5-Gb/s optical transmitter based on incoherent-light-injected RSOAs with graceful upgrade capability for WDM PONs

Zaineb Al-Qazwini and Hoon Kim*

Department of Electrical &Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117583, Singapore

*hoonkim@ieee.org

Abstract: We propose and demonstrate a novel and cost-effective optical transmitter based on incoherent-light-injected reflective semiconductor optical amplifiers (RSOAs) which can be upgraded to higher data rate without discarding the existing low-data-rate transmitter. The transmitter is based on optical time-division multiplexing (OTDM) of return-to-zero modulated RSOAs and thus capable of upgrading the system capacity on an as-needed basis simply by adding RSOAs. By using the proposed transmitter, we experimentally demonstrate a capacity upgrade from 2.5 to 5 Gb/s/channel by using two RSOAs, each operating at 2.5 Gb/s. To the best of our knowledge, this is the highest reported data rate demonstrated using incoherent-light-injected RSOAs. We also demonstrate the performance of the proposed transmitter after 10-km transmission over standard single-mode fiber, and investigate the sensitivity penalty to the power level injected into the RSOAs as well as the optical delay for the OTDM.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2330) Fiber optics communications; (060.4510) Optical communications.

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1. Introduction

As the internet data traffic is expected to grow by 50~60% every year in the foreseeable future, wavelength-division-multiplexed (WDM) passive optical networks (PONs) are regarded as the most future-proof solution to address the growing bandwidth demands for next-generation broadband access networks. Not only they leverage the benefits of passive infrastructure, but they also provide high capacity, network flexibility, infrastructure sharing, and high security [1,2]. These merits notwithstanding, the high initial capital and operational expenditures of WDM PONs still hinder the widespread deployment of the technology.

To cope with the cost issue, there have been intensive studies to develop low-cost solutions for WDM-PON optical transmitters which account for the largest portion of the total system cost [3–5]. Among several proposed candidates, amplified spontaneous emission (ASE)-injected reflective semiconductor optical amplifiers (RSOAs) or Fabry-Pérot laser diodes (FP-LDs) offer a very attractive solution for both downstream and upstream transmission [6–9]. In these schemes, broadband incoherent light generated by an Erbium-doped fiber amplifier (EDFA) is first spectrum-sliced by an arrayed waveguide grating (AWG) to produce multi-channel continuous-wave incoherent light and then fed to RSOAs or FP-LDs for data modulation. These WDM optical transmitters are highly cost-effective, operate in a color-free manner at the customer premises, and produce optical signals with high robustness against fiber nonlinearity and optical reflection (e.g., Rayleigh backscattering) [10–12].

However, one major drawback of these optical transmitters is their limited modulation bandwidth (typically less than 2 GHz) due to the carrier lifetime at the active region of the reflective opto-electronic devices. Therefore, previous experimental demonstrations using ASE-injected RSOAs or FP-LDs are performed at ≤2.5 Gb/s/channel [13,14]. Another issue with WDM-PON transmitter is the additional cost associated with future capacity upgrade. The whole transmitter should be replaced with a new one to upgrade the modulation speed per channel. To address the cost issues of WDM PONs, it is essential to develop optical transmitters which not only can be implemented in a cost-effective manner, but also can allow a graceful upgrade to higher data rates without discarding the old transmitter.

In this paper, we propose a novel and cost-effective optical transmitter for WDM PONs based on ASE-injected RSOAs with graceful upgrade capability. The proposed transmitter utilizes the optical time-division multiplexing (OTDM) technique to circumvent the bandwidth limitation of the RSOAs. The most distinctive feature of this transmitter is that it facilitates graceful upgrade to higher data rates on an as-needed basis without changing the whole transmitter. For example, we can double the data rate by adding an RSOA to the

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existing one. The proposed transmitter is also color-free and can be applied both for downstream and upstream transmission. Using the proposed transmitter, we demonstrate a capacity upgrade from 2.5 to 5 Gb/s/channel. To the best of our knowledge, 5 Gb/s is the highest data rate demonstrated by using ASE-injected RSOAs or FP-LDs.

