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# A centralized-light-source WDM access network utilizing inverse-RZ downstream signal with upstream data remodulation

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**Abstract**

We propose and demonstrate employing inverse-return-to-zero (IRZ) downstream signal format to facilitate upstream data remodulation in a wavelength division multiplexing (WDM) passive optical network (PON) architecture with centralized light sources. The finite optical power in each downstream IRZ bit can be simply remodulated by the upstream data at the optical network unit. This can make each downstream and upstream pair share a single light source and such light reuse can be easily realized. An experiment on 10-Gb/s downstream IRZ signal generation, 2.5-Gb/s upstream signal remodulation, and two-way transmission is successfully demonstrated. The downstream/upstream signal performance in such a PON has also been analyzed, which is useful for system design.


*Keywords:* Inverse-return-to-zero; Optical access network; WDM; Passive optical network; Remodulation

## 1. Introduction

Wavelength-division multiplexing passive optical network (WDM-PON) is a promising technology to meet the ever-increasing access bandwidth demand from commercial and residential subscribers. To facilitate the wavelength management and maintenance, the WDM-PON architecture with centralized light sources (CLS) at the optical line terminal (OLT) has emerged as an attractive solution [1–3]. With no wavelength-registered light source incorporated at the optical network unit (ONU), wavelength provisioning, monitoring and stabilization at every ONU are unnecessary and thus such wavelength independent (so-called "colorless") ONUs greatly eases the network maintenance and reconfiguration. In a realization of such a CLS PON, in additional to the downstream laser sources, extra laser diodes were installed at the OLT to provide light source for the upstream data which increased the system cost [2]. Some other demonstrations avoided this problem by directly reuse the downstream light as the upstream carrier at the ONU. In order to let the upstream signal be modulated onto the downstream light without interference, a portion of the temporal period of the downstream signal was left unmodulated and reserved for upstream data [1]. However, this reduced the downstream bandwidth and the upstream remodulation had to synchronize with the unmodulated downstream time slots. Another approach of downstream light reuse at the ONU was to apply a semiconductor optical saturator/modulator [3] to erase the downstream data before the remodulation. The use of such a proprietary component may be of high cost and be difficult to control. Moreover, the downstream signal should have a low extinction ratio so that data erasure could work, which sacrificed the downstream signal quality.

In the CLS PON demonstrations mentioned above, nonreturn-to-zero was employed as the line coding format. Recently, inverse-return-to-zero (IRZ) was proposed and studied as another line coding format of intensity modulation [4,5]. Its feature of carrying power in both "one" and "zero" bits can help realize some function such as multibit per symbol signaling [4]. In this paper, we propose to employ IRZ as the downstream signal format instead of nonreturn-to-zero to facilitate the upstream data remodulation. The downstream light containing IRZ signals can be directly reused at the ONU, without any data erasure procedure. On the other hand, employing IRZ only

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increases very small complexity compared with nonreturn-to-zero system.

An IRZ signal is formed by inverting the intensity level of a conventional return-to-zero signal, thus it carries a certain level of optical power in both "one" bits and "zero" bits. Therefore, the downstream optical power received at the ONU can be directly remodulated by the upstream data. No downstream data erasure is needed and it can still maintain high extinction ratio of the downstream optical signal. Meanwhile, the downstream IRZ signal can be directly detected by a photodiode followed by an electrical inverting amplifier. This guarantees the complexity of the downstream receiver to be similar with a traditional receiver for nonreturn-to-zero signals. We have experimentally demonstrated such a CLS PON architecture with downstream 10-Gb/s IRZ signal and upstream 2.5-Gb/s remodulated signal. To further understand the remodulation performance and system design issues, we have also analyzed the performance of both the downstream and upstream signals, in terms of receiver sensitivities.

## 2. WDM-PON system using downstream IRZ signals

Figure 1 illustrates the WDM-PON architecture utilizing IRZ as the downstream signal format. Each transceiver at the OLT generates downstream IRZ signals and receives upstream remodulated signals for the corresponding subscriber. The logic-AND operation between the downstream nonreturn-to-zero data and a clock signal can produce a return-to-zero shaped data signal. It is then used to drive a Mach–Zehnder intensity modulator (IM) biased at the quadrature point of the negative slope of the IM response curve, to generate the downstream IRZ signal. In this way, an electrical data bit "zero" modulates the CW light to possess optical power in its full bit period, while a return-to-zero electrical data bit "one" modulates the CW light as a dark pulse waveform. To increase the economical feasibility, an optical IRZ signal can also be generated by directly modulate a laser diode with the electrically inverted logic-AND result if the data rate is within the laser diode's modulation bandwidth. Hence, the generated IRZ signal carries finite optical power at both "one" levels and "zero" levels. On the other hand, it can be simply detected by a photodiode followed with an electrical inverting post-amplifier at the ONU.

