AWG circulant filter and spacing demultiplexing.

Optical transmission over 50 km of SSMF + DCFM (total dispersion -850 ps/nm)

Modulation format = CSRZ –DPSK, Eye diagram captured at -10.7 dBm at the power meter (1:10 FC port)

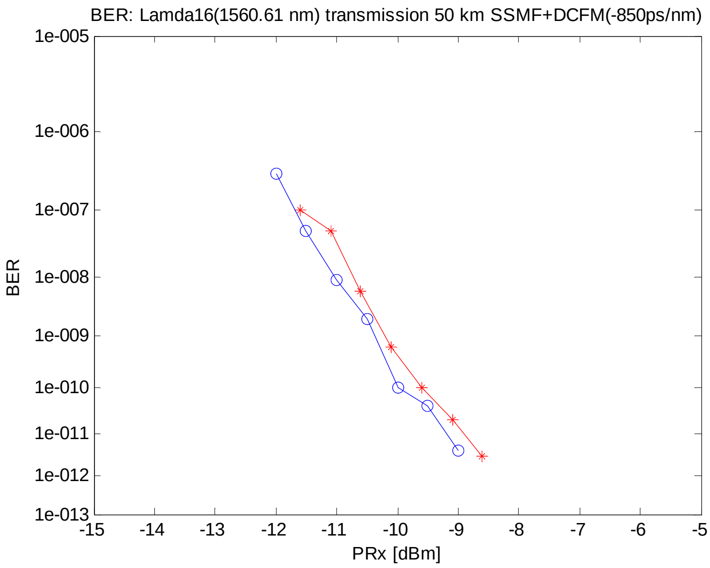


Figure 26 Optical transmission over dispersion managed 50 km of SSMF + DCFM (total dispersion -850 ps/nm); Modulation format = CSRZ –DPSK (red) and RZ-DPSK (blue), Eye diagram captured. Note: full clock recovery used for sampling the EA 44E. Centre wavelength (Lamda 16) = 1560.61 nm

6.2 Transmission over 320 Km SSMF dispersion compensated multi-span 328 KM SSMF + DCF320 transmission

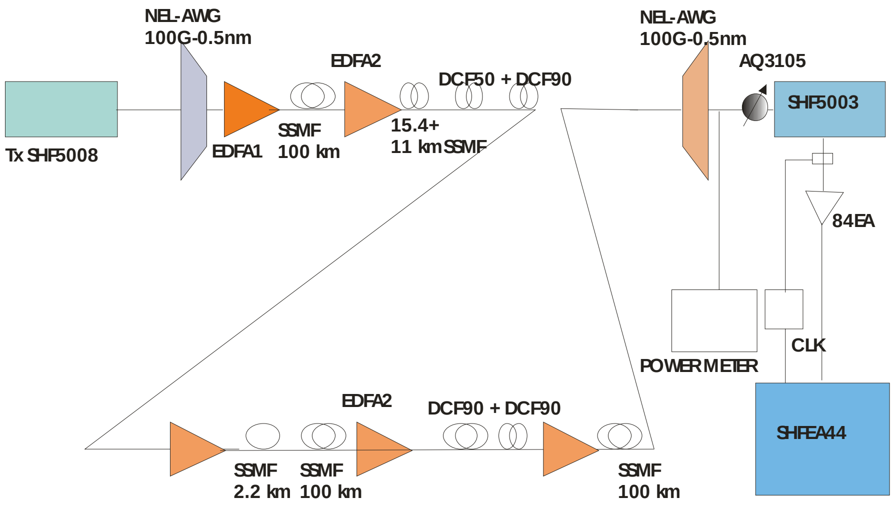


Figure 27 Optically amplified dispersion managed transmission: 328 KM SSMF + 320 DCF transmission with CSRZ-DPSK and RZ – DPSK formats.

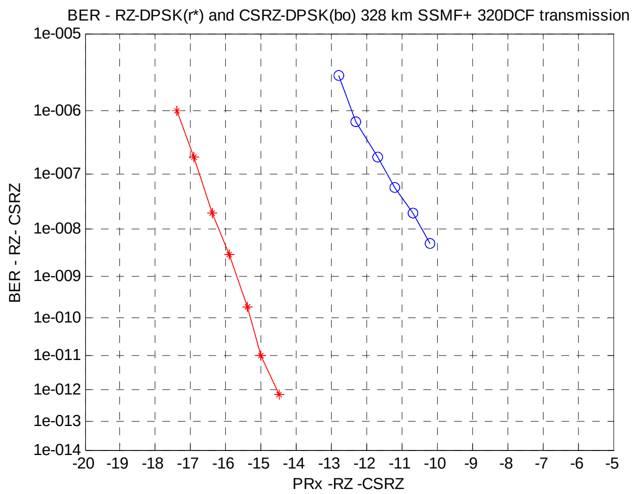


Figure 28 Transmission system: dispersion management 328 kmSSMF + DCM320 compensating fibers. Note: MUX is NEL AWG 0.5 nm 100 GHz Spacing and DEMUX is 1.2 nm OF (thin film structure) (see red curve) – blue is for NEL-AWG+NEL-AWG (100 GHz spacing and 0.5 nm BW) as MUX and DEMUX

7 OPTICAL FILTER EFFECTS ON MODULATION FORMATS

7.1 Filters used in the demonstration (Telstra Labs):

- NEL AWG mux/demux filter **0.45 nm** (3dB bandwidth) - **100 GHz spacing**
- Piri AWG mux/demux filter **0.5 nm** (3dB bandwidth) - **200 GHz spacing**
- FBG – **0.55 nm**

- ♦ AWG 8 Channel Demux – **0.35 nm**
- ♦ JDS tunable filter – **1.3 nm**
- ♦ Santec 0.5 nm – slow roll off.

<u>Notes</u>:

- Pattern 2^{31}-1, gate by time (in Rx): 1ms; polarization has been optimally adjusted.
- Adjusting <u>Variable Attenuator</u> – ANDO-AQ -3105
- Operating at 40 Gbps with clock synchronized at 39.8122 GHz.
- At Rx, heater current: 15.5 mA ; heater Temp: 33.3 º C

7.2 PIRI – AWG Mux/Demux Filter – 0.45 nm

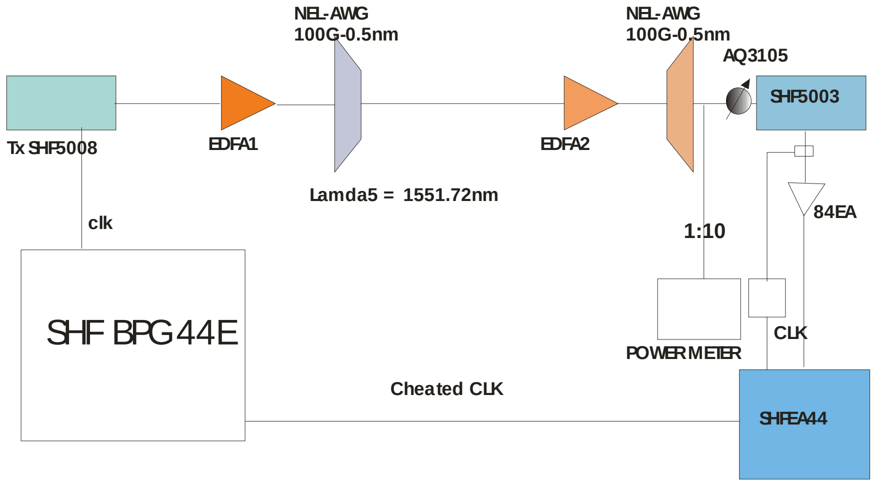


Figure 29 Experimental set-up to measure the optical filtering on modulation formats–Optical filters:ONE FILTER NEL – AWG ONLY.

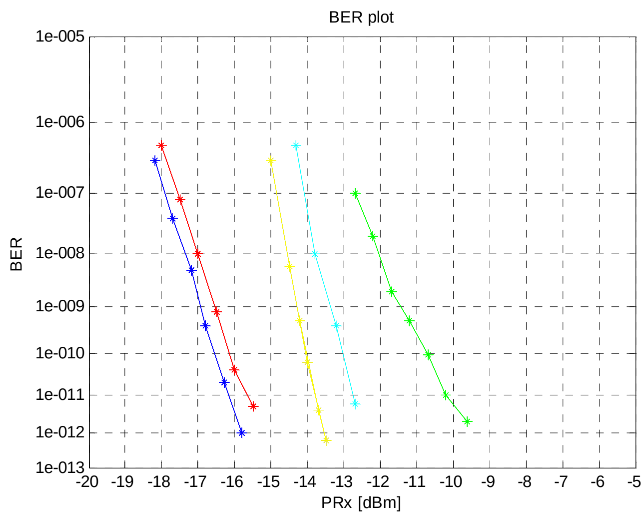


Figure 30 BER versus received optical power (at the power meter – 1;10 coupler before Rx). Note: "blue" CSRZ-DPSK; "red" – RZ DPSK; "green" NRZ ASK; "yellow" – CSRZ- ASK; "c" RZ-ASK; Note' bien: only one optical filter NEL AWG is used

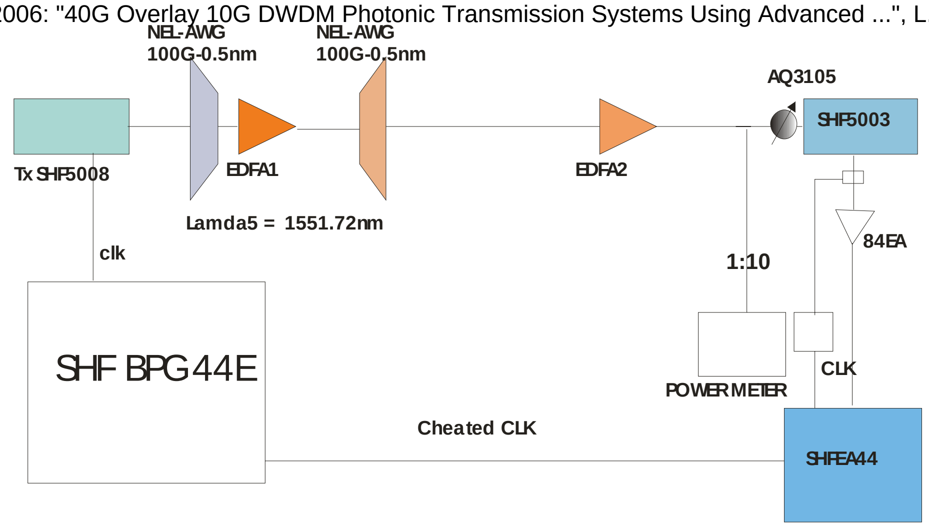


Figure 31 Experimental set up –OPTICAL FILTRER EFFECTS (TWO FILTERS NEL – AWG +EDFA +NEL-AWG +EDFA) ON MODULATION FORMAT. Note: only CSRZ-DPSK and RZ-DPSK gives recorded BER, EDFA1 = 176 mW pump power – saturation mode; EDFA2 = 132 mW pump power – saturation mode