2. System architecture

Figure 1 shows a WDM-PON system utilizing the proposed transmitter. It depicts the downlink only. The proposed transmitter is composed of a pulsed ASE light source, an optical circulator, an AWG, and RSOAs. The pulsed ASE source is composed of EDFAs and an optical modulator. The pulsed ASE source generates an incoherent pulse train over the entire wavelength band of WDM channels. The pulsed ASE is spectrum-sliced by the AWG into multiple-wavelength seed lights to be injected into the RSOAs.

The downstream signals are first converted into return-to-zero (RZ) signals by non-return-to-zero (NRZ)-to-RZ converters and then directly drive the RSOAs. The seed lights are intensity-modulated at the RSOAs and multiplexed by the AWG for transmission. When incoherent light is injected into the RSOA, the device acts as an intensity modulator as well as optical amplifier. Thus, the operating wavelength of the transmitter is determined by that of the seed light. This makes the transmitter color-free and helps to substantially relieve the inventory management issue. The gain-saturated RSOAs in the proposed scheme also serve to suppress the excess intensity noise (EIN) originated from the spontaneous-spontaneous beating between different wavelength components of the spectrum-sliced incoherent light [15,16]. It is worth noting that the cost of the pulsed ASE light source (i.e., optical amplifiers and a pulse carver) can be shared among multiple WDM users, and thus becomes insignificant as the number of users increases. In addition, RSOAs are known to be low-cost devices and can be mass-produced by using the current semiconductor technologies. Since the seed light is incoherent light, the polarization sensitivity is not an issue in this case.

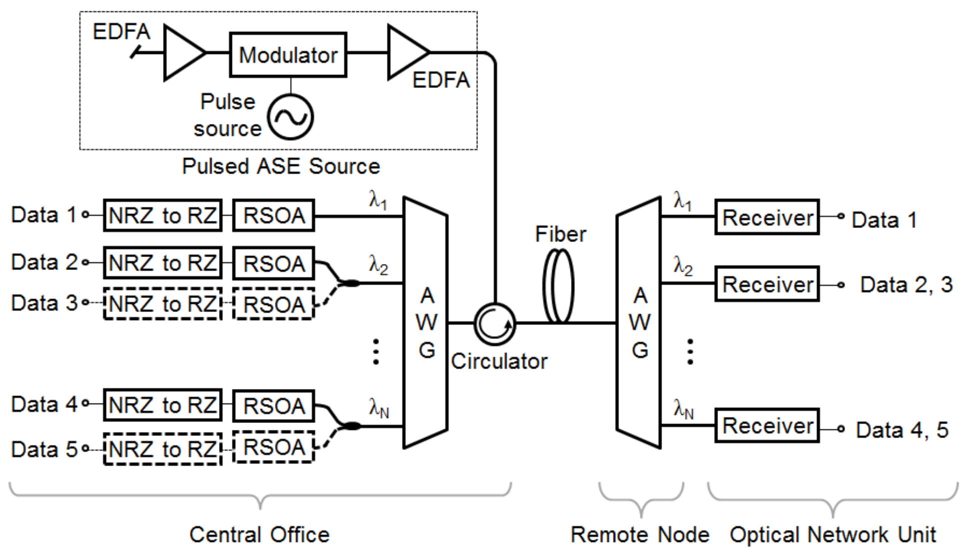

Fig. 1. The schematic diagram of the proposed transmitter for downstream WDM PON. AWG: arrayed waveguide grating, EDFA: erbium-doped fiber amplifier, and RSOA: reflective semiconductor optical amplifier.

When there is a need to upgrade the capacity of a certain channel, an RSOA is added to the existing RSOA-based transmitter, as depicted with dashed lines in Fig. 1. Two RSOAs, each modulated with separate electrical RZ data, are combined with a coupler to make the two RZ optical signals from the RSOAs interleaved and thus double the data rate using the

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OTDM technology. Therefore, the proposed network can be upgraded to higher data rate on an as-needed basis without changing the whole transmitter. This graceful upgradability also provides finer granularity to make the network flexible from a provisioning and restoration point of view.