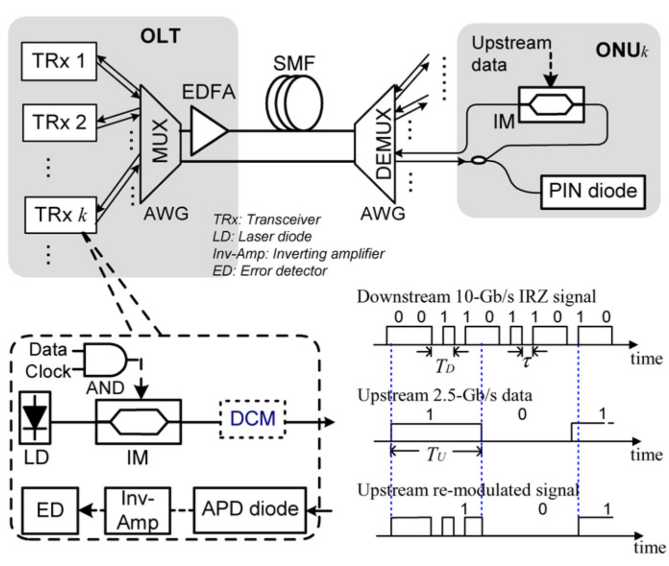


Fig. 1. The architecture schematic of the CLS WDM-PON employing downstream IRZ signals. The insets show typical waveforms of the downstream optical IRZ signal, the upstream data signal, and the remodulated upstream optical signal, respectively.

The downstream IRZ signals from every transceiver in the OLT are WDM multiplexed, via an array waveguide grating (AWG), to the downstream fiber feeder. After transmission, the downstream traffic from the OLT is wavelength routed by another AWG at the remote node toward different ONUs. At an ONU, a portion of the received downstream signal power is tapped off for reception, while the remaining power is fed into an optical intensity modulator for upstream data remodulation. The finite optical power in each bit of the downstream IRZ signal provides the light source for the upstream data in every bit slot. An example ideal IRZ waveform as well as the remodulation process is described in Fig. 1 insets. The portion of downstream light carrying upstream nonreturn-to-zero data was then transmitted back to the OLT, through the remote node and the upstream fiber link. A pair of feeder fibers is used to avoid the possible Rayleigh backscattering induced performance degradation on both the downstream and the upstream signals.

## 3. Experimental demonstration

We have experimentally demonstrated the proposed scheme on one particular channel for simplicity, in a WDM-PON based on the setup in Fig. 1. A CW light from a DFB laser at 1547 nm was modulated by a 10-Gb/s pseudo-random binary sequence (PRBS) downstream data with a length of $2^{31} - 1$. It was then amplified by an erbium-doped fiber amplifier (EDFA) to around 5 dB m and fed into a span of 20-km standard single mode fiber (SMF). At the ONU, a portion of the received downstream power was tapped off by a 3-dB optical coupler and was fed into a PIN photo-detector for downstream data reception. The rest of the optical power was fed into an intensity modulator driven by a 2.5-Gb/s $2^{31} - 1$ PRBS as the upstream data, which was then transmitted back to the OLT via another piece of 20-km SMF.

The BER curves of the received downstream IRZ signal at the ONU were measured, as shown in Fig. 2. After 20-km transmission, a slight negative power penalty was observed compared with the back-to-back case, mainly due to opposite polarity of the Mach–Zehnder IM induced chirp and the fiber dispersion induced chirp. To investigate the dispersion tolerance, we also tried downstream transmission via a piece of 40-km SMF and found 0.5-dB power penalty. However, after the precompensation by a commercially available dispersion compensation module (DCM) for 40-km transmission (shown in Fig. 1, dotted box), the penalty totally disappeared. This indicated that the IRZ signal degradation was mainly due to fiber dispersion in such system, and dispersion compensation could be carried out to increase the system margin if the power budget requirement is critical. At the same time, part of the downstream signal

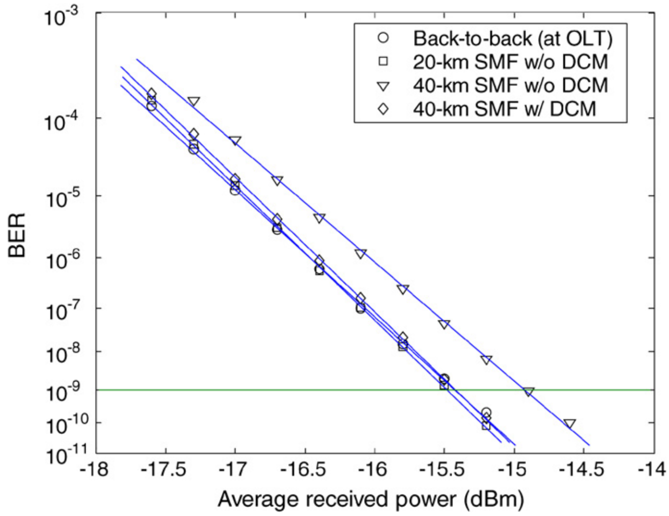


Fig. 2. BER measurements of the 10-Gb/s downstream IRZ signals.