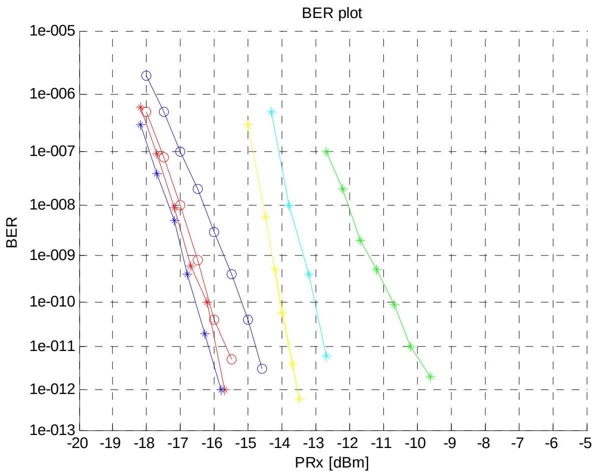


Figure 32 BER versus received optical power (at the power meter – 1;10 coupler before Rx). Legends: "blue" CSRZ-DPSK (one NELAWG); "red" – RZ DPSK(one NELAWG); "green" NRZ ASK(one NELAWG); "yellow" – CSRZ- ASK (one NELAWG); "c" RZ-ASK(one NELAWG); Note: only one optical filter NEL AWG is used; "Red o" CSRZ DPSK TWO AWGs used; "blue o" RZ-DPSK TWO AWGs used

7.3 Testbed set up

Figure 33 shows an example for one of the setup of the experiments.

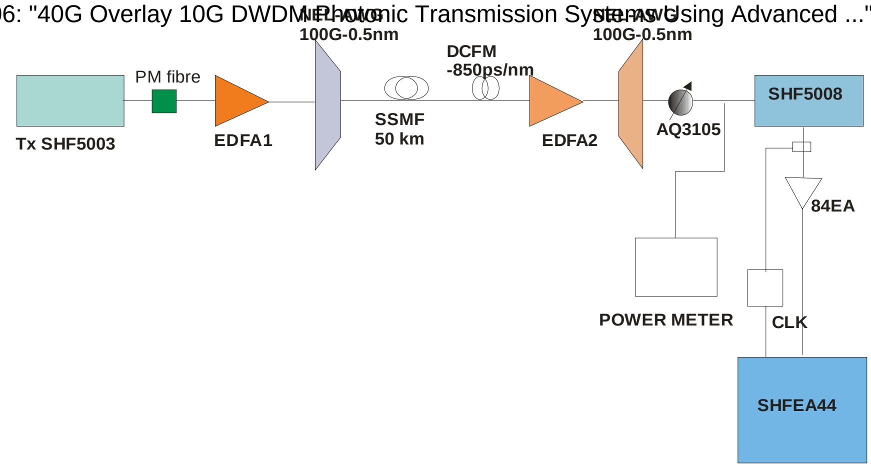


Figure 33 50 Km SSMF transmission experimental set-up

The details of the equipment are

- DPSK Optical Transmitter – SHF 5003
- Bit Pattern Generator – model SHF BPG44E - SHF Communication Technologies
- DPSK Optical Receiver – SHF 5008
- Error Analyzer – SHF EA 44
- 40G Clock Recovery Unit– SHF 1120A
- Laser Source – Anritsu …. Max 8dBm
- Oscilloscope – Tektronix …. With 70GHz optical plug-in and Agilent …. With 50GHz optical plug-in
- Spectrum Analyser – Photonetics OSA.
- Filters: (i) NEL AWG Mux/Demmux 0.45nm bandwidth (ii) AWG JDS 8 channel Mux/Demux 0.35 nm (iii) JDS – 1.2 nm (iv) Santec – 0.5 nm slow roll-off.

7.4 Optical Spectra of Modulation Formats

Centre wavelength of the light source is 1551.72 nm.

7.4.1 Spectrum of NRZ ,RZ and CSRZ

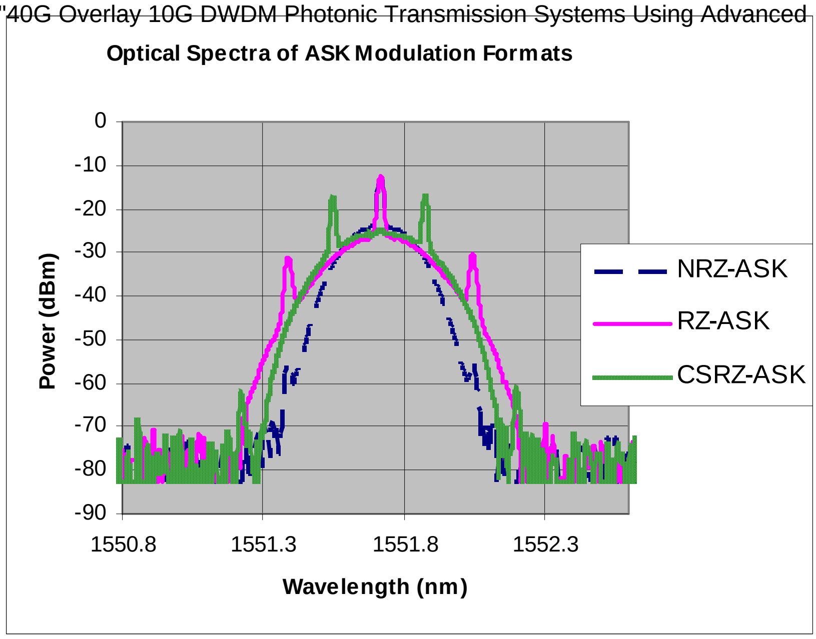


Figure 34 Optical spectra modulation formats amplitude shift keying of various formats

7.4.2 Spectrum of NRZ-DPSK , RZ-DPSK and CSRZ-DPSK

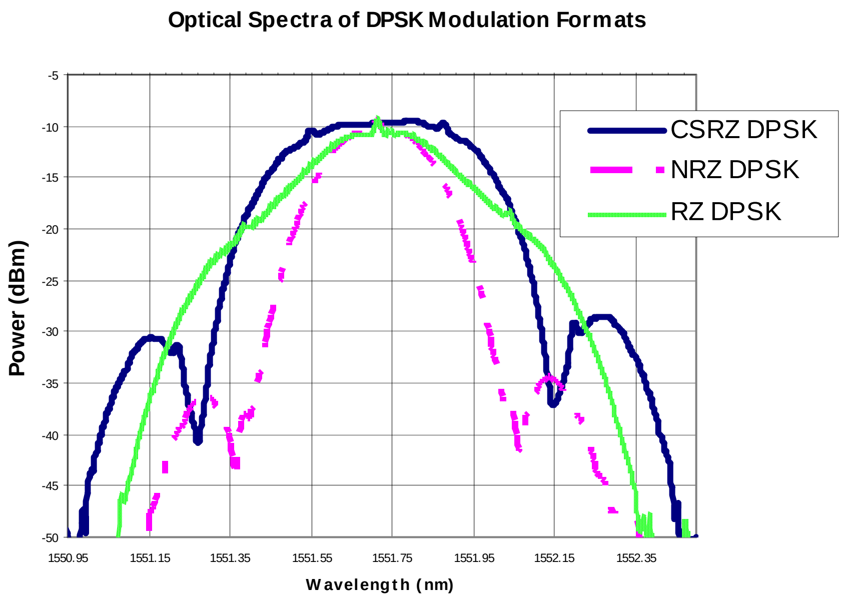


Figure 35 Optical spectra modulation formats phase shift keying of various formats

7.5 Effects of Filter passband on system performance

7.5.1 Effect of single filter

CS-RZ at 40G through 1.2nm tunable and 100GHz AWG (0.5nm 3dB bandwidth):

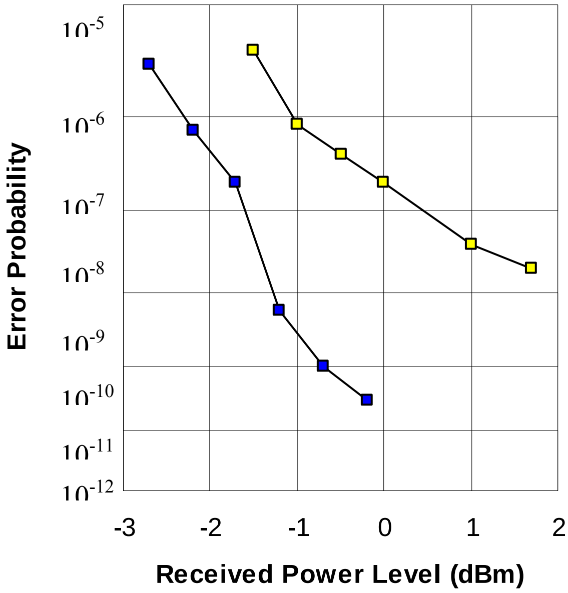


Figure 36 Probability of error versus receiver sensitivity (dBm) for CS-RZ format – blue dots for 1.2 nm thin film filter and yellow dots for 0.5 nm AWG filter (demux with 100 GHz spacing)

The 100GHz AWG is obviously too narrow to pass the complete CS-RZ 40Gbit/s signal. However, 1.2nm (~150GHz) is far too wide for the standard ITU frequency grid.

7.5.2 Effects of double Filters

40G CS RZ DPSK muxed then demuxed via 2 NEL 100GHz AWG's cf 0ne AWG (3dB bandwidth is 0.5nm) + 1.2nm tunable filter- via attenuator only, no fiber. 2 AWG's obviously too narrow to pass 40G CS RZ DPSK sufficiently.