The configuration for upstream transmission is similar to that for downstream transmission depicted in Fig. 1 but with the RSOAs located at the optical network units (ONUs) in the customers' premises. In this case, there are two main issues to be taken into consideration. First, it requires the synchronization of the upstream data with the incoherent pulse train. This can be achieved by first synchronizing the pulse repetition rate with the downstream data rate and then utilizing the recovered downstream clock at the ONU to generate the upstream data [17]. Second, the injection powers into the RSOAs would be lowered if the devices are located at the customer side. This could be resolved by launching a high-power pulse train from the central office and/or by utilizing RSOAs with low saturation power [18].

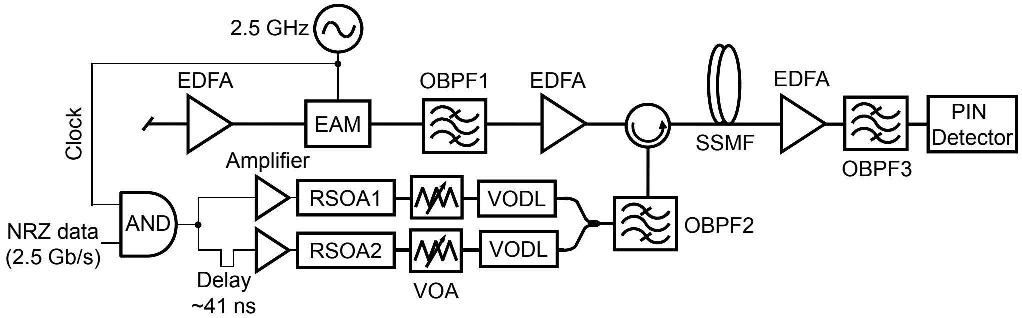

Fig. 2. Experimental setup. EAM: electro-absorption modulator, EDFA: erbium-doped fiber amplifier, OBPF: optical band-pass filter, RSOA: reflective semiconductor optical amplifier, RZ: return-to-zero, SSMF: standard single-mode fiber, VOA: variable optical attenuator, and VODL: variable optical delay line.

3. Experiment and results

Figure 2 depicts the experimental setup used to evaluate the performance of the proposed optical transmitter. A wideband ASE is first generated from an EDFA with no optical input and then fed to an electro-absorption modulator (EAM) driven by a 2.5-GHz sinusoidal wave followed by an optical band-pass filter (OBPF, OBPF1 in Fig. 2) centered at 1551.8 nm with a 3-dB bandwidth of 0.4 nm for spectrum slicing. The spectrum-sliced pulsed ASE light is then fed to another EDFA to compensate for the slicing loss before being sent to the RSOAs for data modulation. We employ uncooled, transistor outline-can-packaged RSOAs operating at a DC bias of 30 mA. We insert variable optical delay lines (VODLs) and variable optical attenuators (VOAs) in front of the RSOAs to investigate the impacts of injected power level and optical delay on system performance. The optical powers injected into RSOA1 and RSOA2 are set to be 5.4 and 4.2 dBm, respectively. The electrical RZ data are generated by using an AND gate fed by a 2.5-GHz sinusoidal wave and an NRZ pseudo-random bit sequence (PRBS) (length = 2^{15}-1). We divide the output of the AND gate into two, one of which is delayed by ~41 ps with respect to the other, and then both the signals are sent to electrical amplifiers to drive the RSOAs. The driving voltage of the RZ signals is set to be 3.2 V_{pp}. The optical RZ signals at the outputs of the RSOAs are then combined using a 50:50 optical coupler, and the resulting 5-Gb/s optical signals are passed through OBPF2 (3-dB bandwidth = 0.9 nm) which emulates an AWG at the central office. This OBPF also rejects the small side-modes of the RSOA output, and thus improves the quality of the signals. The signals are launched into a standard single-mode fiber (SSMF) through the optical circulator. The optical power launched into the fiber link is measured to be −6.5 dBm. After

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transmission, the signal is detected using an optically pre-amplified receiver comprising an EDFA, OBPF3 (3-dB bandwidth = 0.5 nm), and a PIN detector. The electrical bandwidth of the receiver is 3.5 GHz. The received signal is then sent to an error detector for bit-error ratio (BER) measurements. We programmed the error detector to detect the BER of the *non*-PRBS pattern of the OTDM signals.

