



## Characterization of phase modulated non-return-to-zero (PM-NRZ) format for DWDM long reach PONs

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### ABSTRACT

A technique which has been shown to be effective to mitigate the Rayleigh backscattering (RB) noise and potentially suited for use in the carrier distributed passive optical networks (PONs), uses a phase modulator (PM) at the reflective optical networking unit (RONU) to reshape the spectrum of the upstream non-return-to-zero (NRZ) signal, named PM-NRZ. Since the PM-NRZ signal has a much wider spectrum than the conventional NRZ signal, it would be very interesting to know its performance when applied to the multiple channels, or dense wavelength division multiplexed (DWDM) environment. Here, we, for the first time, show how close the neighboring channels can be located in the network by means of numerical simulations. We also provide solutions to reduce the crosstalk produced by neighboring PM-NRZ channels. Since in the WDM-PON system the distances between different ONUs and the head-end office vary, we also analyze the network performance when the powers of adjacent PM-NRZ signals change.

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### 1. Introduction

Most broadband customers today rely on networks comprised of ordinary telephone wire driven to moderate bit rates using the digital subscriber line (DSL), or coaxial cable (hybrid fiber-coax, or HFC) technologies. The first generation of Gigabit passive optical network (GPON) has been standardized and deployed in some countries. Whilst the GPON offers significant bandwidth increase compared to copper-based approaches, it may not provide the best ultimate solution for network operators seeking to significantly reduce the cost of delivering future broadband services to customers in order to sustain profit margins. Hence, the network operators will ask “What comes next after GPON?” Recently, research attention has turned to network solutions based on new types of optically amplified, dense wavelength division multiplexed (DWDM), large split, long reach (~100 km) PONs (LR-PONs), supporting data rate up to 10 Gb/s in upstream and downstream [1,2].

However, one great challenge in these DWDM LR-PONs is the transmitter (Tx) at the optical networking unit (ONU), which must have a wavelength that is precisely aligned with a specifically allocated DWDM grid wavelength. A cost-effective solution is to use the same components in each ONU, and its emitted wavelength is determined by the continuous wave (CW) carrier distributed from the head-end office. Hence, the ONU is operated at reflective

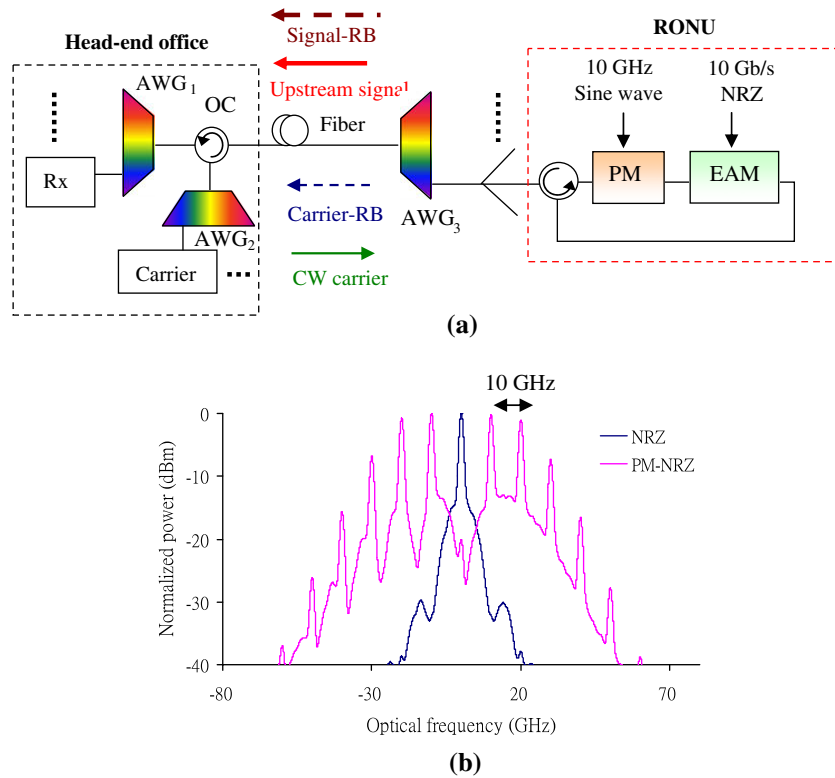
mode (RONU), which is independent of the wavelength (colorless) assigned by the network.