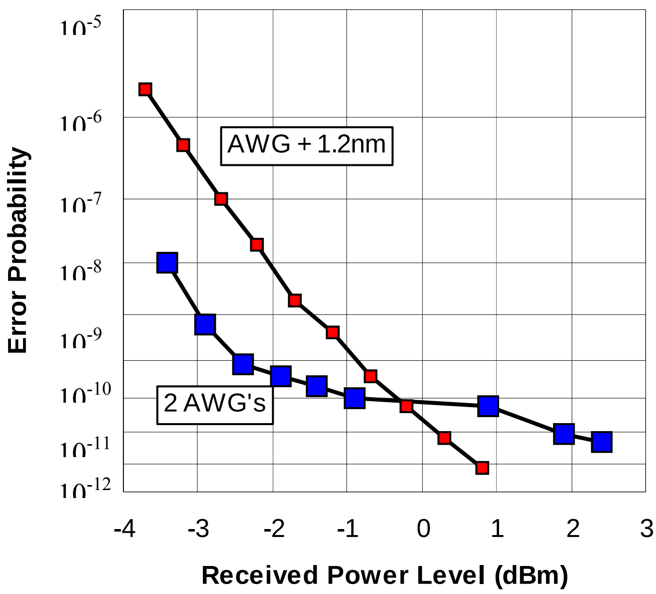


Figure 37 Probability of error versus receiver sensitivity (dBm) for CS-RZ format – blue dots for 1.2 nm thin film filter and yellow dots for two 0.5 nm AWG filter (demuxed with 100 GHz spacing)at the mux and demux stages.

8 MUTUAL IMPACT OF ADJACENT 10G/40G CHANNELS IN OVERLAY TRANSMISSION

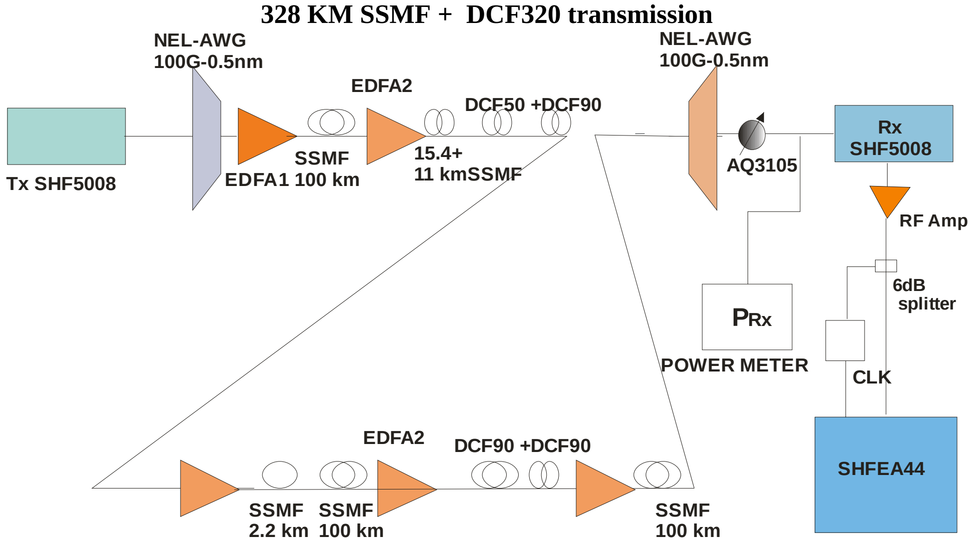


Figure 38 328 KM SSMF + 320 DCF Transmission with CSRZ-DPSK and RZ – DPSK formats Notes: The length of SSMF is selected to be 328 km as it gives the best BER which can be achieved (theoretically, dispersion is nearly completely compensated)

8.1 328km SSMF + DCF for 320 km Tx: Impact of Adjacent 10G/40G Channels

320km transmission performance with a 10G NRZ ASK and a CS-RZ DPSK 40G channel to test adjacent and non-adjacent channel performance with a 100GHz AWG mux and a 1.2nm tunable filter at the input of the Rx. Significant penalty when adjacent 40G channel switched on due to the narrow width of the tunable filter. Non adjacent channel too far off to have any impact.

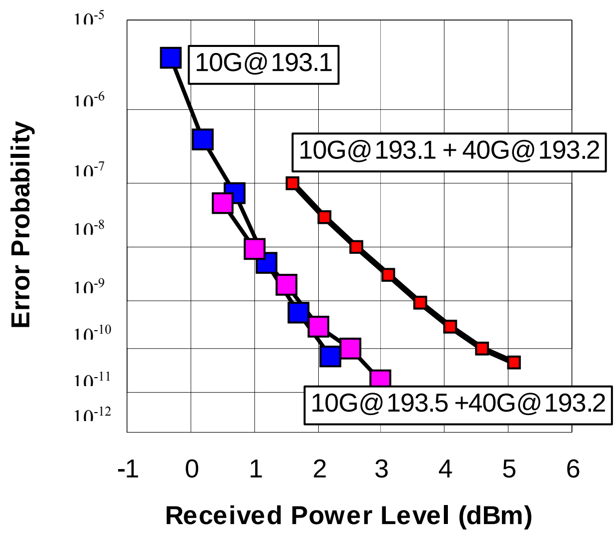


Figure 39 40 G impact on 10G channel: Probability of error versus receiver sensitivity (dBm)- effects of 40 G with 10G (NRZ-ASK) channel simultaneously transmitted for NRZ ASK and CS-RZ DPSK formats – blue dots for 1.2 nm thin film filter and dots for 0.5 nm AWG filter (demux with 100 GHz spacing).

The set up of the transmission system with 320km SSMF and dispersion compensating module with 2 100GHz AWG's as muxes and Rx filter to measure the impact of adjacent CS-RZ DPSK 40G channel on 10G NRZ-ASK performance. No significant impact noted when 40G channel, adjacent or non-adjacent, is switched on. (Note: demo only as 40G channel would not actually perform well through such a narrow filtering arrangement).

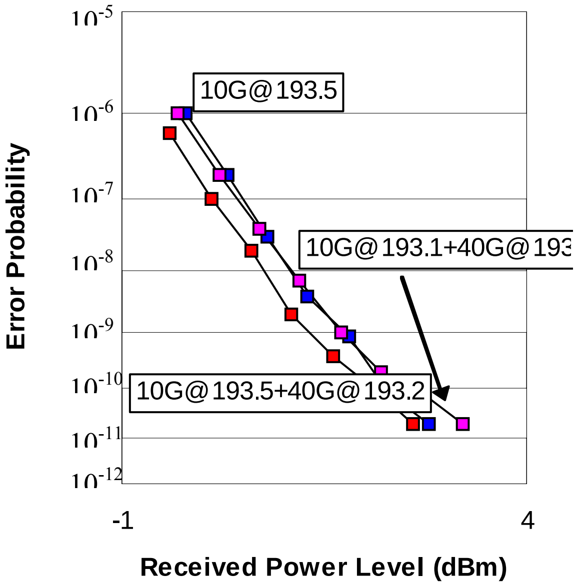


Figure 40 320 km transmission 40 G impact on 10G channel: Probability of error versus receiver sensitivity (dBm)- effects of 40 G (CS_RZ DPSK) with 10G (NRZ-ASK) channel simultaneously transmitted for NRZ ASK and CS-RZ DPSK formats – blue dots for 1.2 nm thin film filter and dots for 0.5 nm AWG filter (demux with 100 GHz spacing)

Result shows that there is no appreciable impact on 10G signal of an adjacent 40G signal. For the case that two 100GHz AWG's are used as the mux and Rx filter for CS RZ DPSK transmission over 320km, we now measure the performance of the 40G stream transmitted simultaneously with adjacent and non-adjacent 10G channel. Note problem with using 2 AWG's at 40Gb/s as there is significant error floor. However we can see that 10G adjacent or non-adjacent creates no impact on 40G signal as expected. Small improvement with 40G channel on probably due to lower noise power contributed from EDFA.

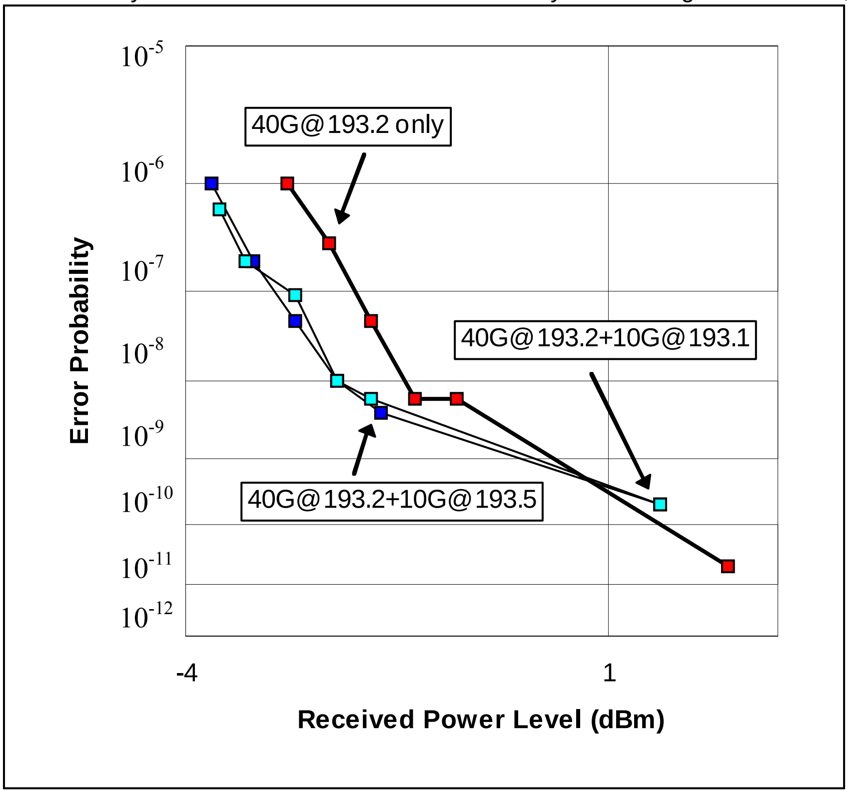


Figure 41 Impact on 40 G with 10 G channel transmission 320 km transmission: Probability of error versus receiver sensitivity (dBm)- effects of 40 G (CS_RZ DPSK) with 10G (NRZ-ASK) channel simultaneously transmitted for NRZ ASK and CS-RZ DPSK formats – blue dots for 1.2 nm thin film filter and dots for two 0.5 nm AWG filter (demux with 200 GHz spacing)

9 "DISPERSION TOLERANCE AND SENSITIVITY OF VARIOUS MODULATION FORMATS

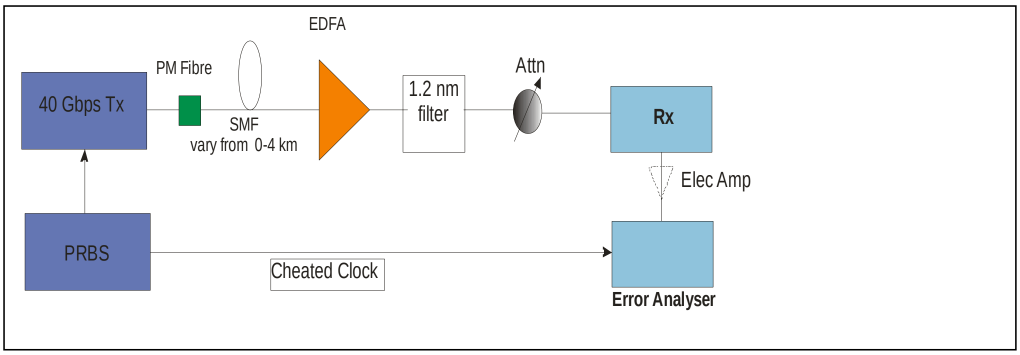


Figure 42 Experimental set up to measure the dispersion tolerance of different modulation formats.

