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All-optical wavelength reuse with simultaneous upstream data and PPS timing signal transfer for flexible optical access networks

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ABSTRACT
All-optical wavelength reuse is a viable approach for realization of low cost colourless ONUs. We experimentally demonstrate a novel all-optical wavelength reuse technique with simultaneous upstream data and pulse-per-second signal transfer, exploiting EDFA gain saturation with a holding beam. A DFB laser is modulated with 8.5 Gbps data and transmitted downstream over 24.7 km fibre. A saturated EDFA located at the ONU is adopted to reduce the extinction ratio of the downstream data from 6.2 dB to 839.1 mdB. This allows for data rewrite and wavelength reuse for upstream transmission. Receiver sensitivities of −20.19 dBm and −19.60 dBm are achieved at back-to-back analysis and 24.7 km downstream link respectively. A holding beam is further exploited to attain simultaneous carrier reuse and PPS clock upstream transfer. PPS jitter stability of 1.01×10^{-08}ns and 6.64×10^{-08}ns are attained respectively. This work offers a convenient all-optical wavelength reuse solutions for optical access networks.

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Erbium-doped fibre amplifier (EDFA); pulse-per-second (PPS); access network; wavelength reuse

1. Introduction

Despite the global internet traffic expanding daily, the average aggregate revenue collected by service providers per user is either stagnant or gradually decreasing. In order to continue maintaining profitable exponential growths, service providers must adopt alternative viable long-term solutions to reduce the network installation and running cost, as well as provide better services to subscribed users. Network operators must exploit architectures that provide benefits in better resource management, are power and spectrum efficient, have simplified network operation and therefore lower costs (*1*).

Wavelength division multiplexing (WDM) optical techniques are the most promising multiplexing solution in terms of power efficiency and unlimited data rate (*2*, *3*). In particular, WDM colourless self-tuning transceivers with ability to automatically and passively assign the source wavelength is a favoured approach in antenna sites applications. However, traditional WDM system architectures are limited by the maximum number of users they can support since each user is assigned a dedicated channel for downstream usage, and a separate channel for upstream. This approach increase network complexity, limits network efficiency and constrains the network for future expansions. Network embedded colourless transmitters employing directly modulated lasers at the central office (CO) and reflective semiconductor optical amplifier (RSOA) for signal reuse and re-modulation at each optical network unit (ONU) have proved to be a viable approach to achieving compact self-tuning transceivers (*4*). Recently, several RSOA-based schemes have been proposed because of its ability to reuse the downstream signal received at the ONU for upstream transmission (*5*–*9*). For instance, (*6*) presented findings for higher data rate carrying architecture using upstream remodulation technique. RSOA was shown to improve transmission performance by adopting a feed-forward cancellation circuitry. This system architecture was also proved to support asymmetrical 2.5 Gbps/1.25 Gbps and symmetrical 10 Gbps/10 Gbps data rates. Moreover, (*5*) demonstrated a self-feedback semiconductor SOA fibre loop operated at power saturation condition used as a data-amplitude clipper to erase downstream PRBS data of a broadband light source. An extinction ration reduction from 13 to 1.6 dB was achieved in this work. However, despite the various attractive feature of opto-electronic based wavelength reuse techniques such as the use of RSOA and SOA, opto-electronic wavelength reuse techniques are still faced with a number of constrains. For instance, due

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to its limited bandwidth of 1.2 GHz some applications such as wireless transmission may require down conversion circuits to convert the standard wireless signal from its RF carrier to an intermediate frequency before uplink transmission (*10*).

In this paper, we propose the use of an erbium-doped fibre amplifier (EDFA) gain saturation with a holding beam to achieve all-optical wavelength reuse with simultaneous upstream data and pulse-per-second (PPS) timing signal transfer of a 8.5 Gbps NRZ signal and 1 PPS timing signal over 24.7 km SMF fibre using a single DFB laser. Our proposed approach is fully optical, comply with strict budget cost and simplified maintenance, integrable with existing optical access networks, and for implementation purposes does not require any customized or additional optics hardware. This technique is novel and is appropriate for flexible optical access networks applications operating at data rates of up to 8.5 Gbps.

