MSc in Photonics

PHOTONICS**BCN**

Universitat Politècnica de Catalunya (UPC)
Universitat Autònoma de Barcelona (UAB)
Universitat de Barcelona (UB)
Institut de Ciències Fotòniques (ICFO)

http://www.photonicsbcn.eu

Master in Photonics

MASTER THESIS WORK

Nyquist WDM for FTTH Applications using Reflective Semiconductor Optical Amplifiers

Sebastian Knorr

Supervised by Dr. José A. Lazaro, (UPC)
and Dr. Bernhard Schrenk, (NTUA)

Presented on date 8th September 2011

Registered at

Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

Nyquist WDM for FTTH Applications using Reflective Semiconductor Optical Amplifiers

Sebastian Knorr
Teoria Senyal i Comunicacions, Universitat Politècnica de Catalunya, Edifici D4, C/ Jordi Girona 1-3, Barcelona 08034, Spain

E-mail: sebastian-knorr@web.de

Abstract. In this paper reflective SOAs are characterized for cost-efficient FTTH applications. The novel Nyquist WDM modulation format is investigated and implemented. An improvement of the bit error performance is achieved by a pre-distortion that compensates the bandwidth limitation of the reflective low-cost transmitter. The resulting modulation improves the BER and transmission speed. Furthermore, the format needs less signal processing compared to OFDM while reaching the same transmission rates.

Keywords: Nyquist WDM, RSOA, PON, FTTH, Optical broadband access

1. Introduction

Reflective semiconductor optical amplifiers (RSOA) are a key element of the customer premises equipment in passive optical networks (PON) for fiber-to-the-home (FTTH) applications. The advantages of these devices over others are the combined possibility to switch the gain fast enough to achieve high data rate intensity modulation and at the same time amplification of the optical input signal. The small chip sizes and low price make this device attractive for optical network units hosted by the end-users. For an efficient bandwidth usage more advanced modulation formats like orthogonal frequency-division multiplexing (OFDM) have been recently introduced [1]. To transmit and receive data Fourier transformations and other heavy and energy-hungry signal processing is required. This results in additional cost and complexity of the cost-sensitive end-user subsystem.
A novel approach to increase channel capacity in a less complex, but equally efficient way is Nyquist wavelength-division multiplexing (NWDM). In contrast to conventional WDM the optical signal is reduced to the minimum spectral width needed for transmitting the signal, which corresponds to the Nyquist frequency. The modulated signal has a rectangular spectral shape and allows tight spacing of neighboring sub channels. The advantage over OFDM is a higher robustness for longer transmission due to less complexity [2]-[3]. So far, NWDM was demonstrated to generate the signal using tunable Nyquist filters and Mach-Zehnder modulators [4] to realize the wave shaping. The so gained spectrum is almost rectangular and allows close spacing of the sub-channels. Nevertheless, the applied tunable filters are in general very expensive and therefore not a cost-effective solution for FTTH yet. A different approach to create the rectangular spectrum is to directly modulate with the appropriate driving signal to limit the bandwidth of the optical signal to the Nyquist frequency [5]. Using this method, the necessity of expensive filters is avoided, which, in turn, paves the way for FTTH applications.

2. Reflective SOA

In optical communication, RSOAs have major advantages compared to traditional photonic devices. They combine in a single element the possibilities of amplification and modulation of an optical signal. The underlying effect for this is the stimulated emitted radiation from electron-hole recombination. Depending on the semiconductor material, the amplification maximum varies and can be adjusted to the specific application. For the 3rd optical communication window at 1550nm it is possible to achieve amplification using InGaAsP, a combination of elements of the 3rd and 5th main group. Since the energy levels in semiconductors split up into a conduction and a valance band it is possible to amplify over a wide range of wavelengths to cover the entire spectral window that is intended to be used for data communication. SOAs can thereby achieve a wider optical gain bandwidth than rare earth-doped fiber-based amplifiers such as the Erbium-doped fiber amplifier.