Notes:

- 40Gbps Tx is SHF 5003 DPSK Transmitter which can generate both ASK and DPSK data
- In case of ASK, "Lab Buddy" Optical Receiver (45 GHz with built-in amplifier) is used
- In case of DPSK, SHF 5008 DPSK receiver is used (MZ – 1 bit delay). Also, the Electrical Amp is utilized to drive the Error Analyser.

- JDS 1.2 nm filter was utilized after EDFA to decrease the ASE noise level.
- Power launched into SMF (right after the Tx) is low , hence nonlinearities do not have any impact.

	NRZ-ASK	RZ-ASK	CSRZ-ASK	NRZ-DPSK	RZ-DPSK	CSRZ-DPSK
Launched Power (dBm)	-4.2	-7.7	-6.2	-3.1	-6.2	-4.8

- “Cheated Clock” i.e. without using the Clock Recovery Unit, the Error Analyser directly using clock pulse of the PRBS.
- Laser Source: 1551.72 nm
- Pulse pattern of PRBS is 2^31 -1

9.1 RZ-ASK

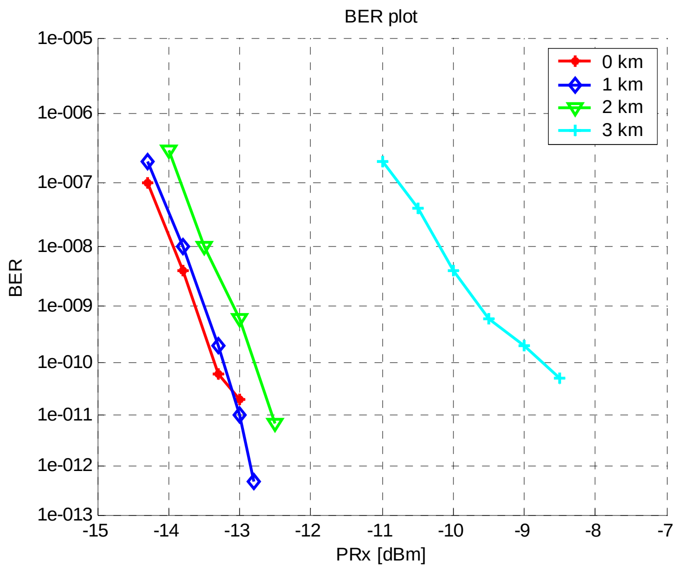


Figure 43 BER as a function of receiver sensitivity with SSMF length as a parameter. Modulation format: RZ -ASK.

- measured BER and Received Power
- % note: received power = reading power (at the power meter) + 10 dB (coupler 1:10) - 0.7 (Insertion loss)

9.2 CSRZ-ASK

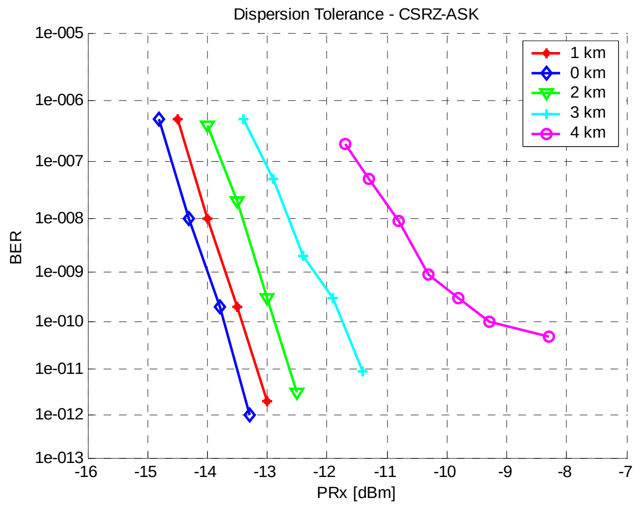


Figure 44 BER as a function of receiver sensitivity with SSMF length as a parameter. Modulation format: carrier-suppressed RZ.

9.3 NRZ-ASK

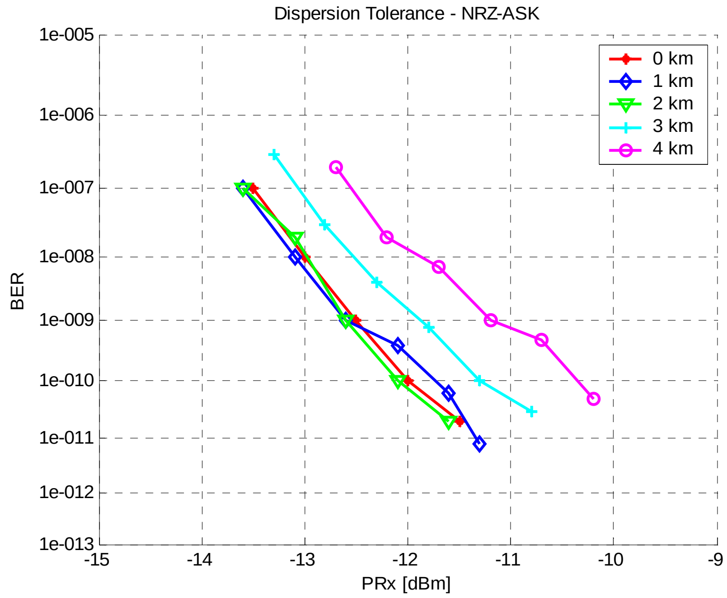


Figure 45 BER as a function of receiver sensitivity with SSMF length as a parameter. Modulation format: RZ-ASK.

9.4 RZ-DPSK

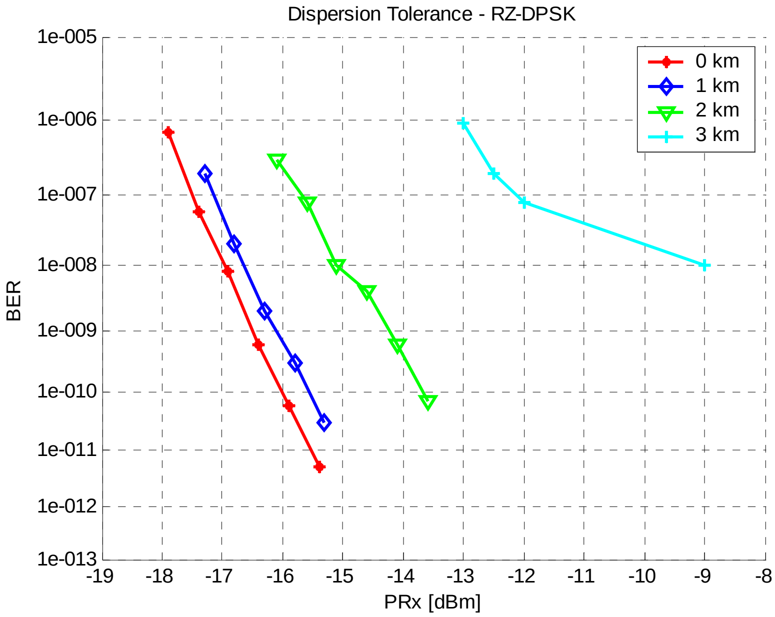


Figure 46 BER as a function of receiver sensitivity with SSMF length as a parameter. Modulation format: RZ-DPSK.

9.5 CSRZ- DPSK

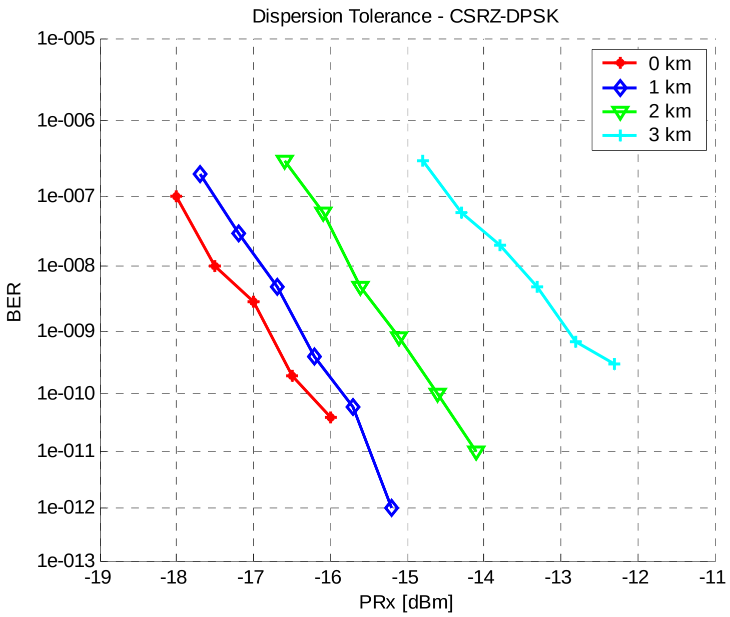


Figure 47 BER as a function of receiver sensitivity with SSMF length as a parameter. Modulation format: carrier-suppressed RZ-DPSK.