2. Experimental setup

A full schematic representation of the test bench for all-optical down-stream data erasing and simultaneous carrier reuse and transmission of standard data with precise time up-stream transmitter link is illustrated in Figure 1. A distributed feedback laser (DFB) biased at 38.10 mA with an optical output power of 4.14 dBm is directly modulated with an 8.5 Gbps non-return-to-zero PRBS data of pattern length 2^7-1.

This is used to supply down-stream data link over an optical line terminal (OLT) made up of a single mode fibre (SMF) of length 24.7 km. circulator 1 was used to maintain the downstream data link in the forward direction therefore all counter-propagating optical signals were received from port 2 of the circulator, then directed to port 3 for analysis as shown in Figure 1. The downstream data was transmitted over a 24.7 km OLT link. An optical splitter was used at the receiver end for simultaneous data analysis and saturation for wavelength reuse as shown in Figure 1. To achieve a fully optical data erase, an Erbium-doped fibre amplifier (EDFA) operating at close to saturation point was used. A continuous wave broadband laser source (with a spectral range between 1530 and 1570 nm) holding beam was used to generate a broadband transient pump lightwave in the C-band transmission window. This was then coupled with the transient upstream data signal into the EDFA at the ONU for optical data erase. Transient effects of the 8.5 Gbps NRZ downstream data signal at 1550 nm were generated in an EDFA due to cross-gain saturation between the information carrying signal and the broadband transient pump lightwave to attain optical suppression of signal power transients as shown in Figure 1. Therefore, the broadband holding beam and the optical coupler before circulator 2 were mainly used to optimize EDFA performance for all-optical data erase. To characterize the all-optical data erasing ability of our technique, the residual data carried on the downstream link before and after