Although the carrier distributed DWDM LR-PONs have many attractive features, they suffer from interferometric beat noise induced by Rayleigh backscattering (RB) at the head-end upstream receiver (Rx). This will be discussed in next section. Modulation schemes capable of mitigating the RB noise have recently been the subject of increasing interest. Effective techniques employ advanced modulation formats to reduce the spectral overlap between signal and interferer [3–5]. A technique, which has been shown to be effective to mitigate the RB noise and potentially suited for use in the carrier distributed access networks, uses a phase modulator (PM) at the RONU to reshape the spectrum of the upstream non-return-to-zero (NRZ) signal. The upstream NRZ signal was phase modulated by a 10 GHz sinusoidal signal, thus we named it phase modulated-NRZ (PM-NRZ) signal. In [5] a novel detuned arrayed waveguide grating (AWG) filtering scheme was introduced to the PM-NRZ signal to further reduce the RB noise and it is characterized as a function of the optical signal to Rayleigh noise ratios (OSRNRs).

Ref. [5] only reported the operation mechanism of the PM-NRZ modulation format, and showed that it can mitigate RB. Afterward, the PM-NRZ format was applied to a network experiment [6]. However, only single channel (single wavelength) was used in the testing [6]. Then, Ref. [7] numerically analyzed the effects of the PM-NRZ signal when passing through two different kinds of AWGs at different wavelength detuning (frequency offsets). Since the PM-NRZ signal has a much wider spectrum (Fig. 1b) than the

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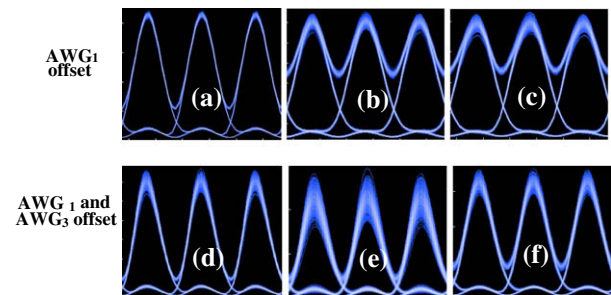


**Fig. 1.** (a) Schematic of DWDM-PON. AWG: arrayed waveguide grating, OC: optical circulator, PM: phase modulator, EAM: electro-absorption modulator, Carrier-RB and Signal-RB: carrier and signal generated Rayleigh backscattering. Inset: upstream PM-NRZ signal. (b) Optical spectra (resolution of 0.01 nm) of the PM-NRZ and conventional NRZ signals.

conventional NRZ signal, it would be very interesting to know its performance when applied to the multiple channels (WDM and DWDM) environment, which has not been studied before. Besides, the signal degradation introduced to the PM-NRZ signals under different AWG offsets and profiles is important for system planning and analysis, which is also missing in previous publication. Here, we based on the analysis in Ref. [7] and selected the 30 GHz frequency detuning when 50 GHz bandwidth AWG is used; and selected 15 and 20 GHz frequency detuning when 25 GHz bandwidth AWG is used. We show, for the first time, how close the neighboring channels can be located in the network. We also try to provide solution to reduce the crosstalk produced by neighboring PM-NRZ channels by using both head-end and remote-node offset-AWG filtering. Since in the WDM PON, the distances between different ONUs and the head-end office vary, we also analyze the network performance when the powers of adjacent PM-NRZ signals change.