Note: NRZ – DPSK does not work probably and drifting …… only work on PRBS pattern of 2^7-1

10 "FILTER EFFECTS" BACK TO BACK JUST WITH NEL AWG AND 2 NEL AWG CASCADED WITHOUT SPLITTER

10.1 <u>Single NELAWG filter:</u>

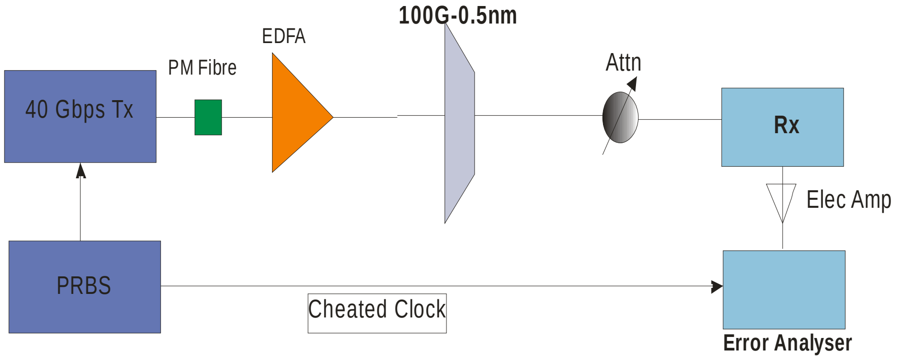


Figure 48 Experimental set up to measure the optical filtering effects on different modulation formats

10.2 Cascaded NELAWG filters

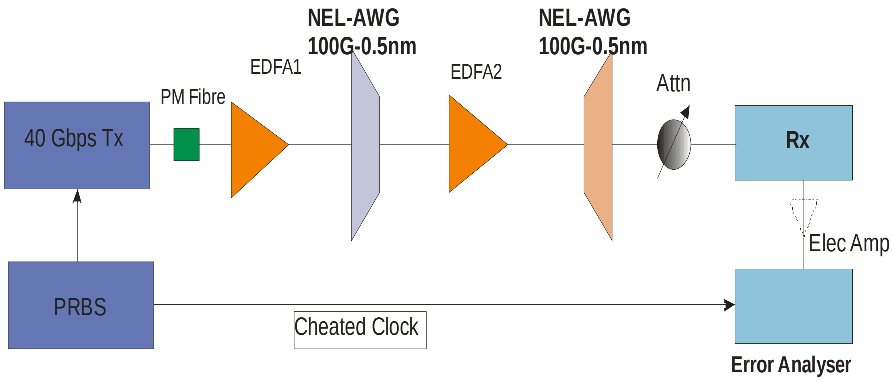


Figure 49 Experimental set up to measure the optical filtering effects on different modulation formats using two filters.

Notes: In this experiment, the 6 dB splitter was not utilized, which is very significant for later on to understand that the Received Power with 6dB splitter will be higher.

10.3 ASK

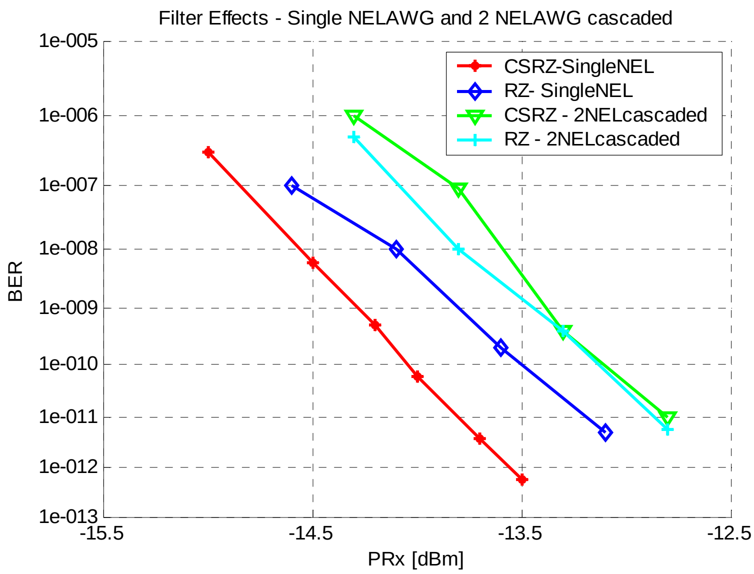


Figure 50 Effects of filtering - BER as a function of receiver sensitivity with modulation formats as a parameter: CSRZ –ASK, RZ-ASK and CSRZ-ASK

10.4 DPSK

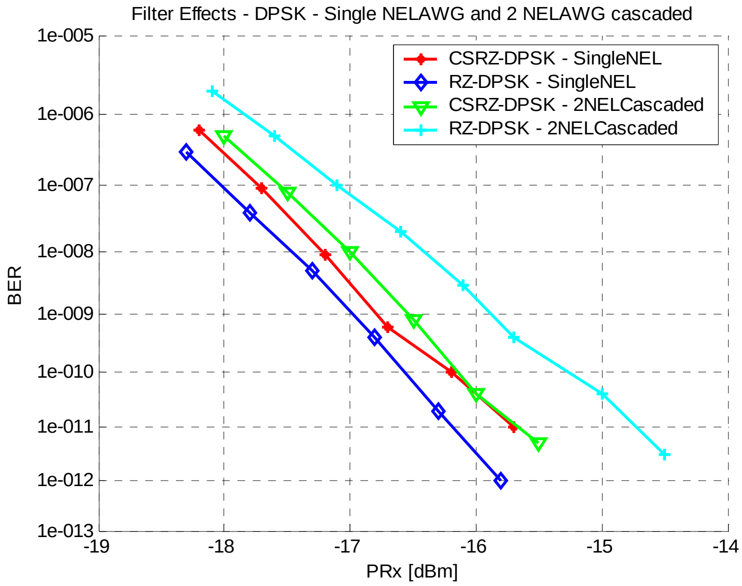


Figure 51 Effects of filtering - BER as a function of receiver sensitivity with modulation format of phase difference: RZ, NRZ and CSRZ.

11 NON-LINEAR EFFECTS (DCF+50KMSSMF; 50KM SSMF + DCF; 234KM SMF+DCF FOR 230 KM)

11.1 DCF – 50km SMF transmission

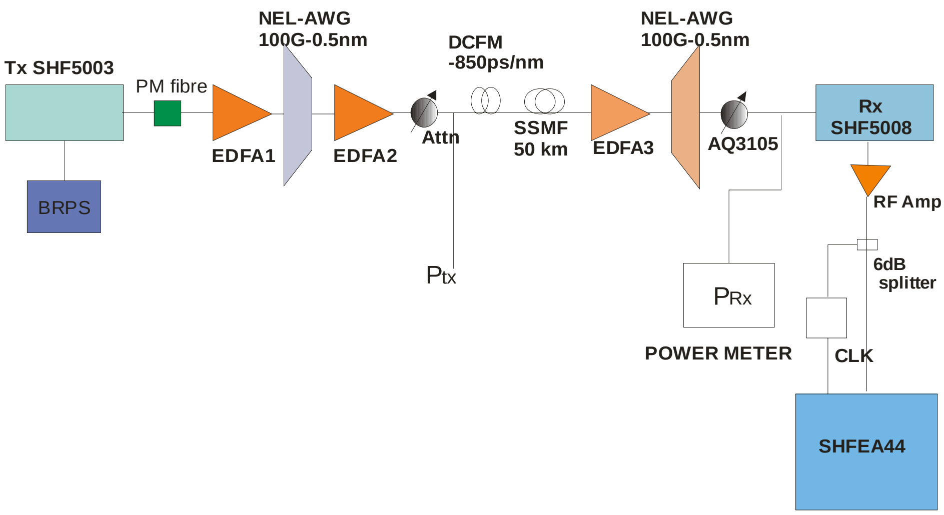


Figure 52 50 km DCF +SMF Transmission system set-up

Photonic components driving conditions

- Laser source: tunable laser set at 1551.72 nm for centred wavelength (lamda 5) and 1548.51 nm for lamda 1 – 1560 nm for lamda 16.
- NEL-AWG = frequency spacing 100G 3 dB BW of 0.5 nm. Circulating property so spectrum would appear cyclic (note the spectrum) - note of the channel input and out put – e.g input at port 5 of Lamda 5 then output at port 8. Input Lamda 1 at port 1 then output at port 8 (Lamda 1).
- Tx can be set at CSRZ-DPSK or RZ- DPSK
- Clock recovery using 6 dB splitter

- Tuning of MZ phase decoder at the Rx is necessary when lamda channels are changed
- EDFA 1 driven at 178 mW pump power (saturation mode).
- EDFA2 driven at 197 mW (saturation mode).
- Attenuator is used to vary the optical power input at the receiver.

  Notes: DCF has lower nonlinear power threshold. Hence, it is expected that nonlinearities starts their effects at lower launched power compared to 50km SMF-DCF

Receiver Sensitivity

Notes:

- Tune the wavelength of the laser source : lamda1 = 1548.51nm , lamda5 = 1551.72 nm and lamda 16 = 1560.61 nm (according to ITU grid standard). This is to show that…different channels through the Mux/Demux with different dispersiioncharacteristics- → it is important to do mobbing for achievement of complete dispersion compensation.

- Mod formats implemented are: RZ-DPSK and CSRZ-DPSK..

- Power launched into the Sumitomo DCFM was measured to be 7.1 dBm. It is expected that

- 40GHz clock Recovery unit was utilized.

- Use two NELAWG Mux/Demux filters 100GHz spacing – 3dB bandwidth 0.45 nm -→ alike the currently deployed real 100 GHz spacing system .

- DCF module for dispersion compensation is: Sumitomo DCFM (-850 ps/nm@ 1550nm).
- Power used in the BER plot is the reading power at the power meter. The received power can easily be calculated by:

Received Power = Reading power + 10dB (1:10 coupler) – 0.7 (insertion loss of the coupler)

Compare BER with different Tx wavelengths (showing the importance of mobbing/compensating dispersion on different channels in the system.)

11.1.1 RZ-DPSK

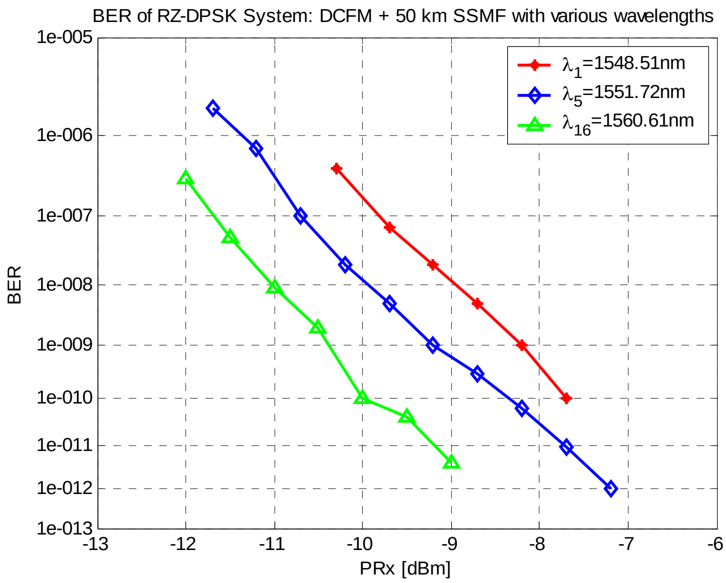


Figure 53 transmission over 50 km SSMF: BER versus Rx sensitivity. Modulation format: RZ-DPSK.