The gain of the RSOA and, as a result, the introduced optical modulation, are influenced by the charge carrier distribution inside the semiconductor, which is given by

$$\frac{dn(z,t)}{dt} = \frac{I(t)}{edLW} - R(n) - \frac{\Gamma}{dW}\left\{\sum_{k=1}^{N_s} g_m\,(\nu_k, n)[E_s^+(z) + E_s^-(z)]\right\} - \\ -\frac{2\Gamma}{dW}\left\{\sum_{j=1}^{N_m-1} g_m\,(\nu_j, n)K_j\left[N_j^+(z) + N_j^-(z)\right]\right\} \tag{1}$$

where $I(t)$ is the modulated input current, dLW the dimensions of the active region, $R(n)$ the sum of parasitic recombination rates and Γ the confinement factor [6]-[7]. The first summation term is the stimulated recombination that is calculated by multiplying the frequency-dependent material gain with the intensity of the traveling wave in both propagation directions. In the second summation, the amplification of the spontaneous emission (ASE) is calculated in the same way. The gain g_m in (1) can be expressed as a function of a particular wavelength ν and number of carriers n by

$$g_m(\nu, n) = \frac{c^2}{4\sqrt{2}\pi^{\frac{3}{2}}n_1^2\tau_e\nu^2}\left(\frac{2m_e m_{hh}}{\frac{h}{2\pi}(m_e + m_{hh})}\right)^{\frac{3}{2}} \cdot \sqrt{\nu - \frac{E_g(n)}{h}}\,(f_c(\nu) - f_v(\nu)) \tag{2}$$

with n_1 the refractive index of the active medium, τ_e the radiative carrier recombination lifetime, m_e and m_{hh} the mass of electron and heavy hole respectively, $E_g(n)$ the carrier dependent band gap and f_c and f_v the Fermi distribution in the conduction and valance band. With the differential equation (1), the amplification of the optical input signal depending on the injected charge carriers can be calculated using traveling wave equations for the signal field in positive and negative propagation direction along the amplifying medium

$$\frac{dE_S^+(z)}{dz} = \left(-j\beta_k + \frac{1}{2}\left(\Gamma g_m(\nu_k, n) - \alpha(n)\right)\right)E_S^+(z) \tag{3}$$

$$\frac{dE_S^-(z)}{dz} = \left(j\beta_k - \frac{1}{2}\left(\Gamma g_m(\nu_k, n) - \alpha(n)\right)\right)E_S^-(z) \tag{4}$$

where β_k is the signal propagation coefficient and $\alpha(n)$ the signal attenuation coefficient of the material. The same equations are also valid for the respective ASE calculations.

With the combination of the coupled differential equations, it is possible to simulate the response of the RSOA deriving from a modulation of the input bias current. For a simple rectangular modulation, this is shown in figure 1, where the input current is just switched between two levels. The lower level is chosen with a residual value to keep the ROSA in operation above the quasi-threshold current. As it can be clearly seen, the change of charge carriers introduces delays and when switching the input current, it takes time for the system to reach the equilibrium state. This results in overshoots when increasing the current.

For the modulation with more sophisticated techniques this introduces distortion of the signal and limits in bandwidth, which can result in bit errors. These problems need to be taken into account when modulating at the bandwidth limits of the electro-optical transmitter device.

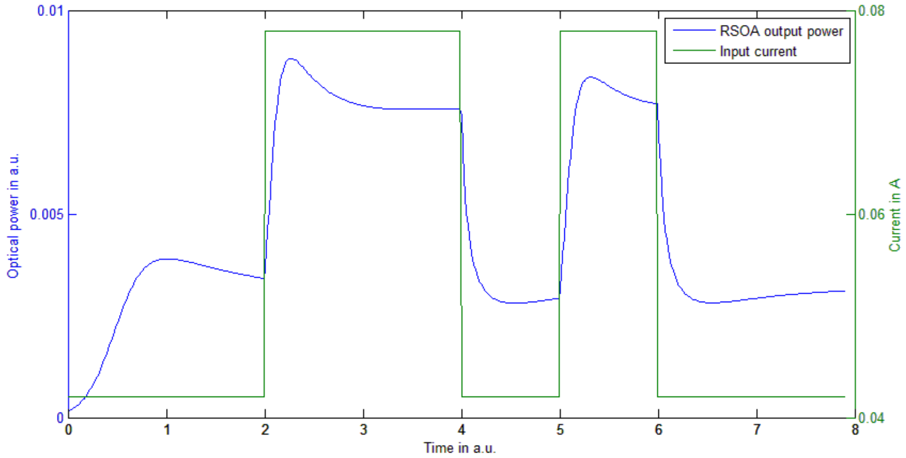


Figure 1. Simulated behavior of RSOA output power (blue) for modulated input current (green)

3. Modulation formats

3.1. Common modulation formats

Regarding the simple NRZ (Non-Return to Zero) format, the spectrum of the signal is broadened significantly compared to the modulation frequency. To achieve better efficiencies in bandwidth usage, new promising techniques are under development. Currently, OFDM is the one at which most research groups are aiming for, since it is possible to reach the Nyquist limit. Using interference free orthogonal frequencies, a rectangular pulse in time domain is created and the information is carried in the spectrum. To code and decode the information, Fourier transformation is necessary, what requires a huge amount of electrical pre- and post-processing. This decreases the robustness of the modulation format.