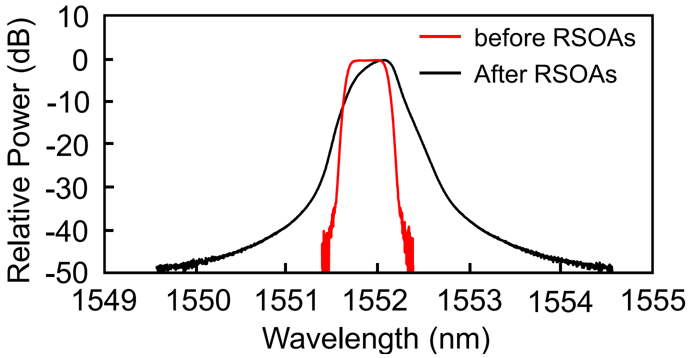

Fig. 3. Measured optical spectra before and after the RSOAs in red and black, respectively.

Figure 3 shows the optical spectra of the spectrum-sliced pulsed incoherent light before and after the RSOAs. The 3-dB and 20-dB bandwidths of the spectrum-sliced incoherent light before the RSOAs are measured to be 0.43 and 0.6 nm, respectively. After passing through the RSOAs, the signal spectrum is broadened and red-shifted due to phase-modulation-induced chirp and intra-channel four-wave mixing inside the gain-saturated RSOAs [15]. For example, the 20-dB bandwidth of the signal after the RSOAs is broadened to 1.0 nm.

Figure 4 shows the measured BER curves for the back-to-back operation and after 10-km transmission. We first measure the BER curves of the 2.5-Gb/s RZ signals generated by a single RSOA only. In this case, we turn the other RSOA off and increase the attenuation of the corresponding VOA to avoid any optical reflections. The electrical bandwidth of the receiver used to detect the 2.5-Gb/s RZ signals is 1.8 GHz. At the back-to-back case, the receiver sensitivities (at a BER of 1.8×10^{-4}) of the 2.5-Gb/s RZ signals (i.e., before OTDM) are measured to be –46.0 and –47.0 dBm using RSOA1 and RSOA2, respectively. Here we assume Reed-Solomon (255, 239) forward-error correction (FEC). RSOA2 exhibits better performance than RSOA1 mainly due to higher extinction ratio (ER). For example, the ER of the RSOA2 output signal is measured to be 15 dB whereas it is 10 dB for the RSOA1 signal. After 10-km transmission, the sensitivity penalties are measured to be 0.5~1.0 dB with respect to the back-to-back case which is mainly attributed to fiber dispersion. The pulse broadening by the chromatic dispersion at 5 Gb/s after 10-km transmission would be ~70 ps, which is only 1/3 of the bit duration. Therefore, the dispersion penalty of the OTDM signals should be attributed to breakdown of the intensity correlation created by the gain-saturated RSOA. When the incoherent light is intensity-smoothed by a gain-saturated semiconductor optical amplifier, a strong intensity correlation is created between the wavelength components of the output light. Fiber dispersion, however, serves to break the intensity correlation of the intensity-smoothed RSOA output, and thus undoes the EIN suppression [19]. This limits the maximum transmission distance of the intensity-smoothed incoherent light signals.