11.1.2 CSRZ-DPSK

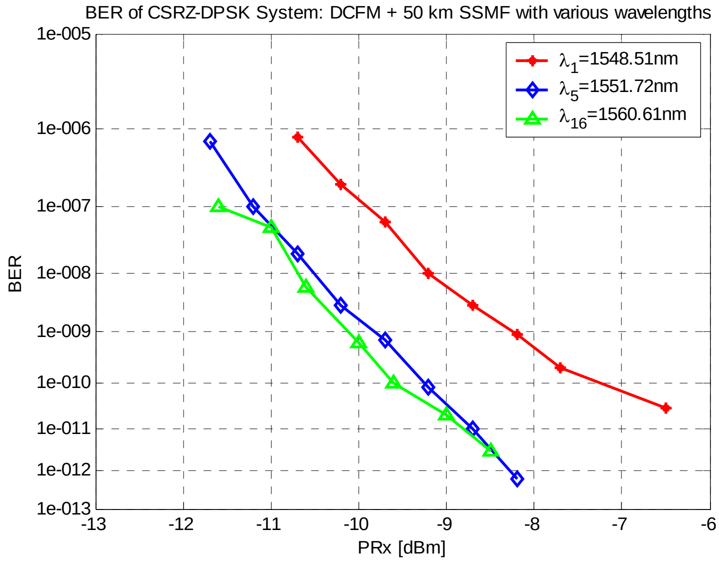


Figure 54 transmission over 50 km SSMF: BER versus Rx sensitivity. Modulation format: CSRZ-DPSK

At interested λ = 1551.72 nm , compare BER between CSRZ- DPSK and RZ-DPSK on the system of DCF- 50 km SMF

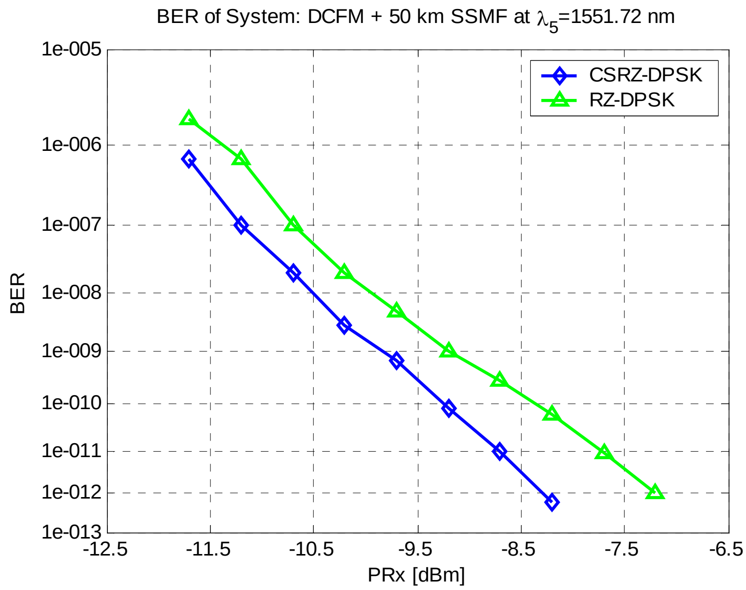


Figure 55 transmission over 50 km SSMF: BER versus Rx sensitivity. Modulation format: CSRZ and RZ- DPSK.

11.1.3 CSRZ-DPSK

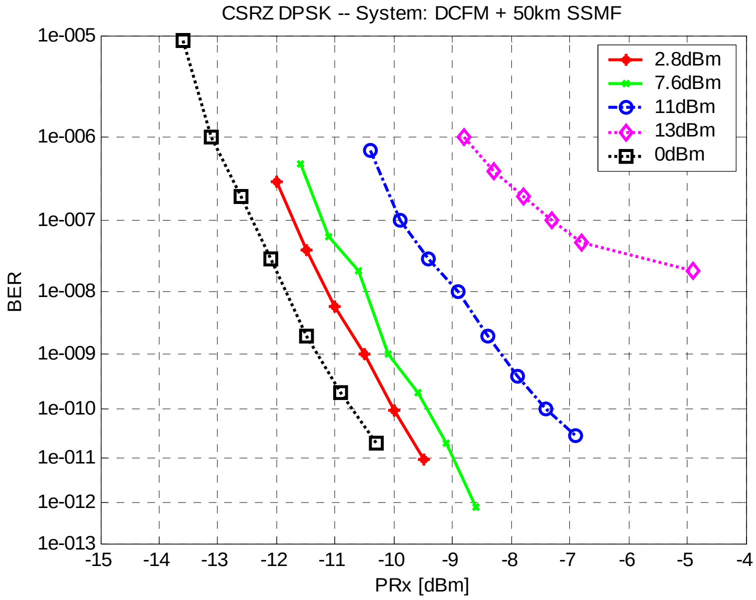


Figure 56 Transmission over 50 km SSMF: BER versus Rx sensitivity with total launched power as a parameter. Modulation format: CSRZ-DPSK.

11.1.4 RZ-DPSK

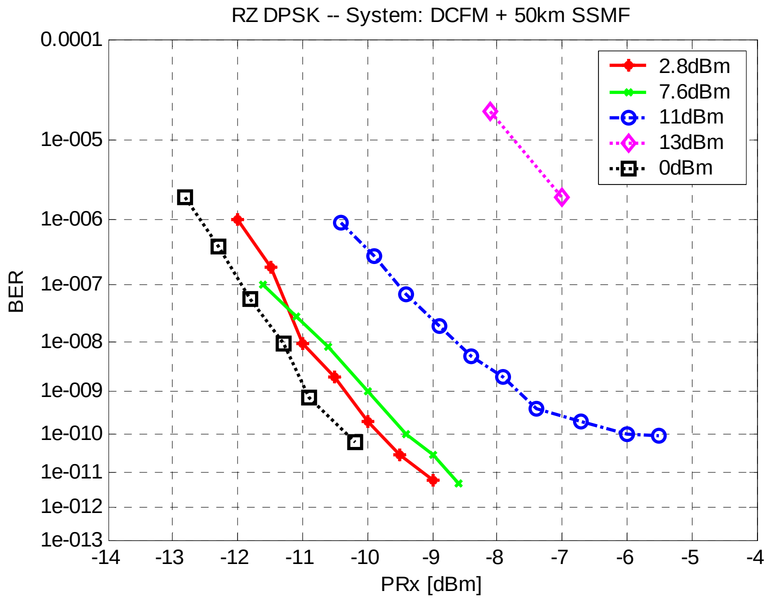


Figure 57 transmission over 50 km SSMF: BER versus Rx sensitivity with total launched power as a parameter. Modulation format: RZ-DPSK

11.1.5 CSRZ-ASK

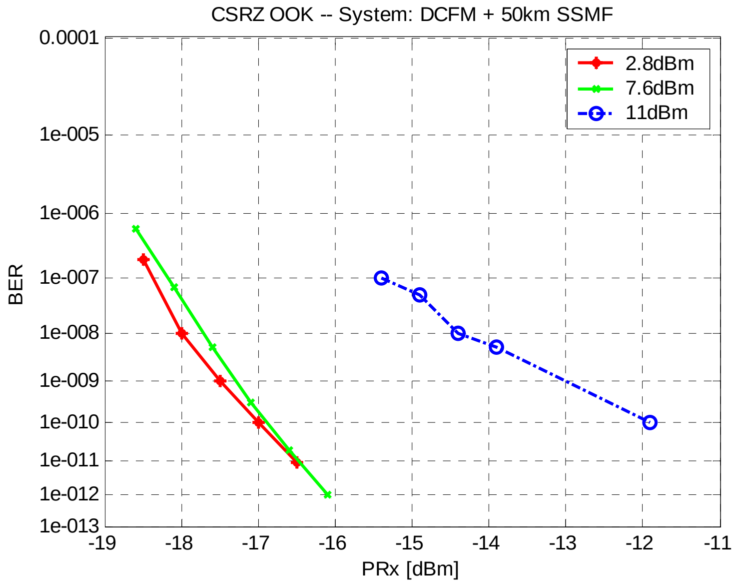


Figure 58 transmission over 50 km SSMF: BER versus Rx sensitivity with total launched power as a parameter. Modulation format: CSRZ-ASK

11.1.6 RZ-ASK

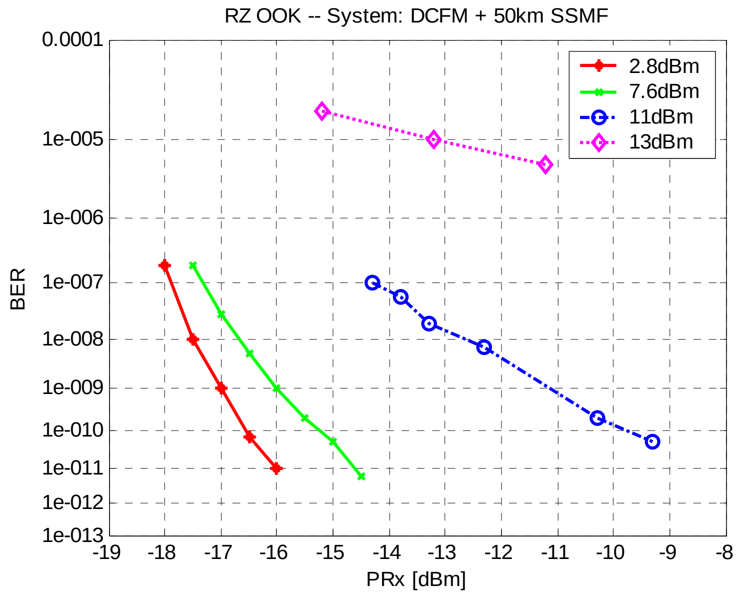


Figure 59 transmission over 50 km SSMF: BER versus Rx sensitivity with total launched power as a parameter. Modulation format: RZ-ASK