3.2. Nyquist modulation

In contrast to OFDM, Nyquist WDM creates the rectangular shape in frequency domain. This allows a close spacing of each carrier without crosstalk in between the channels. To achieve this, several methods are possible. Since all the information carried by frequencies larger than $f_{mod}/2$ is not necessary to recover the information, it is possible to filter tightly [2]. The drawbacks of this method are the high costs for such precise filters.

A better method in terms of cost efficiency is to modify the input signal and directly create the rectangular shape in frequency at the output of the modulator. The shape of each bit is therefore the inverse Fourier transformation of the rectangular, what is the *Sinc* function with periodicity of $T = 1/f_{mod}$. However, to implement this function it needs to be finite and causal. To fulfill these requirements the implemented signal is windowed and time shifted.

The Nyquist modulation can therefore be calculated according to [5]

$$E(t) = \sum_{n=-\infty}^{\infty} c_n \, sinc\left(\pi \frac{t-nT}{T}\right) \cdot \prod\left(\frac{t-nT}{kT}\right) \qquad (5)$$

where c_n is the information encoded in the nth symbol and $\Pi(t/\tau)$ a rectangular window of width τ centered on t = 0. The parameter k determines the number of bits the window is extended to. A typical encoded bit sequence for k = 8 is given in figure 2, together with the ideal sampling points. Since the *Sinc* function is orthogonal, the intensity levels for each sampling point are the same.

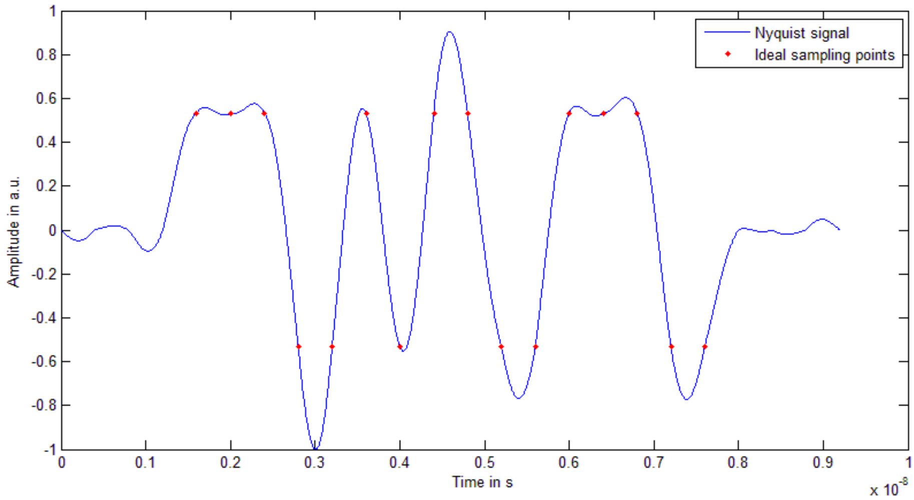


Figure 2. Sequence for k = 8, $c_n \epsilon \{1,-1\}$ and the ideal sampling points.

The requirement of a finite signal has significant influence on the shape of the desired rectangular spectrum. By increasing the length of the window, the intensity of the side lobes is reduced. As it can be seen in figure 3, the spectrum can be limited by extending the signal to enough neighboring bits as shown for a window of 4T, 16T and 64T. To avoid significant crosstalk an extension of the *Sinc* function to at least 64T is necessary.
On the other hand, extending the signal to more neighboring bits generates higher peaks at the electrical modulating signal, so that an optimal trade-off has to be found.

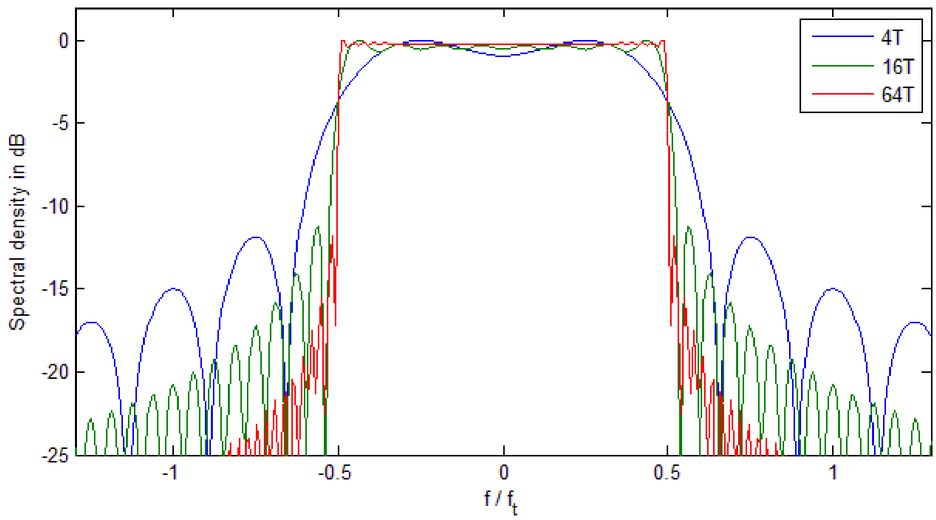


Figure 3. Spectral density for *Sinc* function extended to 4, 16 and 64 neighboring bits.