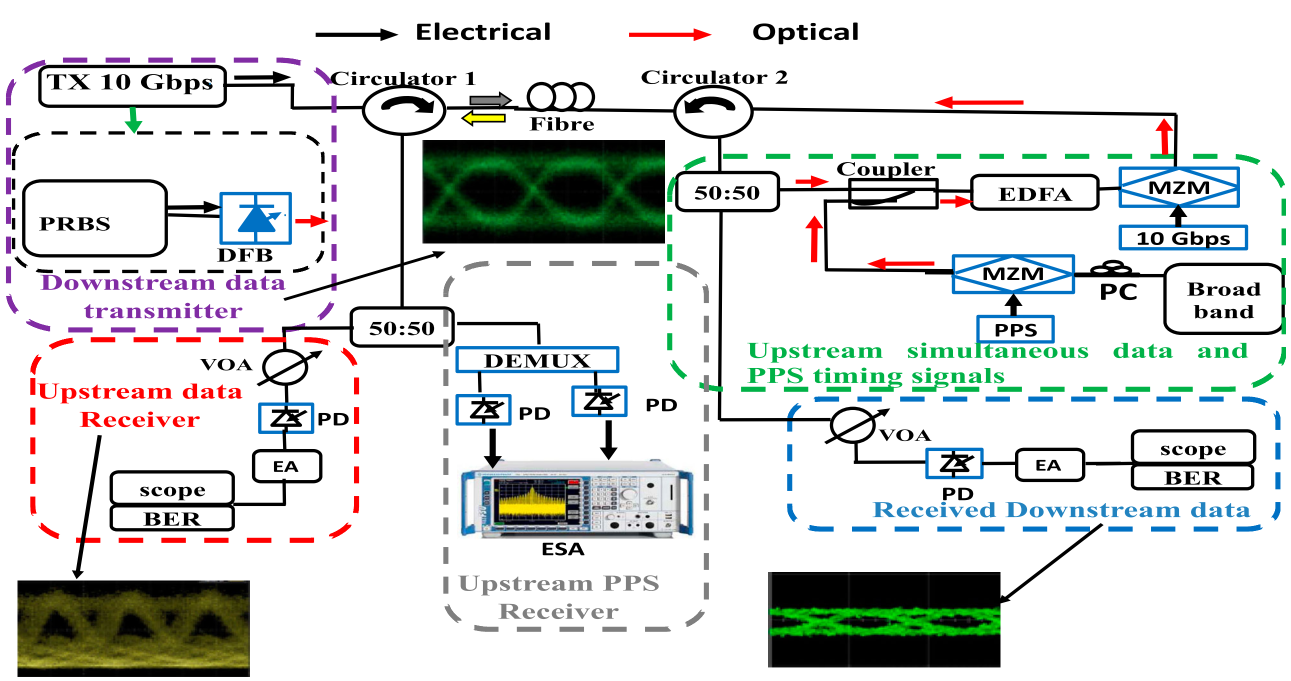

Figure 1. Schematic of the experimental set-up to demonstrate all-optical data erase with simultaneous data rewrite and PPS upstream transmission: MUX-wavelength division multiplexer, DEMUX – wavelength division de-multiplexer, VOA-variable optical attenuator, EA – electrical amplifier, PD-photo detector, PPS – pulse per second, BER-bit error rate tester, MZM – Mach Zehnder modulator.

erasing was analysed by a sampling oscilloscope (Agilent 86100D). An upstream carrier reuse was achieved by remodulation the channel externally with an 8.5 Gbps NRZ data externally via the Mach Zehnder modulator (MZM). To further maximize on the network capacity, a second MZM was used to modulate all the channels of the holding beam with a pulse per second (PPS) timing clock signal for simultaneous upstream transmission with the data signal over the same optical fibre. The 8.5 Gbps wavelength reused upstream data received by a standard NRZ receiver (Agilent 86100D) was analysed by a commercial BER detector for quality of signal performance of the link. Jitter stability analysis of the simultaneously transmitted upstream PPS clock signal was captured by a Tektronix 5 series mixed signal oscilloscope and analysed offline via DSP circuits developed in MATLAB. Optical filters were used to separate between the channels for individual analysis. For demonstration purposes, PPS jitter stability results for only one channel are presented as a proof of concept.

3. Results and discussion

3.1. Jitter stability analysis of the pulse-per-second clock signal

In this section, we present the jitter stability analysis of the received pulse-per-second (PPS) clock signal after simultaneous carrier reuse and upstream transmission of the PPS clock with standard data over 24.7 km of G.655 SMF fibre.

A low noise FS725 rubidium oscillator (SRS model PRS10) with an estimated 20 years aging time of less than 5×10^{-9} was used in this work. The FS725 is an ideal instrument for calibration in laboratories or any applications requiring precision frequency standards (*11*). The experimentally measured electrical PPS signal clock jitter stability results are shown in Figure 2. Several traces centred at the rising edge of the received PPS clock signal were captured by a 5 series mixed signal oscilloscope from Tektronix and analysed using DSP circuits developed offline for jitter stability measurement. From Figure 2, a jitter stability of 1.34×10^{-09} ns was experimentally measured for the electrical PPS clock signal. This was within the range of 1 ns jitter stability value specified by the FS725 rubidium oscillator user manual in (*11*). The PPS pulse width was also measured directly at full width at half maximum (FWHM). A PPS pulse width of 9.99 µs was attained as shown in Figure 2. However, after simultaneous carrier reuse with standard data and upstream transmission, the measured jitter increased to 1.01×10^{-08} and 6.64×10^{-08} ns for back-to-back analysis and over 24.7 km of G.655 SMF fibre transmission respectively as shown in Figure 2.

3.2. Performance analysis of the upstream and downstream data transmission

To enable all-optical data erase for wavelength reuse after the 24.7 km downstream transmission, we propose the use on an EDFA with gain saturation. The experimentally measured output optical power characteristics as a function of the input optical power of the used EDFA is shown in Figure 3. It was noted that the output characteristics of the EDFA were linear at low optical input power,