11.2 50km SMF + DCF Transmission

Nonlinear effects Investigation by varying the launched power

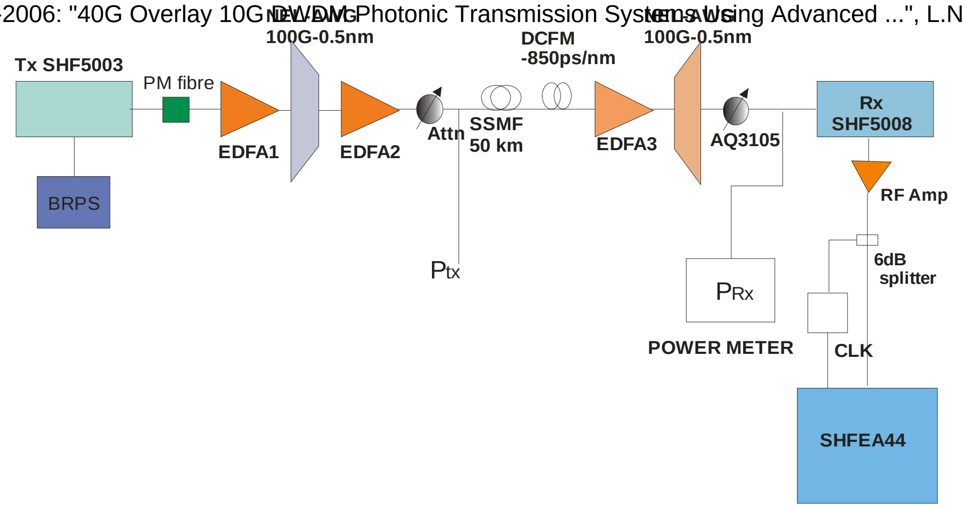


Figure 60 Transmission performance of dispersion managed fibres: 50km SMF + DCF-850

11.2.1 CSRZ-DPSK

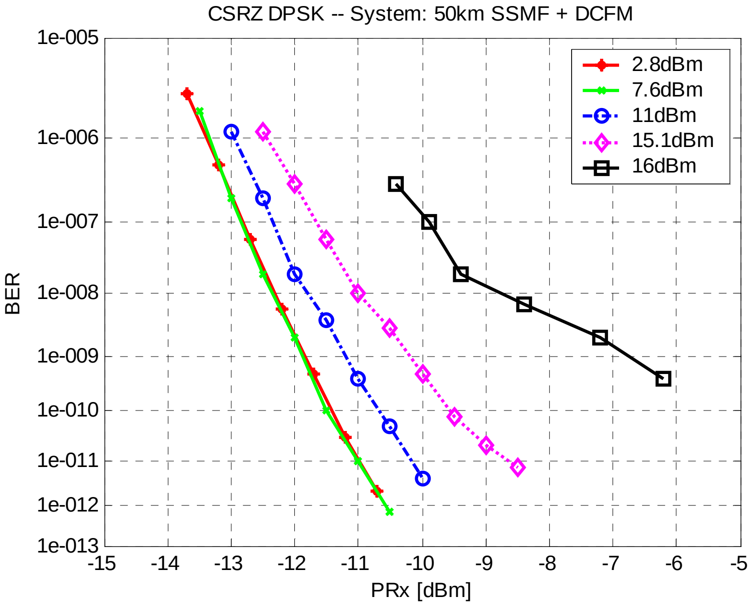


Figure 61 Transmission over 50 km SSMF dispersion management: BER versus Rx sensitivity with total launched power as a parameter. Modulation format: CSRZ-DPSK

11.2.2 RZ-DPSK

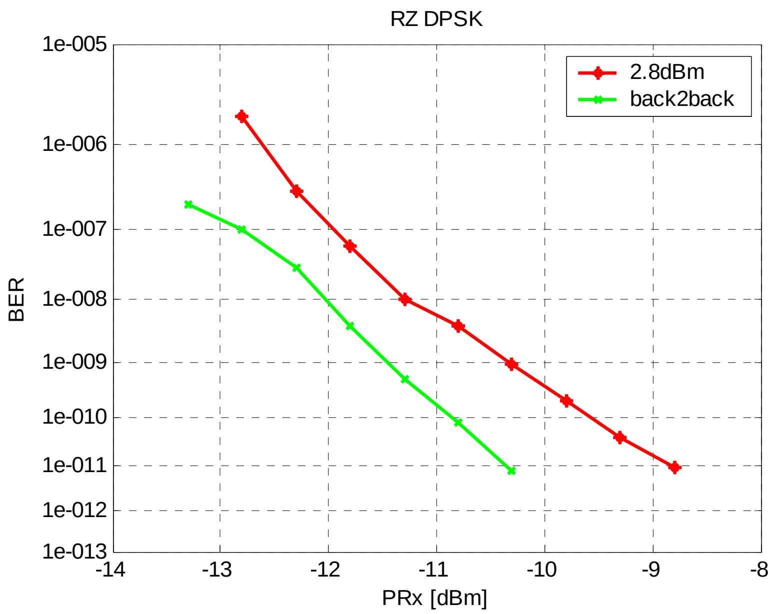


Figure 62 Transmission over 50 km SSMF: BER versus Rx sensitivity with total launched power as a parameter. Modulation format: RZ-DPSK

12 * 234KM SMF AND DCF FOR 230 KM TRANSMISSION

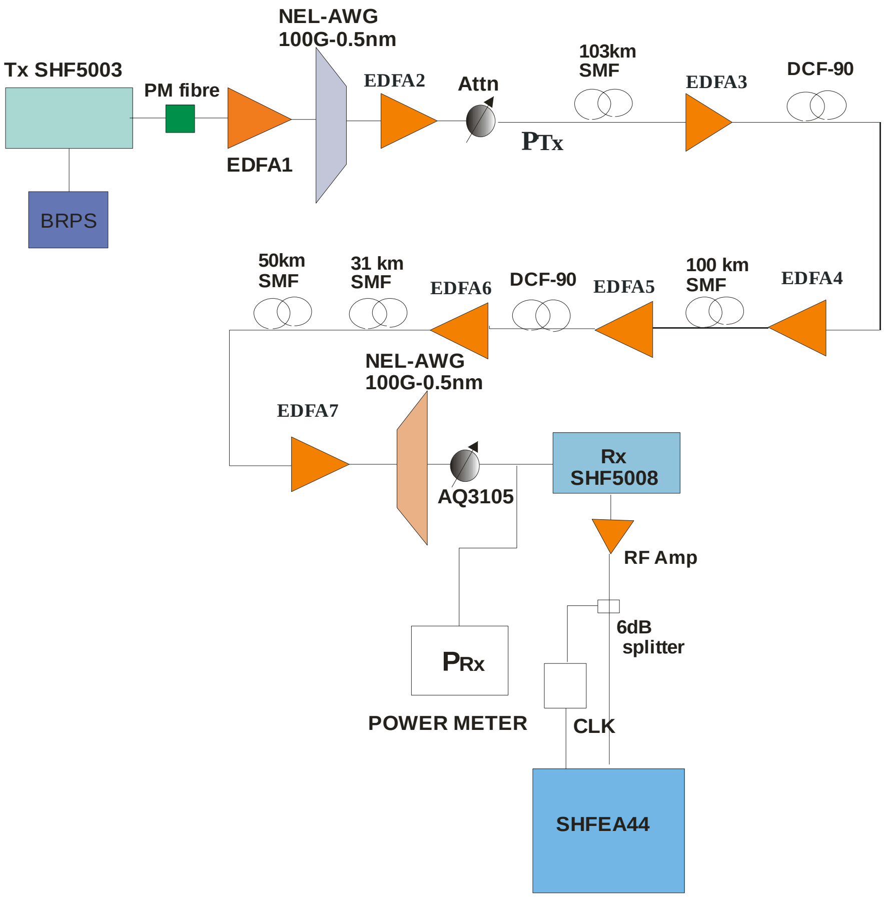


Figure 63 - Experiment setup: CSRZ DPSK 230km transmission, 234km SMF + DCF for 230km

Notes:

- Mobbing up the dispersion to have the best BER → λ10 = 1555.75 nm compared to λ5= 1551.72 nm. Hence, laser source is tuned to λ10.

- The nonlinear effect is explored by varying the optical power lauched into the SMF from 0dBm to 15dBm. The power lauched into the DCF is kept unchanged at 0dBm (nonlinearities are generated in SMF not DCF).

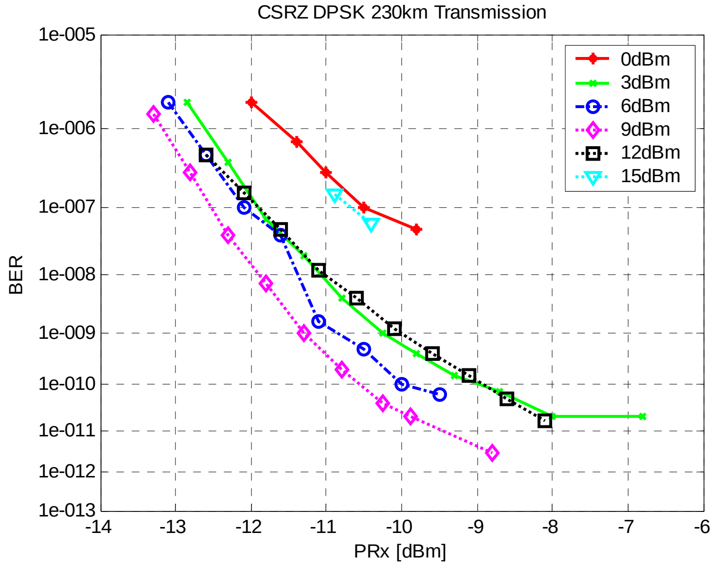


Figure 64 Figure 65 transmission over 234 km SSMF: BER versus Rx sensitivity with total launched power as a parameter. Modulation format: CSRZ-DPSK

- Optical filter JDS 0.35 nm 100G/8channel Mux/Demux filter .

12.1 "Filter Effects" with the same set up for comparison.