## 2. Description of numerical analysis

Fig. 1a shows the schematic of a carrier distributed DWDM-PON, in which CW carrier is launched from the head-end via AWG<sub>2</sub>, optical circulator (OC) and AWG<sub>3</sub> to the RONU. The CW carrier will then be modulated inside the RONU, forming the upstream PM-NRZ signal, which will then be transmitted via AWG<sub>3</sub>, OC and AWG<sub>1</sub> towards the head-end Rx. In the whole system, it has three AWGs. For the WDM analysis, we used standard AWG with wavelength separation of 100 GHz (0.8 nm), Gaussian-shaped with 3-dB bandwidth of 50 GHz (0.4 nm). The AWGs can be wavelength stabilized by temperature control or using athermal design and packaging. Fig. 1a also shows the two dominant contributions to the RB in carrier distributed PONs, which interfere with the upstream signal at the Rx. The Carrier-RB (generated by the backscattering of the CW carrier) and the Signal-RB (generated by the



**Fig. 2.** Eye diagrams of PM-NRZ signals with (a, d) 30 GHz-offset-AWG (3-dB width = 50 GHz), (b, e) 25 GHz-offset-AWG (3-dB width = 25 GHz) and (c, f) 15 GHz-offset-AWG (3-dB width = 25 GHz).

**Table 1**

EOP of PM-NRZ signals at different AWG offset and profiles.

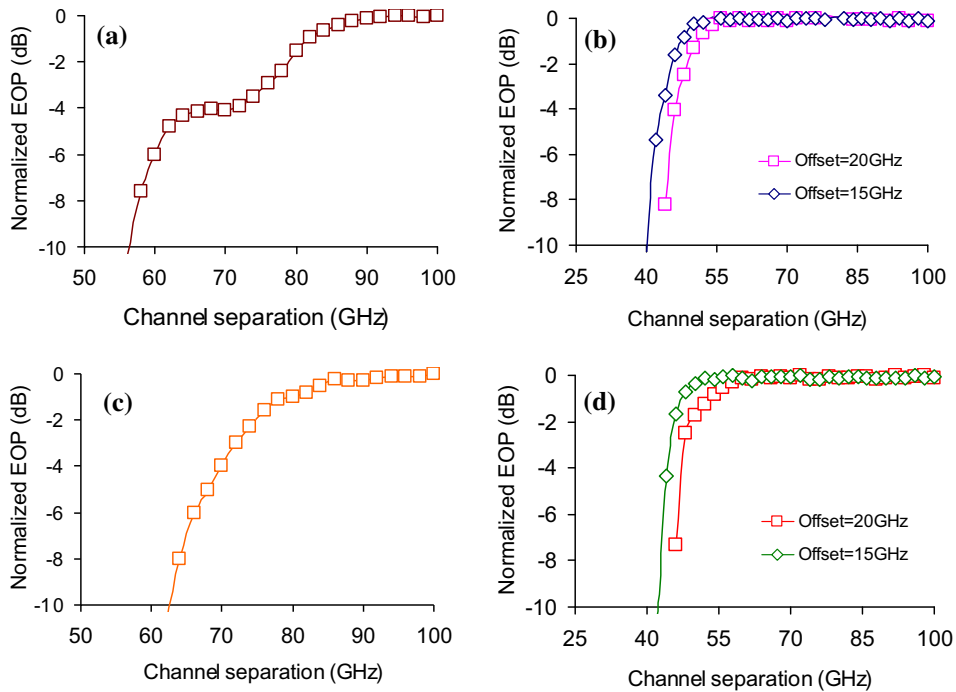
	AWG <sub>1</sub> offset (dB)	AWG <sub>1</sub> and AWG <sub>3</sub> offset (dB)
50 GHz bandwidth, 30 GHz-offset	-0.36	-1.29
25 GHz bandwidth, 20 GHz-offset	-0.92	-3.72
25 GHz bandwidth, 15 GHz-offset	-0.98	-1.27

modulated upstream signal, which re-enters the RONU and is reflected towards the Rx). They have different spectral shapes and their relative impacts depend on the exact network configuration and hence, for a full understanding, separate analysis of each effect should be needed [5].