After doubling the data rate by using OTDM, the resulting 5-Gb/s signal exhibits an error floor at a BER of $\sim 10^{-8}$ (solid squares in Fig. 4). The error floor should be attributed to the crosstalk between the 2.5-Gb/s tributaries. Unlike a typical OTDM transmitter where passive optical modulators are used before multiplexing low-data-rate tributaries, active optical components are employed in the proposed scheme. Therefore, ASE noise can be generated from the RSOA even at the moment when the input seed light is very low in intensity. The ASE from one of the RSOAs then interferes with the output signal from the other RSOA and

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induces penalty after OTDM. Despite the ASE-induced crosstalk, we have a receiver sensitivity of −41.2 dBm at the FEC threshold of 1.8×10^{-4}. Power addition of crosstalk (rather than field addition) for unpolarized incoherent light helps to achieve the good receiver sensitivity in the presence of the crosstalk. After 10-km transmission, the error floor of the 5-Gb/s signal shifts to a BER of $\sim 10^{-6}$ (empty squares in Fig. 4) and the receiver sensitivity is measured to be −40.0 dBm with a dispersion penalty of 1.2 dB.

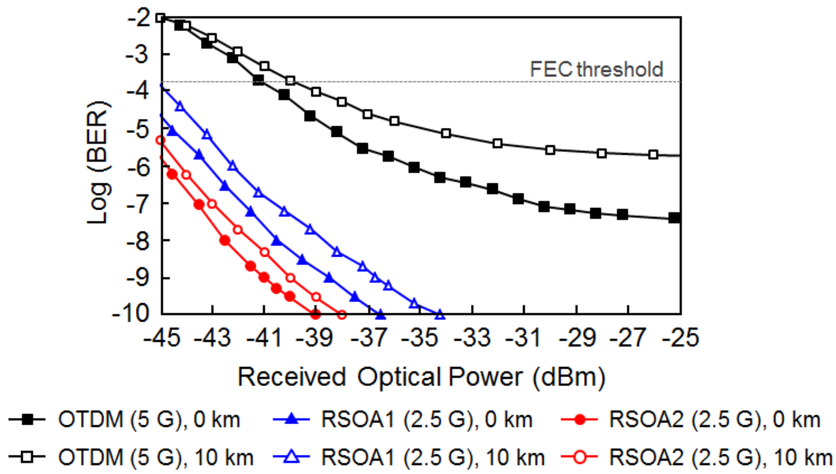

Fig. 4. Measured BER curves of the 5-Gb/s optical signals after OTDM (black squares). Also shown are the BER curves of the 2.5-Gb/s RZ signals using RSOA1 (blue triangles) and RSOA2 (red circles) before data-rate upgrade. The solid and empty shapes represent the BER curves at the back-to-back case and after 10-km transmission, respectively.

The ASE-induced crosstalk from the RSOAs also explains the reason why the RSOAs are driven by RZ data rather than NRZ data even though the seed light is a pulse train. When the RSOAs are driven by NRZ data, the RSOA generates more ASE noise due to higher instantaneous RSOA current at the bit center of other tributaries. Indeed, we observe an error floor at around 10^{-3} when the RSOAs are driven by an NRZ signal.

Figure 5 shows the electrical eye diagrams measured at the receiver. The eye diagrams of the 2.5-Gb/s RZ signals at the back-to-back case in Figs. 5(a) and 5(b) show clear eye openings, but after transmission, Figs. 5(d) and 5(e) show a slight degradation with some scattered dots in the middle of the eyes. The eye diagrams of the RZ signals using RSOA2 show clearer eye opening than those using RSOA1.

Next, we measure the sensitivity penalties incurred by changing the power levels injected into the RSOAs and plot in Fig. 6(a). The penalties are measured with reference to the receiver sensitivity at the FEC threshold of 1.8×10^{-4}. We first tune VOA2 to change the optical power injected into RSOA2 while maintaining the power level injected into RSOA1 to 5.4 dBm and plot the sensitivity penalties in red circles in Fig. 6(a). It is found that the power level injected into RSOA2 should be kept within 2.6~4.2 dBm to keep the penalty below 2 dB. In our system, the maximum power that can be injected into RSOA2 is 4.2 dBm, and thus we are unable to measure the receiver sensitivity when the power level exceeds this level. We also measure the sensitivity penalty when the optical power into RSOA1 is tuned while maintaining the optical power into RSOA2 to 4.2 dBm and plot in Fig. 6(a) (blue triangles). The results show that the power level injected into RSOA1 should be kept between 3.2 and 6.4 dBm to maintain a penalty window smaller than 2 dB.