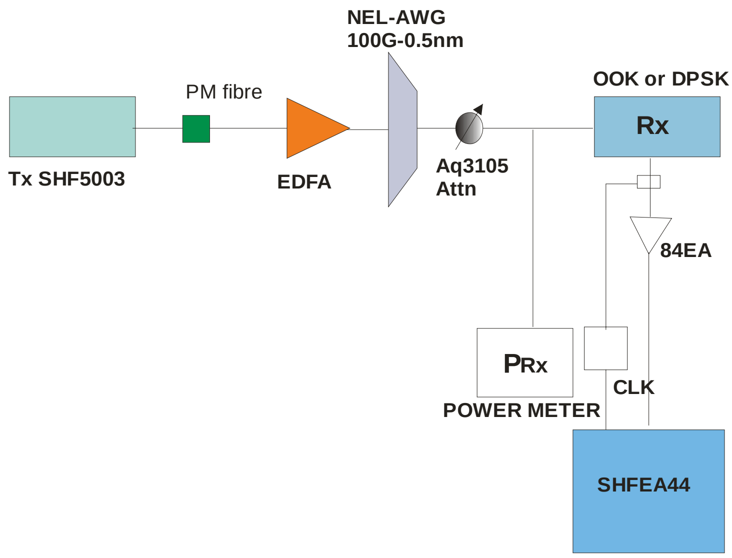


Figure 66 Measurement set-up of BER and Rx sensitivity due to filter effects

12.1.1 CSRZ-DPSK Filter Effects

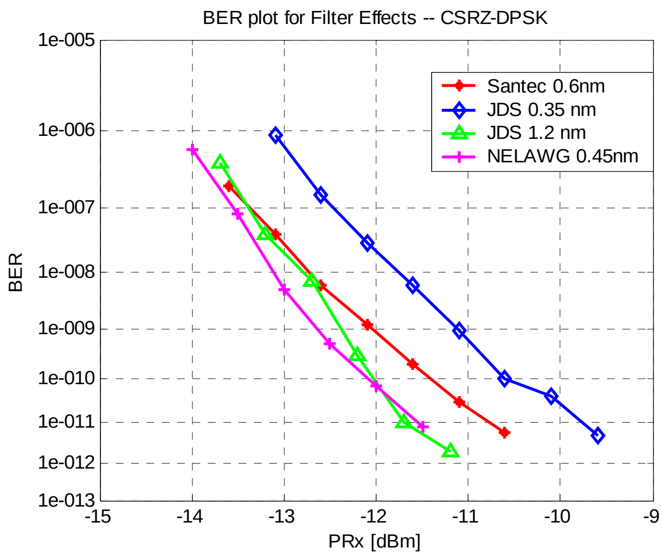


Figure 67 Optical filtering effects: BER versus Rx sensitivity format CS_RZ DPSK

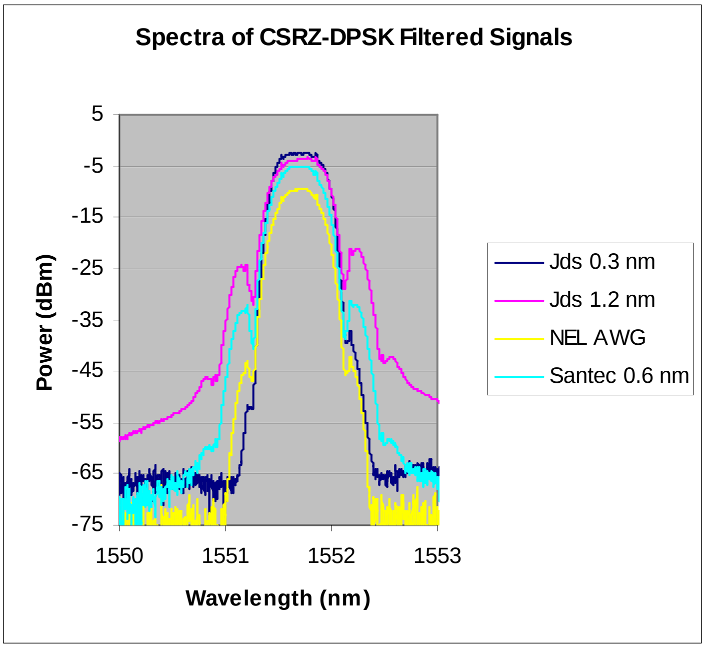


Figure 68 Optical Spectra of filtered lightwave signals

12.1.2 RZ-DPSK Filter Effects

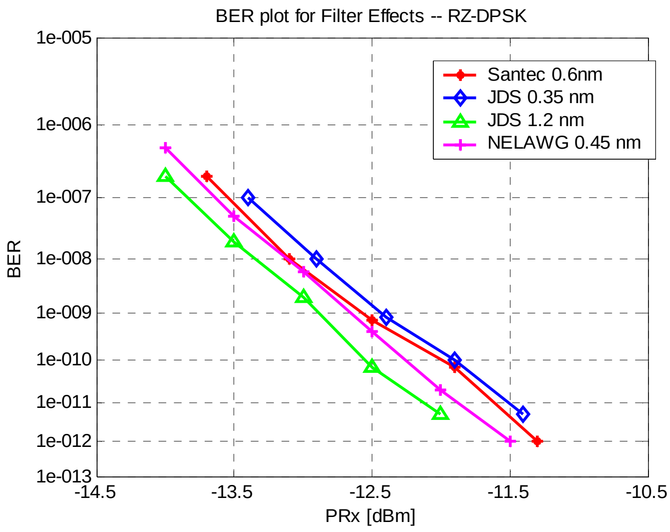


Figure 69 BER versus Rx sensitivity format RZ DPSK

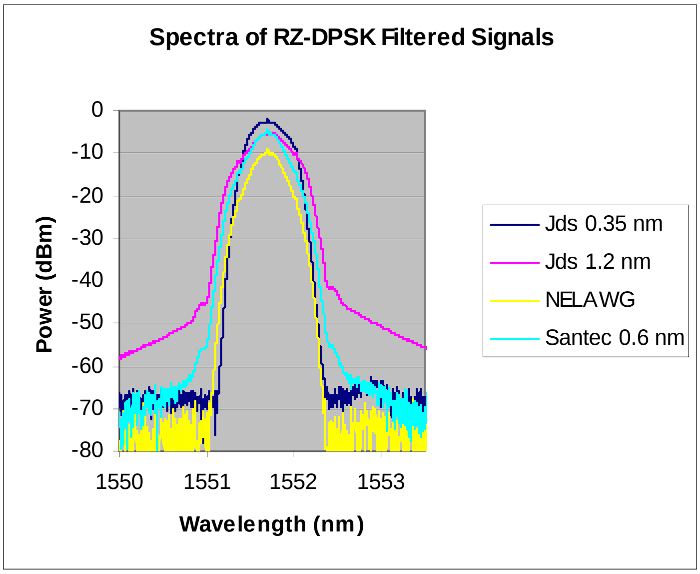


Figure 70 Optical Spectra of filtered lightwave signals- format RZ-DPSK

12.1.3 RZ-ASK Filter Effects

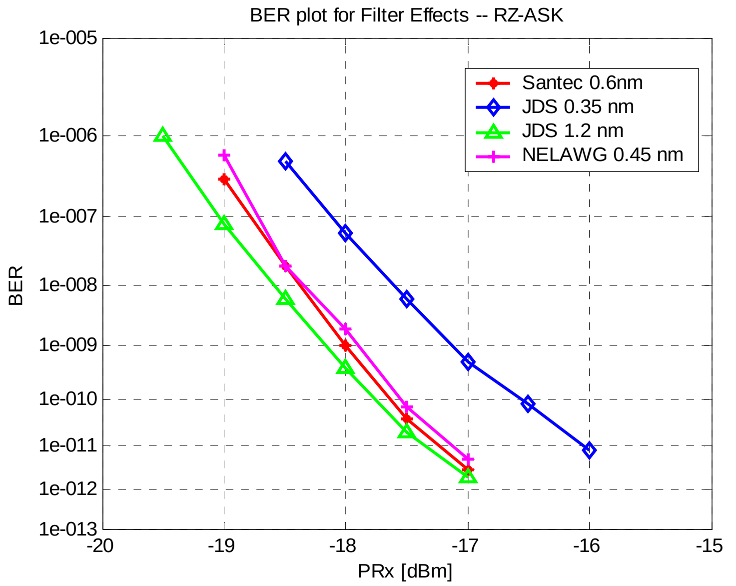


Figure 71 BER versus Rx sensitivity format RZ ASK

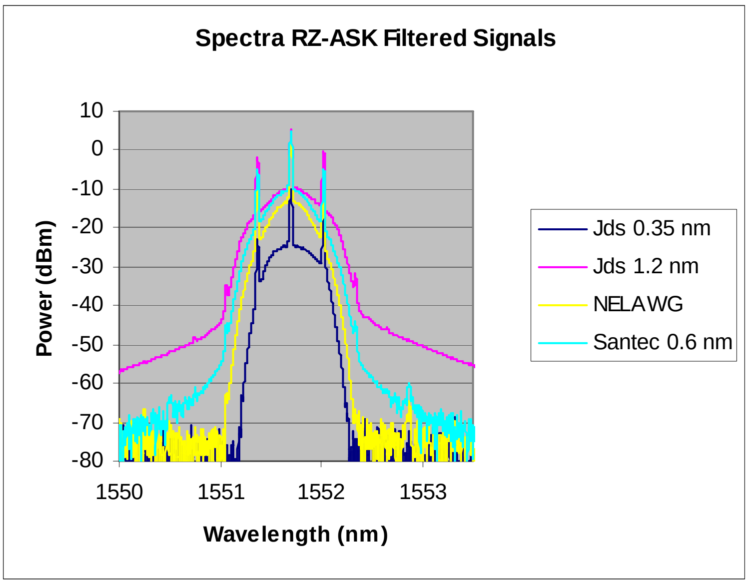


Figure 72 Optical spectra of optically filtered format RZ-ASK

- "CSRZ-DPSK + 0.35 nm JDS Mux/Demux filter" and detuning the wavelength of laser source to ensure that such a narrow filter is still be applicable to 40G/s CSRZ-DPSK signal.

13 CONCLUDING REMARKS AND FURTHER WORKS

The demonstration of the transmission of 40 Gb/s channels over 10 Gb/s DWDM optically amplified fibre communications systems has been proven that:

- It is possible to transmit 40Gb/s channels when the data sequence is encoded with amplitude and phase difference modulation.
- The formats CSRZ seems to offer the best performance and more dispersion tolerable than other reported formats.
- The impacts of optical filters employed in 10 Gb/s and 100 GHz channel spacing DWDM optically amplified system are minimal and should create no more than 2 dB penalty. This can be easily compensated with optical amplification of either EDFA or Raman distributed amplification.

- The nonlinear SPM effects are also investigated and it is proven that the 40 Gb/s does not suffer, especially when the CSRZ format is used.

Our next stage of investigation is to demonstrate the transmission of 40 Gb/s over a commercial 10 Gb/s DWDM optically amplified fibre transmission system, the Siemens TranXpress Multiwavelength Transport System as shown in Figure 73. A polarization emulator will be inserted in the fibre transmission path to simulate the real PMD effects in installed transmission fibres.

Once this demonstration is proven feasible we would arrange for permission to transmit 40 Gb/s channels over installed long haul transmission systems, e.g. Melbourne – Sydney or Adelaide to Perth optical transmission link.

Figure 73 The Siemens TranXpress Multiwavelength Transport System