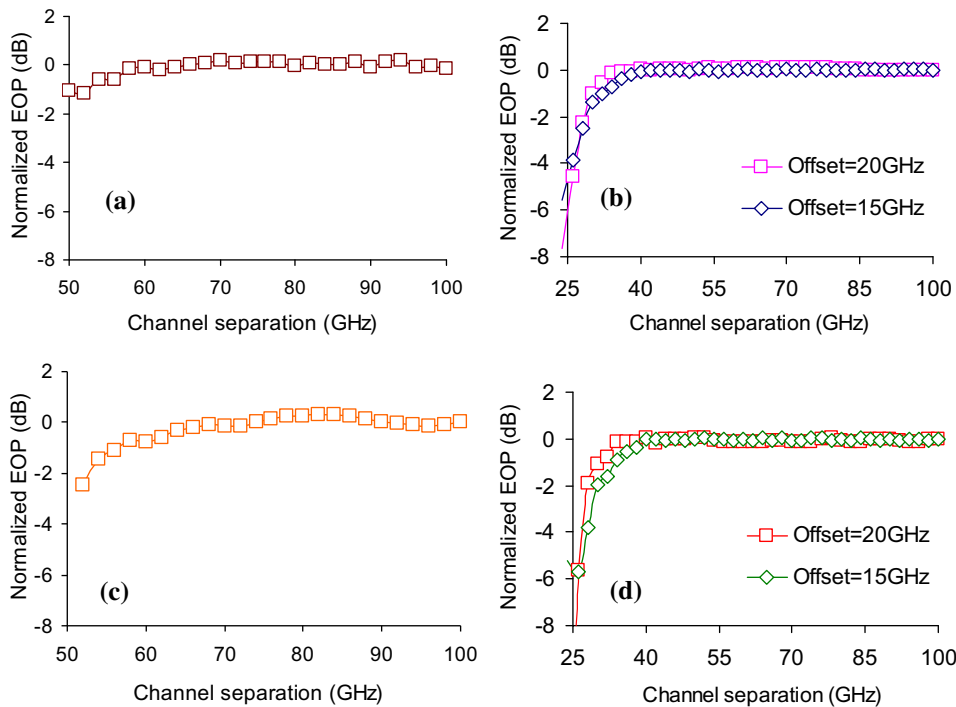
Numerical analysis (VPI TransmissionMaker V7.1) was performed at 10 Gb/s. And three activated RONU are used, with the target RONU operating at 1554 nm wavelength, and the two

neighboring channels are  $1554 \text{ nm} \pm$  channel separation. The electro-absorption modulator (EAM) and PM were electrically driven with 10 Gb/s NRZ data and 10 GHz sinusoidal signals, respectively. In the PM, the phase modulation index ( $\beta$ ) was set so as to suppress the centre wavelength, i.e. to make the amplitude of the 0th order Bessel function equal to zero. The smallest modulation index that achieves the required suppression is  $\beta \sim 2.4$ , about  $1.6 V_{\pi}$ . The

head-end Rx is optically pre-amplified by an erbium doped fiber amplifier (EDFA) with noise figure of 4 dB, which is followed by a PIN photodiode with 3rd order Bessel bandwidth of 7.5 GHz. We evaluate the performance in terms of an eye opening penalty (EOP), defines as  $20 \log_{10} [(U_{1\min} - U_{0\max}) / (\mu_1 - \mu_0)]$ , where  $U_{1\min}$  is the minimum value of ones,  $U_{0\max}$  is the maximum value of zeros, and  $\mu_1$  and  $\mu_0$  are the respective means.



