Digital Nyquist WDM for Access Networks using Limited Bandwidth Reflective Semiconductor Optical Amplifiers

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Abstract: Digital Nyquist-WDM is experimentally demonstrated using RSOA-based colorless ONUs, providing a 6-fold enhancement of transmission capacity through 25km fiber, and showing digital Nyquist-WDM as promising candidate for cost-effective flexible bandwidth allocation in PONs.
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1. Introduction

Reflective semiconductor optical amplifiers (RSOA) are a key element of the customer premises equipment in passive optical networks (PON) [1]. 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 [2].

A novel and equally efficient approach to increase channel capacity is Nyquist wavelength-division multiplexing (Nyquist-WDM). 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 and consequently a high spectral efficiency (SE). The advantage over OFDM is a lower complexity in implementation aspects, e.g. it requires a significantly lower electrical transmitter and receiver bandwidth [3, 4].

So far, Nyquist-WDM has been demonstrated in PON scenarios using tunable Nyquist filters and Mach-Zehnder modulators [5] to realize the wave shaping. The 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 PON yet. Moreover, penalties arise when the ideal constraints of Nyquist WDM implementation are relaxed [4]. A different approach to create the rectangular spectrum is to perform spectral shaping in the digital domain through the use of digital signal processing (DSP) and digital-to-analog conversion (DAC) at the transmitter [6]. This approach, called digital Nyquist-WDM [7], has been recently compared by simulations with previous, said optical Nyquist-WDM, confirming the good performance of digital Nyquist-WDM, as a promising technology for the generation of ultra-high spectral-efficiency signals [7], and avoiding the necessity of expensive optical filters.

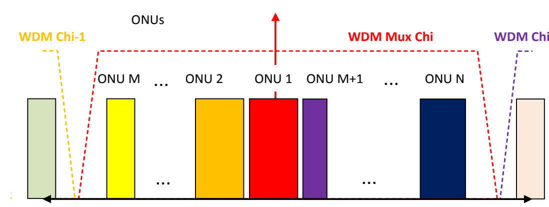

Fig.1. Nyquist-WDM variable bandwidth channels allocation for ONUs upstream transmission in a high capacity converged wireline-wireless access networks [8].

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, providing a convenient and flexible bandwidth allocation in WDM for PON applications, where, as for ODFM, different ONUs can be assigned Nyquist WDM channels with variable bandwidth, depending on their traffic demands as shown in Fig 1, for high capacity converged wireline-wireless access networks as proposed in [8].

One of the advantages of digital Nyquist-WDM compared with filter-based optical Nyquist-WDM is the higher flexibility on electronics, based on the combination of DSP and DAC for a flexible bandwidth of the Nyquist channel. In contrast, the optical Nyquist-WDM solution requires expensive bandwidth variable Nyquist filters.

Nyquist-WDM is based on modifying the input signal and directly creating 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, that is the sinc function with periodicity of $T = 1/f_{mod}$. A feasible version of the sinc function requires a delayed and windowed version of the sinc function, as usually proposed [9].

While several previous works have been focused on proposing improved Nyquist pulses based on windowed or truncated sinc functions [9, 10], to the best of our knowledge, no experimental test has been published yet. We