4. Experimental

4.1. RSOA characteristics

4.1.1. Setup.

The RSOA used in this work is a cheap commercial transmitter-outline component by Kamelian with a bidirectional optical pigtail. To compose the necessary input current for the optical amplifier, the RF signal is amplified additionally and combined with a DC bias current using a bias tee. The combined electrical amplification system and mostly the chip-bonding wires inside the RSOA package show strong limitations regarding the electro-optical bandwidth [7]. For the analysis of best operation conditions, the setup in figure 4 is used to characterize the frequency dependency with respect to bias current and optical input power. The laser for stimulating the emission of the RSOA is set to the 3rd optical window and coupled to the semiconductor device using a 50/50-coupler. Isolators at the input and output of the coupler together with APC connectors at all optical connections avoid back reflection into the laser and RSOA. To measure the frequency dependency, an arbitrary waveform generator (AWG) is used to create a frequency sweep. The system response is then analyzed with a combination of PIN photodiode and oscilloscope.

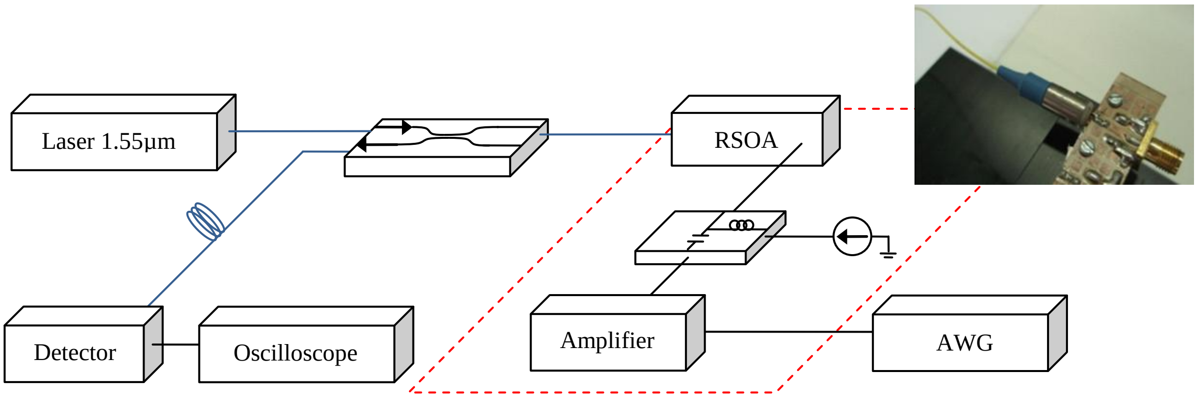


Figure 4. Setup for characterization of RSOA and Amplifier.

4.1.2. Results.

To determine the electro-optical small signal response, the bias current was set to 40mA, 60mA and 80mA, while the optical input power to the RSOA was varied between -6.5dBm, -10dBm and -15dBm at a wavelength of 1.55µm.