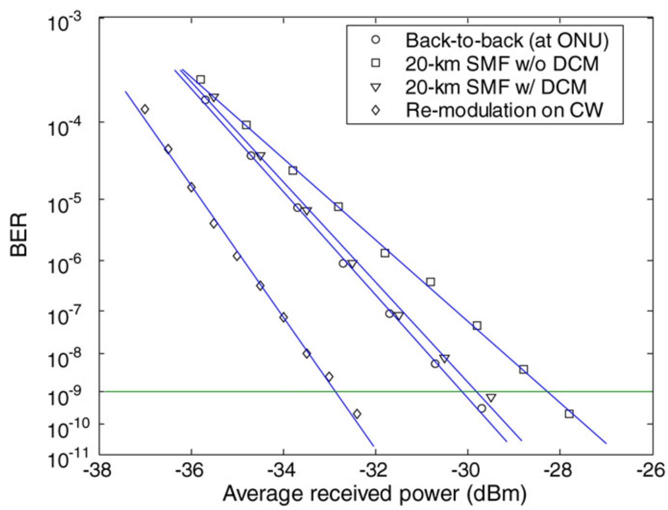


Fig. 3. BER measurements of the 2.5-Gb/s upstream remodulated signals.

is synchronously remodulated by the local 2.5-Gb/s upstream data at the ONU. An APD photodiode was employed at the OLT for detection, followed by an electrical inverting amplifier and an electrical low-pass filter (ELPF) with a 3-dB bandwidth of 1.87 GHz. The back-to-back receiver sensitivity of the remodulated upstream signal was around −30.1 dB m, as shown in Fig. 3. After upstream 20-km SMF transmission, it suffered from a 1.8-dB power penalty, which could be nearly eliminated if the DCM was incorporated in the system as stated above. We have also compared our scheme with the case of using an additional CW light to carry the upstream signal, showing about 2.7-dB power penalty in the data remodulation on the downstream IRZ signals.

## 4. Results and discussion

In our demonstration, the signal power fed into the downstream transmission link was 5 dB m. The downstream loss caused by transmission and demultiplexing was 12.5 dB in total, thus the downstream power arrived at the ONU was −7.5 dB m. For 50/50 power splitting between downstream reception and upstream remodulation, the downstream received power was −11 dB m, implying at least 3-dB system margin for downstream signals. Another portion of −11-dB m downstream light was remodulated by the upstream data, experiencing an excess loss of 7 dB. The optical power received at the OLT was about −30 dB m, similar with the measured upstream receiver sensitivity. In a practical PON system, the power loss of the round-trip transmission between the remote node and each ONU may be different, due to the possible different lengths of the distribution fibers. However, this variation in the lengths of distribution fibers would be usually within a few kilometers in PON applications, thus the induced fiber loss variation would be less than 4 dB (round-trip) among different upstream channels. For proper power budget, the ONU could adopt an electro-absorption modulator integrated with amplifier that can provide power gain. An optical amplifier shared by all upstream signals can also be adopted at the OLT, alternatively, and this would result in a receiver sensitivity of better than −45 dB m, offering sufficient system margin for the upstream signal.

For the downstream IRZ signal, its duty cycle determines the amount of optical power contained in the "one" bit, and thus would influence the performance of both the downstream signals and the remodulated upstream signals. We define the duty cycle of the downstream IRZ signal as $\xi = \tau/T_D$, where $T_D$ is the downstream signal period ($T_D = 100$ ps for 10-Gb/s signal), and $\tau$ is the width of the inversed pulse in the "one" level. The generated IRZ duty cycle in the experiments was estimated to be around 0.6. The ELPF at the receiver can be modeled as an integrator over a signal period [6]. Therefore for the downstream IRZ signal, the decision variables for the "one" and "zero" levels are $V_{D1} = \int_0^{T_D} RP_{D1}(t)\,dt/T_D = \xi PR$ and $V_{D0} = \int_0^{T_D} RP_{D0}(t)\,dt/T_D = 0$ respectively, where $R$ is the photodiode's responsivity, $P_{D1}(t)$ and $P_{D0}(t)$ are the respective inversed temporal power profiles for the downstream "one" and "zero" levels. In access scenario without amplifier chains, it is reasonable to assume Gaussian noise statistics and the noise variances for "ones" and "zeros" are equal ($\sigma_1 = \sigma_0 = \sigma$); and the $Q$ factor can be expressed as $(V_{D1} - V_{D0})/(2\sigma)$ and approximates 6 to achieve BER $= 10^{-9}$ [7]. That is, for the downstream $Q_D = (V_{D1} - V_{D0})/(2\sigma) = \xi PR/(2\sigma) = 6$. Together with the expression of the average received downstream optical power $\bar{P}_D = (1/2)(1-\xi)P + (1/2)P = (1-\xi/2)P$, we have $\bar{P}_D = (12\sigma)(1-\xi/2)/(R\xi)$ which is the receiver sensitivity of the IRZ signal. This can also be expressed with respect to the receiver sensitivity of a conventional nonreturn-to-zero signal (i.e., $\xi = 1$) as $\bar{P}_{D,rec}[\text{dB m}] = \bar{P}_{D,rec,\xi=1}[\text{dB m}] + 10\log_{10} 2(1-\xi/2)/\xi$. Figure 4 depicted the relation of $\bar{P}_{D,rec}$ (normalized with respect to $\bar{P}_{D,rec,\xi=1}$) against the value of $\xi$.