**Fig. 3.** Performance of PM-NRZ at different channel separations at back-to-back using (a) 30 GHz-offset-AWG<sub>1</sub> (3-dB width = 50 GHz) and (b) 15 or 20 GHz-offset-AWG<sub>1</sub> (3-dB width = 25 GHz); and after 40 km SMF transmission using (c) 30 GHz-offset-AWG<sub>1</sub> (3-dB width = 50 GHz) and (d) 15 or 20 GHz-offset-AWG<sub>1</sub> (3-dB width = 25 GHz).



**Fig. 4.** Performance of PM-NRZ at different channel separations at back-to-back using (a) using 30 GHz-offset-AWG<sub>1</sub> and AWG<sub>3</sub> (3-dB width = 50 GHz) and (b) 15 or 20 GHz-offset-AWG<sub>1</sub> and AWG<sub>3</sub> (3-dB width = 25 GHz); and after 40 km SMF transmission using (c) using 30 GHz-offset-AWG<sub>1</sub> and AWG<sub>3</sub> (3-dB width = 50 GHz) and (d) 15 or 20 GHz-offset-AWG<sub>1</sub> and AWG<sub>3</sub> (3-dB width = 25 GHz).

### 3. Results and discussion

It is worth to mention that in the OSRNR analysis of PM-NRZ signal reported in [5], the OSRNRs are studied in terms of Carrier-RB and Signal-RB. It shows that, for example, when using a 50 GHz, 3-dB bandwidth Gaussian AWG filtering at a detuning of 30 GHz, OSRNR improvement for the Carrier-RB is 8 dB and OSRNR degradation for the Signal-RB is 3 dB [5]. The opposite OSRNR behavior is due to different attenuations caused by the offset-AWG towards the PM-NRZ, Carrier-RB and Signal-RB, and these have been studied in [5,7]. The 30 GHz-offset of 50 GHz bandwidth AWG is chosen in the experiment [5], due to the best overall performance tradeoff between signal power loss, Carrier-RB and Signal-RB performances. For DWDM operation, narrower AWG (25 GHz bandwidth) should be used. It shows that 15 GHz-offset-AWG (3-dB bandwidth = 25 GHz) can provide the equivalent Carrier-RB suppression as in the detuning of the 30 GHz-offset-AWG (3-dB bandwidth = 50 GHz) [7]. Additional detuning to 20 GHz can further improve the Carrier-RB suppression to OSRNR < 6 dB [7], and provide the equivalent Signal-RB suppression as in the detuning of the 30 GHz-offset-AWG (3-dB bandwidth = 50 GHz). Hence, in this study, we analyze the PM-NRZ signal when subjected to three conditions: (i) Gaussian shaped AWG offsets by 30 GHz (AWG 3-dB bandwidth of 50 GHz), (ii) Gaussian shaped AWG (AWG 3-dB bandwidth of 25 GHz) offsets by 20 GHz and (iii) 15 GHz.

Fig. 1b shows the simulated optical spectra (resolution of 0.01 nm) of the PM-NRZ and the conventional NRZ signals. We can see that the optical spectrum of the PM-NRZ is much wider than conventional NRZ signal. The centre wavelength of the PM-NRZ signal is highly suppressed in order to reduce the spectral overlap between the CW carrier and the PM-NRZ signal, so that the RB noise can be mitigated. In the first analysis, only the head-end AWG ( $AWG_1$ ) is offset to provide the necessary OSRNR improvement. In the second analysis,  $AWG_1$  and  $AWG_3$  are offset to provide further neighboring channel crosstalk suppression.