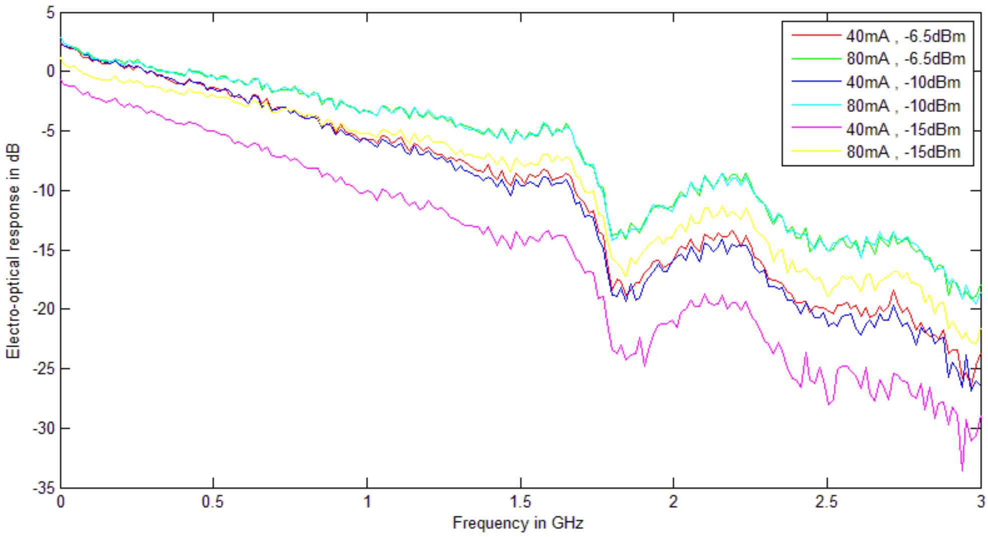


Figure 5. Frequency response of RSOA + RF amplifier at 40mA and 80mA bias and -6.5dBm, -10dBm and -15dBm optical input power.

The resulting frequency response shows, that 60mA and 80mA bias result in similar electro-optical characteristic, allowing also a high modulation extinction ratio. In figure 5, the electro-optical response is plotted over the RF input frequency for a bias current of 40mA and 80mA with an optical input power of -6.5dBm, -10dBm and -15dBm. The graph shows that the 3dB bandwidth is best with 500MHz for -6.5dBm and 80mA bias. While there is not much difference between injection power levels of -6.5 and -10dBm, a further decrease to -15dBm leads to a steeper slope in case of a reduced bias current. Taking this result, the highest modulation frequency for NRZ modulation without distortions is around 700MHz, meaning a maximum delivered data rate of 700Mb/s.

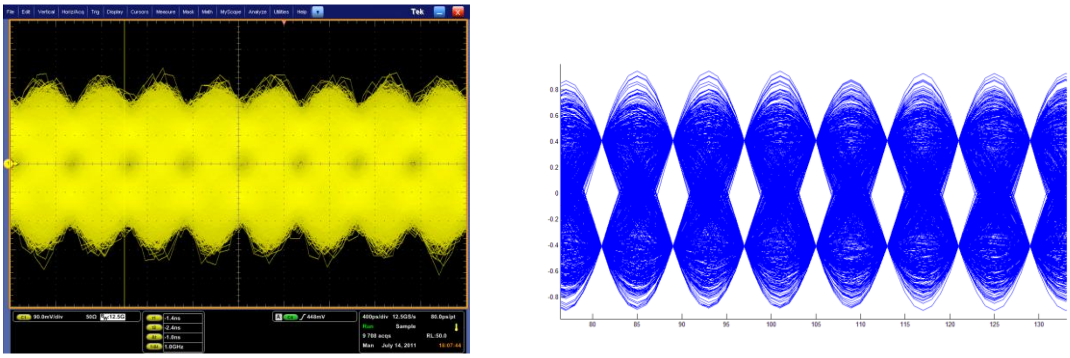
4.2. Nyquist WDM

4.2.1. Setup.

To evaluate the advantages of NWDM over conventional NRZ modulation, the setup from figure 4 is used to measure the back-to-back performance of the different formats. The NWDM signal is created by convolution of the information with the Sinc function. To make sure that the AWG is able to create the desired signal an oversampling factor of at least 3 samples per bit is chosen.

4.2.2. Result.

With the given setup and the best conditions of 80mA bias current and -6.5dBm optical input power, the RSOA is modulated with 2Gbps NWDM signal. Examining the eye diagram (figure 6(a)), we can see that the bandwidth limitations distort the signal in a way, that significant bit errors are introduced compared to the simulation for the best shape in figure 6(b). The distortion affects the signal so strong, that the bit error rate (BER) is penalized, and even lower than in case of NRZ at 2Gbps.



(a) (b)

Figure 6.Eye diagram from (a) measurement at 2Gbps, 80mA bias and -6.5dBm opt. input and (b) optimum shape from simulation.

To overcome these limitations and to increase the bit rate of the system, a further compensation is necessary. Since the rectangular spectrum of the *Sinc* function is distorted by the characteristics of amplifier and RSOA the driving signal has to be modified. Therefore the *Sinc* spectrum is multiplied by the inverse of the system characteristics to enhance frequencies that are attenuated stronger. The new pre-distorted *Sinc* function can be calculated to

$$\mathcal{F}t\left(Sinc_{pre-distorted}\right) = \frac{\mathcal{F}t(Sinc)}{F_{system}} \tag{6}$$

where F_{system} is the frequency dependency characterized in of chapter *4.1.2.* and $\mathcal{F}t(F)$ the Fourier transformation of the function *F*. In this way, the introduced pre-distortion compensates the system limitations without adding further physical components. In figure 7 the *Sinc* function and the pre-distorted signal are plotted for a bit rate of 2.5Gbps, a bias current of 80mA and an optical input power of -6.5dBm into the RSOA.