Similarly, the ELPF in the upstream receiver at the OLT also functions as an integrator over an upstream signal period $T_U$. The decision variable for bit "zero" is $V_{U0} = \int_0^{T_U} RP_{U0}(t)\,dt/T_U = 0$ whereas for bit "1" $V_{U1} = \int_0^{T_U} RP_{U1}(t)\,dt/T_U$ has many possible values, where $P_{U0}(t)$ and $P_{U1}(t)$ are the respective temporal power profiles for the upstream "zero" and "one" bits. The integration starting position can be at any timing point

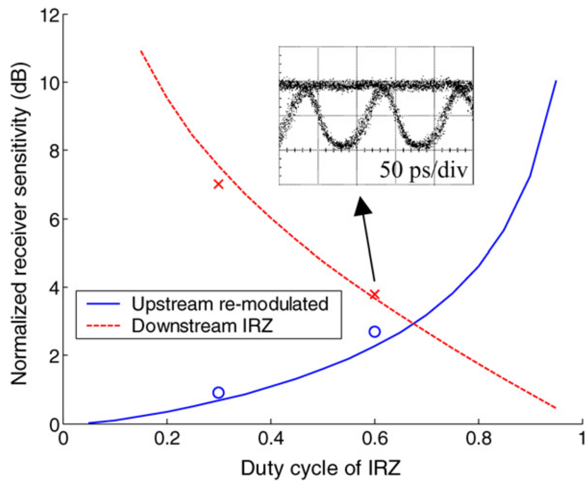


Fig. 4. The normalized back-to-back receiver sensitivities of the 10-Gb/s downstream IRZ and the 2.5-Gb/s upstream remodulated signals versus the IRZ duty cycle. Symbols indicate the experimental measurements while lines indicate the theoretical performance. The inset shows the measured eye diagram of the downstream IRZ signal.

within a downstream bit and the integrating period may contain different downstream bit patterns. Here we consider a case where the starting position of an upstream bit is exactly the same as that of a downstream bit, in which an upstream remodulated bit contains four full-period downstream bits. According to different bit pattern combinations of the four downstream bits, $V_{U1}$ has five possible values $(1-\xi)PR$, $(1-0.75\xi)PR$, $(1-0.5\xi)PR$, $(1-0.25\xi)PR$, and $PR$, with their respective occurrence probabilities being 1/32, 1/8, 3/16, 1/8, and 1/32. Based on the above analysis, the error probability of the upstream signal can be derived by summing up the product of each error probability and its corresponding occurrence probability. We have numerically solved the error probability function and obtained the receiver sensitivity of the upstream remodulated signal normalized with respect to the case using CW light as the upstream carrier (i.e., $\xi=0$), as depicted in Fig. 4. By respectively using the IRZ transmitter in our experiment and another method of IRZ generation based on dual-drive Mach–Zehnder IM [5], the downstream and upstream receiver sensitivities at $\xi=0.6$ and 0.3 were also measured. It is shown that the calculations agree with the measured receiver sensitivities ("×" for the downstream IRZ signal and "○" for the upstream signal). These relations are useful to facilitate the system designs in terms of system margin, power budget, downstream/upstream power splitting ratio, etc.

## 5. Summary

We have proposed and experimentally demonstrated a novel CLS WDM-PON architecture, by using IRZ as the downstream signal format on which the upstream data could be simply remodulated. The finite optical power reserved in each bit of the downstream IRZ signal facilitates the upstream remodulation at the ONU side. Small power penalties for both the downstream and the upstream 20-km transmission were achieved without dispersion compensation, and the penalties could be almost eliminated with dispersion compensation. Both the downstream and the upstream signal performances have also been discussed in terms of their receiver sensitivities, which can be used to facilitate the system designs.

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