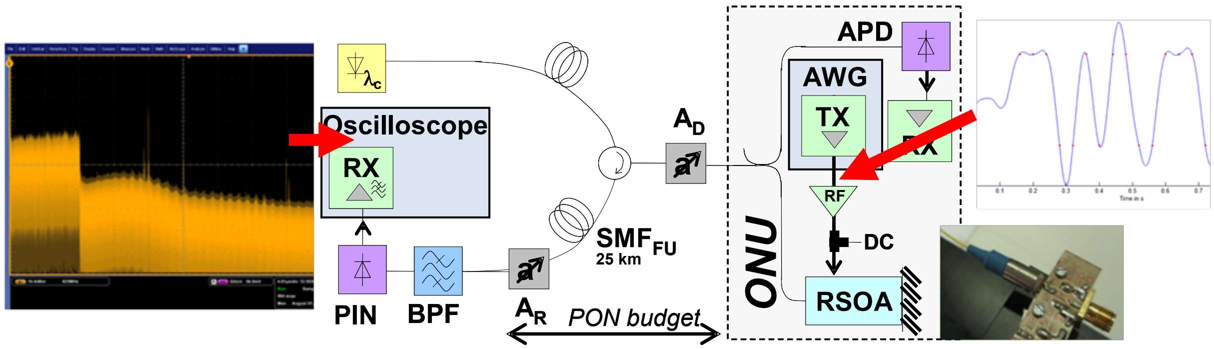

Fig.2. Setup for digital Nyquist-WDM transmission with RSOA-based ONU (central); example of time domain Nyquist modulation signal at the output of the Arbitrary Waveform Generator (AWG) and ideal sampling points (right); electrical spectrum at receiver side for 2.5 Gbps (left).

demonstrate the feasibility for intensity modulation direct detection (IM-DD), as the simplest solution for PONs. In Fig 2, an example of Nyquist modulation and the compact rectangular spectral shape obtained are shown.

3. Experimental generation of Digital Nyquist-WDM with bandwidth limited RSOA

The RSOA used in this work is a cost-effective commercial transmitter-outline component (TO-can), Fig 2. The combined electrical amplification system and mostly the chip-bonding wires inside the RSOA package show strong limitations in terms of electro-optical bandwidth [11]. 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 1550nm, and coupled to the semiconductor device using a circulator with APC connectors to avoid reflections and a Network Analyzer (NA) not shown in Fig 2.

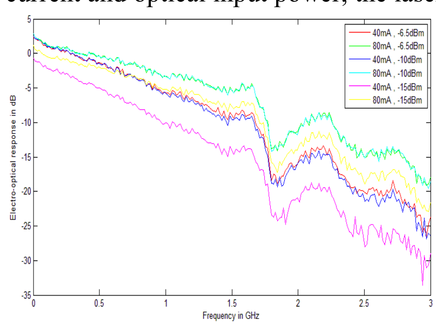

Fig.3. Frequency response of RSOA + RF amplifier at 40mA and 80mA bias and -6.5dBm, -10dBm and -15dBm optical input power.

The electro-optical small signal response was measured; for bias currents of 40mA, 60mA and 80mA, while the optical input power to the RSOA was varied between -6.5dBm and -15dBm at 1550nm as it shown in Fig 3. The best 3dB bandwidth is 500MHz for -6.5dBm and 80mA bias, providing a highest delivered data rate for an undistorted NRZ modulation of 700Mb/s.

The digital Nyquist-WDM signal is created by convolution of the information with the sinc function as shown in Fig 4(central). 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. With the given setup, the RSOA is operated at the best conditions, 80mA bias and -6.5dBm optical input power, and modulated with a 2Gbps digital Nyquist-WDM signal. Examining the eye diagram Fig 4(left), we can see that the bandwidth limitations distort the signal so strongly, that the bit error rate (BER) is penalized, performing worse than usual NRZ at 2Gbps.

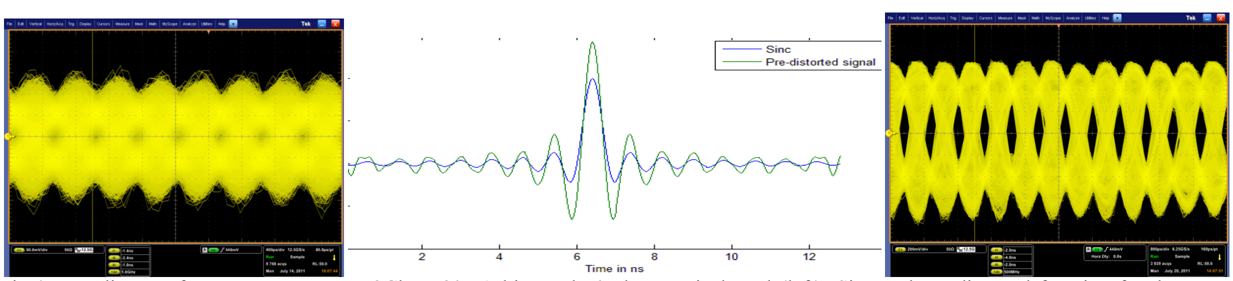

Fig.4. Eye diagram from measurement at 2Gbps, 80mA bias and -6.5dBm optical seed (left); Sinc and pre-distorted function for the same conditions (central); eye diagram of pre-distorted signal (right).