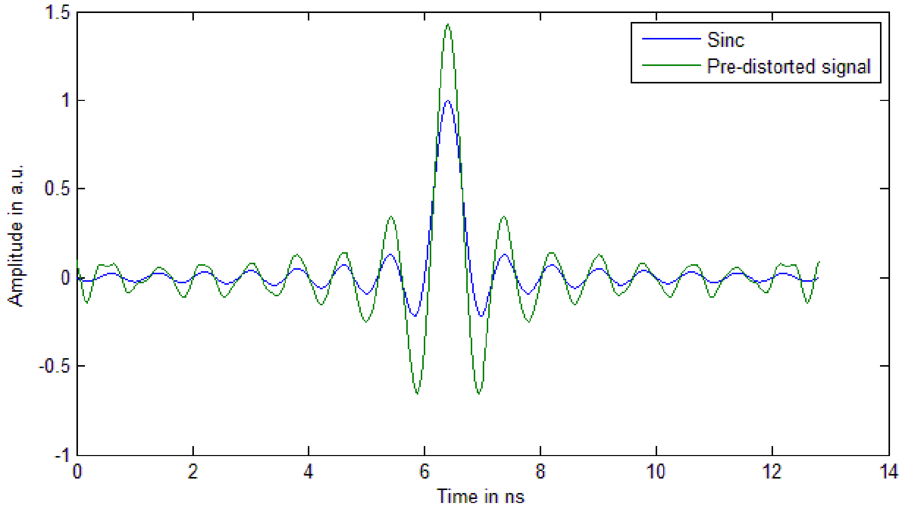


Figure 7. Sinc and pre-distorted function for 2.5GHz, 80mA bias and -6.5dBm optical input power.

Using the pre-distorted signal, the same configuration is tested again and the eye diagram is captured after the detector. As shown in figure 8 the bandwidth limitations take less influence on the transmission of the data signal. The received eye is now open and the detection of the information is possible by measuring whether the output voltage of the PIN diode is over a certain threshold level for giving decision point in time. On top of this it is possible, due to oversampling at the detector, to average over the neighboring samples for a further improvement of the bit error performance.

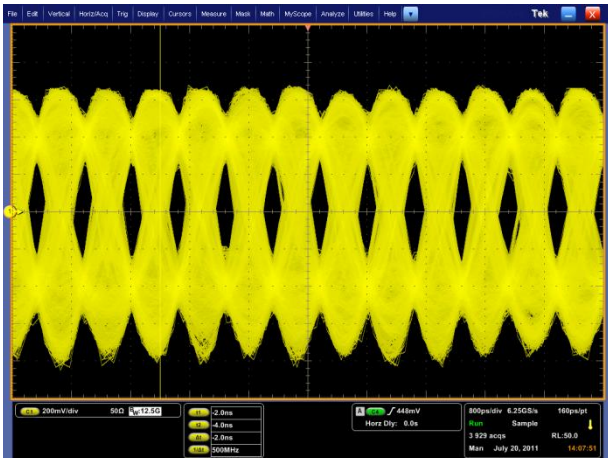


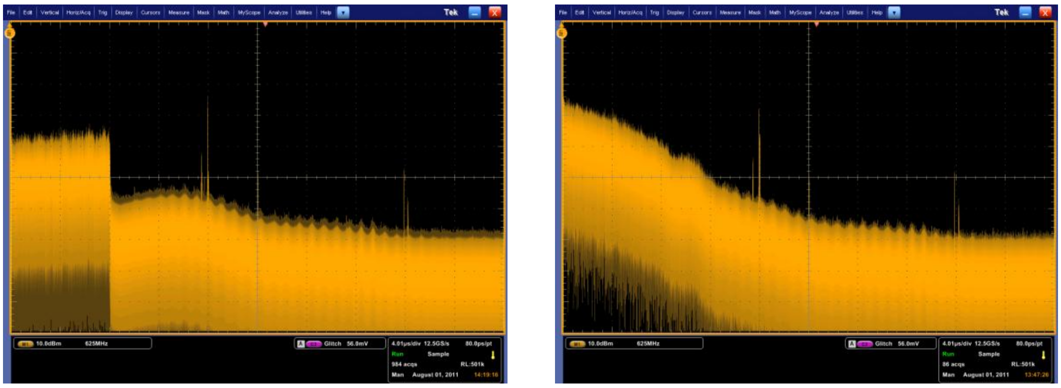
Figure 8. Eye diagram of pre-distorted signal.