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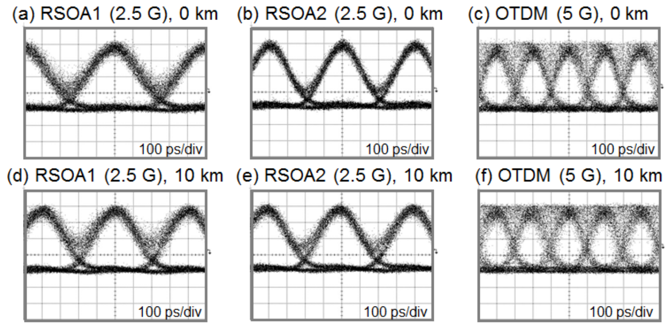

Fig. 5. Electrical eye diagrams. At the back-to-back case: (a) 2.5-Gb/s RZ signal using RSOA1, (b) 2.5-Gb/s RZ signal using RSOA2, and (c) 5-Gb/s signal after OTDM. After 10-km transmission over SSMF: (d) 2.5-Gb/s RZ signal using RSOA1, (e) 2.5-Gb/s RZ signal using RSOA2, and (f) 5-Gb/s signal after OTDM.

In the proposed system, timing synchronization should be achieved between the seed pulse and the modulating signals, as well as between the two interleaved 2.5-Gb/s tributaries. However, our system is less sensitive to the former where the penalty is measured to be <1 dB after 50-ps shift from the optimal synchronization. The latter is investigated and plotted in Fig. 6(b). The receiver sensitivity is measured while we give one of the 2.5-Gb/s tributaries an optical delay with respect to the other. Here, zero optical delay refers to the case when the RZ signals at the outputs of both RSOAs are perfectly interleaved for optimal OTDM. It is found that the optical delay should be kept within ± 50 ps to keep the penalty below 2 dB. Note that once the delay and optical power levels are optimized, they remain unchanged during the system operation.

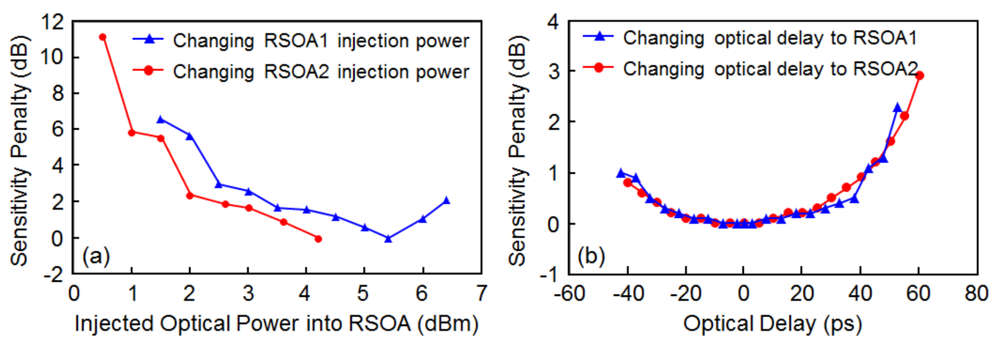

Fig. 6. Measured sensitivity penalty of 5-Gb/s signal as a function of (a) the optical power injected into the RSOA and (b) the relative optical delay with respect to the other RSOA.

4. Summary

We have proposed and demonstrated a simple and cost-effective optical transmitter based on incoherent-light-injected RSOAs capable of graceful capacity upgrade in WDM PONs. By employing multiple RSOAs and optical time-division multiplexing technology, we can upgrade the system capacity on an as-needed basis without discarding the old low-data-rate transmitters. Using the proposed scheme, we have demonstrated a capacity upgrade from 2.5- to 5-Gb/s/channel over 10 km of standard single-mode fiber.

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