Fig. 2 shows the simulated eye diagrams of PM-NRZ at back-to-back when subjected to different AWG offsets and profiles, with the corresponding EOP summarized at Table 1. The PM-NRZ signal with offset-AWG filtering is RZ-like, which is due to the coherent beating in the photodiode between the 10- and 20 GHz Bessel harmonics on one side of the PM-NRZ spectrum after offset-AWG filtering. If the AWG is removed, and all the harmonics of the PM-NRZ signal are launched into the photodiode, the shape of the PM-NRZ signal will be NRZ-like. Sharper RZ pulses can be observed by using a wider AWG [Fig. 2a and d], since it allows relatively higher powers of 10- and 20 GHz harmonics to pass and then be detected by the Rx. We observed higher EOP in both offset- $AWG_1$  and offset- $AWG_3$  cases (Table 1) when compared with the corresponding cases when only  $AWG_1$  is offset. This is because the offset- $AWG_3$  introduces attenuation towards the CW carrier distributed from the head-end, which then decreases the signal to noise of the PM-NRZ signal.

Figs. 3 and 4 show the normalized EOP of the PM-NRZ signal against different WDM channel separations. Fig. 3a shows that by using 30 GHz head-end offset-AWG ( $AWG_1$ ) (3-dB bandwidth 50 GHz) negligible crosstalk can be observed in the target PM-NRZ channel with channel separation is 100 GHz, a typical DWDM operation. By using AWG with 3-dB bandwidth of 25, 50 GHz channel separation is just managed to achieve in the 15 GHz-offset case, but has -1.3 dB normalized EOP at the 20 GHz-offset, as shown in Fig. 3b. Similar behaviors can be observed in Fig. 3c and d, respectively, when the signals were transmitted through 40 km single mode fiber (SMF) (dispersion parameter: 17 ps/nm/km). By using the two offset-AWGs, 50 GHz channel separation is possible in all cases as shown in Fig. 4a and b due to the double filter effect,

which further suppresses the crosstalk produced by neighboring channels. Similar behaviors can also be observed in Fig. 4c and d, respectively, when the signals were transmitted through 40 km SMF.

Fig. 5a depicts the normalized EOP of the target PM-NRZ channel at different relative powers between the neighboring channels (by attenuating the target channel and keeping the powers of the two neighboring channels the same) using head-end 15 GHz-offset-AWG ( $AWG_1$ ) (3-dB bandwidth = 25 GHz), showing that 50 GHz channel separation can be used if the power different between neighboring channels is -6 dB with EOP < 2 dB. However, channel separation should be increased to 60 GHz if the power different between neighboring channels is reduced to -12 dB. In practice, the output powers from different ONUs could be controlled by adjusting the output power of the CW laser source located at the head-end office. In order to compensate the losses of the PM and the EAM inside the RONU, semiconductor optical amplifier (SOA) can be added in the RONU. In this case, the output power of the RONU can be controlled by changing the gain of the SOA. We can observe that in Fig. 5b, by offsetting both AWGs, <50 GHz channel separation can be easily achieved even the relatively power different is reduced to -12 dB with EOP < 2 dB. And the power different can be further reduced to -20 dB at channel separation of 50 GHz if higher EOP of 6 dB is allowed. Although the double filtering effect of the two offset-AWGs can greatly reduce the channel separation, it is worth to note that this also attenuates the CW carrier sent from the head-end; hence this may reduced the split ratio and reach of