To evaluate the performance of NRZ, state-of-the-art NWDM and NWDM with pre-distorted *Sinc*, the BER is measured for a back-to-back configuration and different modulation frequencies and an input power to the PIN detector of -14dBm. Table 1 shows that an applied pre-distortion in case of NDWM can significantly improve the BER. Having a system with a bandwidth of 500MHz, it is possible to modulate with more than 6 times the bandwidth with acceptable penalties in the BER. Compared to NRZ it is possible to use the modulator more effectively and also to reduce the spectral bandwidth to the Nyquist limit.
Using forward error correction (FEC) techniques, a BER as low as 2e-4 is acceptable for receivers implementing Reed Solomon(255,239) FEC. In this case at 2.5Gbps only NRZ and pre-distorted NWDM are acceptable. Furthermore, pre-distorted NWDM permits a transmitted bit rate of up to 3Gbps.

Table 1. BER for NRZ, NWDM and Pre-distorted NWDM for different modulation frequencies.

	NRZ	**NWDM**	**Pre-distorted NWDM**
2.5 Gbps	2e-5	1.9e-3	<1e-5
3.125 Gbps	1.4e-2	2.7e-2	2.9e-4

Regarding the electrical signal detected by the PIN diode, we measure the expected rectangular shape of the spectrum. The width of the spectrum is with 1.25GHz exactly half of the Nyquist frequency and the level of the higher frequencies is 20dB lower than the signal, as shown in figure 9(a). Compared to the NRZ spectrum in figure 9(b), NWDM gives major improvements in spectral efficiency.



(a) (b)

Figure 9. Electrical spectrum 2.5GHz modulation frequency for (a) NWDM and (b) NRZ.

For further evaluation of the optical transmission link, the optical spectrum is measured. For this, a second laser is tuned to the same wavelength as the transmission wavelength and coupled to the signal. The interference of the two signals is then detected and the spectrum measured. In figure 10 the optical spectra of NRZ and NWDM are plotted for the same bit rate of 2.5GHz relative to carrier frequency. The resulting spectrum of NWDM makes it possible to space consecutive bands closer together and increase therefore the transmission capacity of current systems.

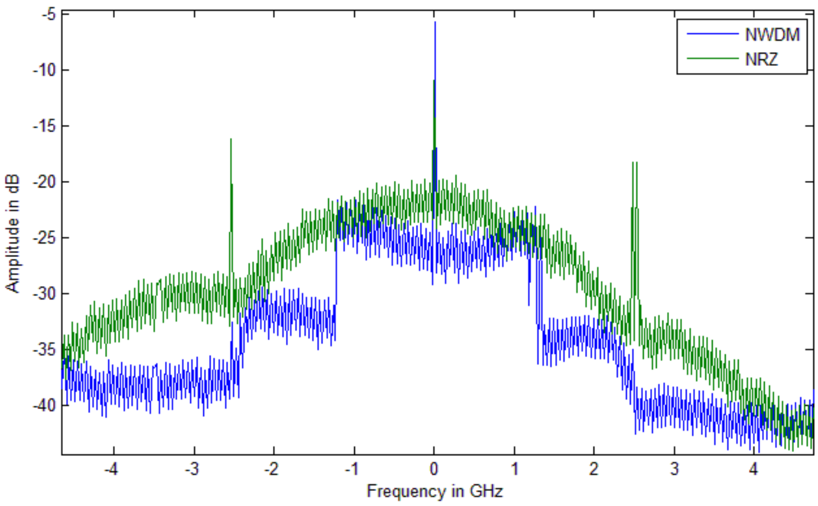


Figure 10. Optical spectrum for NDWM and NRZ for 2.5Gbps relative to the carrier frequency.

4.3. *Transmission over fiber*

4.3.1. Setup

For the application in a PON it is important that the system works for different optical power levels at the input of the RSOA. To investigate this, the setup from figure 4 is extended by a standard single mode fiber (SSMF) of 25km length. In addition, the power level at the input of the RSOA is varied between -6.5dBm and -15dBm. To always compare the best operating conditions, the pre-distortion is adapted to the respective power levels. The data rate was kept at 2.5Gbps.

4.3.2. Results

The transmission through 25km of SSMF for the optimum conditions of -6.5dBm optical input power shows no significant change in the BER (figure 11). In a series of 100.000 random created bits no error could be detected, what equals an error rate of lower than 10^{-5}. For a wide rage till -12.5dBm, the BER is low enough for applying FEC and guarantee error free transmission. However, for power levels lower than -12.5dBm the introduced bit errors exceed the acceptable minimum for FEC. The electro-optical response curve for these low input powers is too steep to be compensated by an appropriate pre-distortion.