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 amplifier and RSOA characteristics, the driving signal has to be modified. Therefore the sinc spectrum is multiplied by the inverse of the system characteristics to enhance the frequencies that experience a stronger attenuation. The new pre-distorted sinc function can be calculated as

$$\mathcal{F}t(\mathrm{sinc}_{\text{pre-distorted}}) = \frac{\mathcal{F}t(\mathrm{sinc})}{F_{system}}, \tag{1}$$

where F_{system} is the frequency dependency characterized in Fig 3, and $\mathcal{F}t(F)$ is the Fourier transformation of the function F.

In this way, the introduced pre-distortion compensates the system bandwidth limitations without adding further physical components. In Fig 4(central), 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. Using the pre-distorted 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 appropriate sampling time, minimizing inter-symbol interference (ISI) [6], as shown in Fig 4(right).

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

	NRZ	**Digital Nyquist**	**Pre- dig Nyquist**
2.5 Gbps	**2 10^{-5}**	**1.9 10^{-3}**	**<1 10^{-5}**
3.125 Gbps	**1.4 10^{-2}**	**2.7 10^{-2}**	**2.9 10^{-4}**

To evaluate the performance of NRZ, state-of-the-art digital Nyquist-WDM and pre-distorted digital Nyquist, the BER is measured for a back-to-back configuration and different modulation frequencies for a reference 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 2.10^{-4} is acceptable for receivers implementing Reed Solomon (255,239) FEC. In the case, at 2.5Gbps only NRZ and pre-distorted NWDM are acceptable. Furthermore, pre-distorted NWDM permits a transmitted bit rate up to 3Gbps.

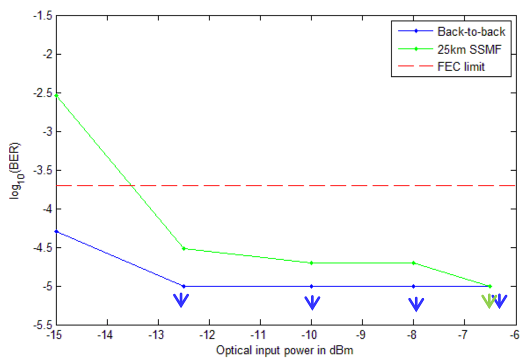

Fig.5. BER vs. optical seed input power of RSOA for 2.5Gbps transmission for back-to-back and 25km SSMF.

For the application in a PON, transmission has been performed at 2.5Gbps along standard single mode fiber (SSMF) of 25km length, SMF_{FU} in Fig 2, with optical power levels at the input of the RSOA varying between -6.5dBm and -15dBm. To always compare the best operating conditions, the pre-distortion is adapted to the respective power levels, taking advantage of the flexibility provided by digital Nyquist. The transmission through 25km of SSMF for the optimum conditions of -6.5dBm optical seed to the RSOA shows no significant change in the BER (Fig 5). Within the maximum length of the bit stream (limited by the data buffer of the AWG), it corresponds to an upper BER bound of 10^{-5} with respect to a confidence interval of 95%. For a wide range until -12.5dBm, the BER is low enough for applying FEC and guarantee error free transmission. However, for RSOA seed 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, Fig 3, to be compensated by an appropriate pre-distortion.

4. Conclusion

First experimental demonstration of the potential of digital Nyquist-WDM to provide high spectral efficient signals using colorless ONUs based on commercial electro-optical bandwidth limited RSOAs. It has been also demonstrated that a maximum transmitted bit rate up to 6 times the 3dB bandwidth of the RSOA can be obtained without additional components, by using adequate pre-distorted Nyquist-WDM signal, achieving transmission through 25km of SSMF for RSOA input power levels > -12.5dBm.

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