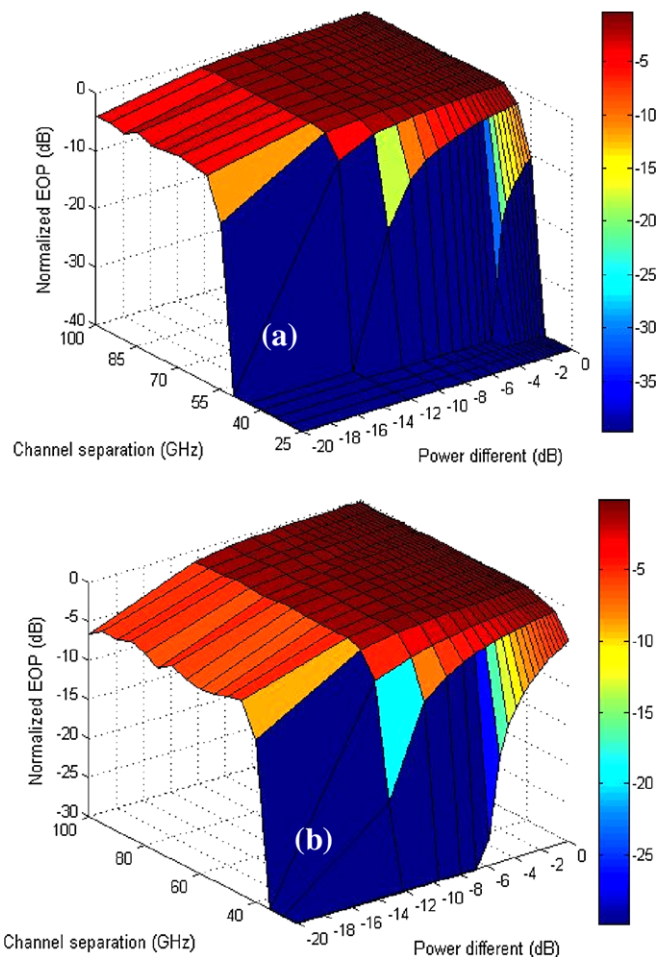
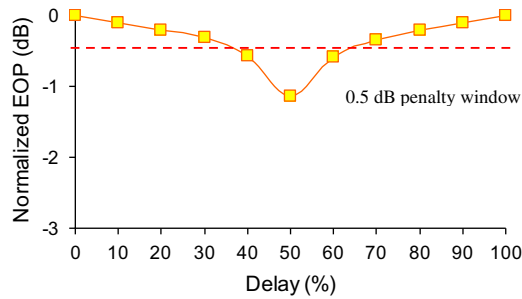


Fig. 5. EOP of PM-NRZ at different powers between neighboring channels and channel separations with 15 GHz-offset-AWG (3-dB width = 25 GHz) in (a) only  $AWG_1$  offset and (b) both  $AWG_1$  and  $AWG_3$  offset.



**Fig. 6.** Normalized EOP of the received PM-NRZ signal under different time-offsets between the PM and the EAM.

a PON unless high enough gain is included in the RONU to compensate the attenuation introduced by the offset-AWG<sub>3</sub>. Another solution could be an AWG<sub>1</sub> with a tailor-made pass-band which provides the same effective filtering effect of AWG<sub>1</sub> plus AWG<sub>3</sub>, however, it will increase the component cost of the system.

Inside the RONU, the synchronization between the PM (10 GHz sinusoidal signal) and the EAM (10 Gb/s NRZ data signal) is needed. Fig. 6 presents the normalized EOP of the received PM-NRZ signal at the head-end office under different time-offsets between the PM and the EAM. The simulation results show that the tolerance is >60% in the 0.5 dB penalty window.

#### 4. Conclusion

We presented a performance analysis of the PM-NRZ signal, which is shown to be highly effective to mitigate RB noise in carrier distributed PON, at different AWG offsets and profiles; and at different channel separations in DWDM-PONs, showing different tradeoffs in achieving DWDM (50 GHz channel separation) operation. The results show that using 30 GHz head-end offset-AWG

(3-dB bandwidth 50 GHz); negligible crosstalk can be observed in the typical DWDM condition (channel separation of 100 GHz). By using AWG with 3-dB bandwidth of 25, 50 GHz channel separation is achieved in the 15 GHz-offset case. By using the two offset-AWGs, 50 GHz channel separation (ultra-DWDM) is possible due to the double filter effect, however, this will cause attenuation to the CW carrier distributed from the head-end office. In the relative power studies, using head-end 15 GHz-offset-AWG (3-dB bandwidth = 25 GHz), 50 GHz channel separation can be used if the power different between neighboring channels is -6 dB. By offsetting both AWGs, <50 GHz channel separation can be easily achieved even if the relatively power different is reduced to -12 dB. In practice, the output powers from different ONUs could be controlled by changing the launched CW powers to the RONUs.

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