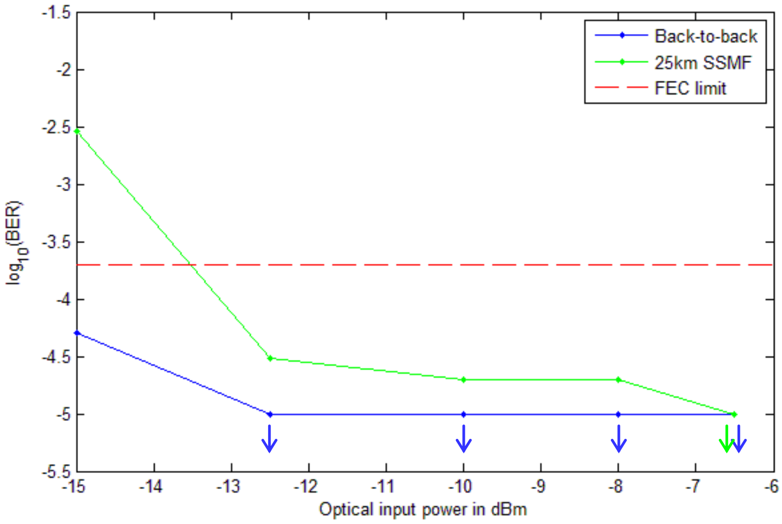


Figure 11. BER over optical input power of RSOA for 2.5Gbps for back-to-back and 25km SSMF.

5. Conclusions

In this work the advantages of Nyquist WDM over conventional NRZ are presented. The reduction of the optical spectrum to its minimum allows tighter spacing of the sub bands and therefore higher transmission capacity for a given channel. In addition, the Nyquist signal is generated by modifying the modulation current, which makes the use of expensive sharp filters to create the rectangular spectrum unnecessary. This makes the concept more flexible and, due to lower costs, attractive for FTTH applications.

While current Nyquist WDM modulation does not enhance the modulation frequency of limited bandwidth, but cost-efficient RSOAs, by a new introduced pre-distortion of the modulating signal, it is possible to extend the modulation frequency up to 6 times the 3dB bandwidth of the RSOA without additional physical components necessary and at the same time to improve the BER. The pre-distortion also makes it possible to adapt the modulation to the bandwidth characteristics of the RSOA and therefore improve the performance in a PON, where the number of users results in a changing power level at the input of the semiconductor.

6. Outlook

The new approaches developed and demonstrated in this work were submitted to the Spanish patent office for a first evaluation. On this basis further studies are necessary to investigate and improve the concept for an application in the industry. Since current developments of semiconductor modulators further improve the performance of these transmitters of potential low cost, the advantages of higher bandwidth RSOAs, reduced chirp RSOAs or SOA+REAM combinations need to be investigated for NWDM.

Acknowledgement

Thanks to my supervisors José A. Lazaro and Bernhard Schrenk for supporting me during my thesis and to Victor Polo and the PhD students for helping me with my setups during the experimental work.

References

[1] Wei J L, Yang X L, Giddings R P and Tang J M 2009 Colourless adaptively modulated optical OFDM transmitters using SOAs as intensity modulators *Opt. Express* **17** 9012-9027

[2] Bosco G, Carena A, Curri V, Poggiolini P and Forghieri F 2010 Performance Limits of Nyquist-WDM and CO-OFDM in High-Speed PM-QPSK Systems *Photonics Tech. Letters* **22** 1129-1131

[3] Bosco G, Carena A, Curri V, Poggiolini P, Torrengo E. and Forghieri F 2010 Investigation on the Robustness of a Nyquist-WDM Terabit Superchannel to Transmitter and Receiver Non-Idealities *ECOC'10* Tu.3.A.4

[4] Dong Z, Yu J, Chien H, Chi N, Chen L, and Chang G 2011 Ultra-dense WDM-PON delivering carrier-centralized Nyquist-WDM uplink with digital coherent detection *Opt. Express* **19** 11100-11105

[5] Winter M 2011 Nyquist Pulse Signalling for Spectrally Efficient Terabit/s Superchannels http://www.marcuswinter.de/media/publications/rejected/ptl2011.pdf

[6] Connelly M 2002 *Semiconductor Optical Amplifiers* (Boston: Kluwer Academic Publisher)

[7] Schrenk B 2011 *Characterization and Design of Multifunction Photonic Devices for Next-Generation Fiber-to-the-Home Optical Network Units* (Barcelona) PhD dissertation, Univ. Politec. Catalunya