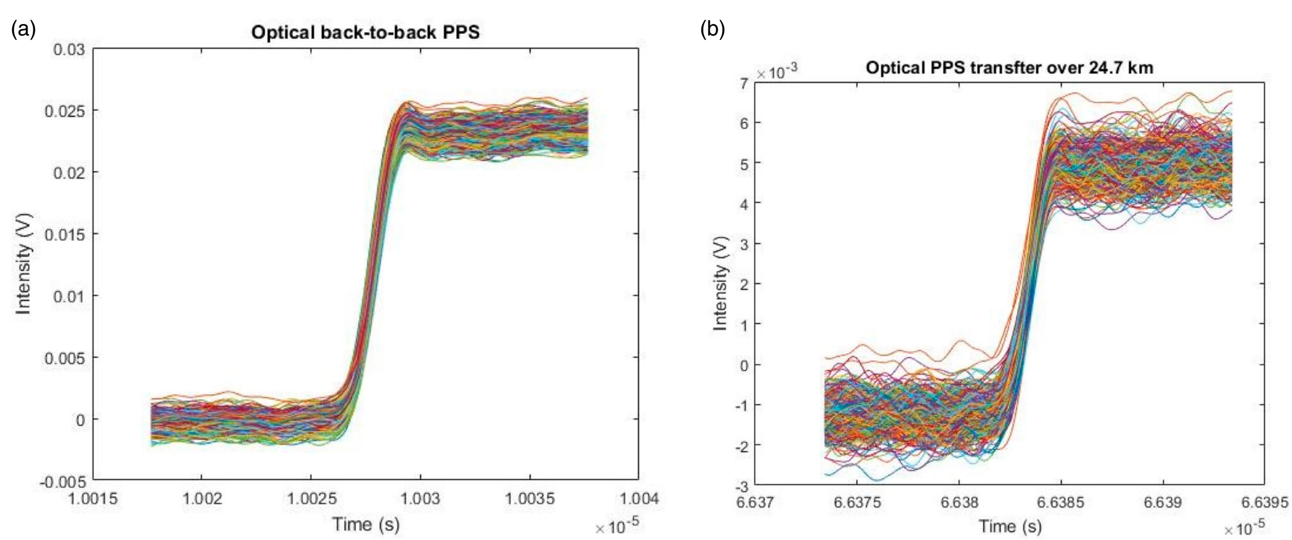

Figure 2. Experimentally measured PPS clock signal jitter stability for (a) back-to-back PPS electrical signal, (b) PPS pulse width for back-to-back electrical signal, (c) PPS jitter stability at back-to-back after simultaneous carrier reuse with standard data, (d) PPS jitter stability after simultaneous carrier reuse with standard data and upstream transmission over 24.7 km of G.655 SMF fibre.

and nonlinear at a high optical input power. As the input optical power increased, the gain became very small and eventually saturated at higher powers. From experimentally measured results in Figure 3, the output power P_{out} remained linear for input powers P_{in} below – 20 dBm. However, as the input power was increased from −10 to 0.3 dBm, P_{out} was noted to saturate at approximately 6.7 dBm. The same trend was noted with and without modulation as shown in Figure 3, where the addition of modulation resulted to the EDFA saturating at slightly reduced P_{out}. Exploiting the gain saturation of the EDFA, the difference in the '1' level with respect to the '0' level remained very low due to EDFA gain saturation there erasing the data. Figure 3, shows experimentally measured EDFA output power at 1551.40 nm as a function of input optical power at bias currents of 1160 and 850 mA, respectively. From results in Figure 3, a higher output power was attained at higher EDFA bias currents at the same input powers.

After attaining a successful data erase and rewrite, an upstream data transmission with the reused wavelength was done for over 24.7 km fibre length. To confirm the signal quality of the reused wavelength, bit error rate (BER) curves were measured. Figure 4 shows the experimentally measured BER results for back-to-back down link, 24.7 km downstream transmission, back-to-back (B2B) uplink after data erase and rewrite, 24.7 km wavelength reuse with EDFA gain saturation and upstream fibre transmission. The receiver sensitivity for achieving a BER $= 10^{-9}$ for B2B and 24.7 km downstream link transmission was measured as −20.19 and −19.60 dBm, respectively. However, after data erase and rewrite on the reused wavelength for upstream link, the experimentally attained BER measurements at the same BER threshold were recorded as −17.52 and −17.14 dBm for back-to-back and 24.7 km upstream link transmission respectively as shown in Figure 4. The respective eye diagrams showing the attained extinction ratios (ER) are shown in Figure 5. ER of 6.2 and 4.2 dB was achieved for B2B downstream analysis and 24.7 km SMF downstream link transmission, respectively. Moreover, a B2B analysis of upstream link after a successful data erase and rewrite

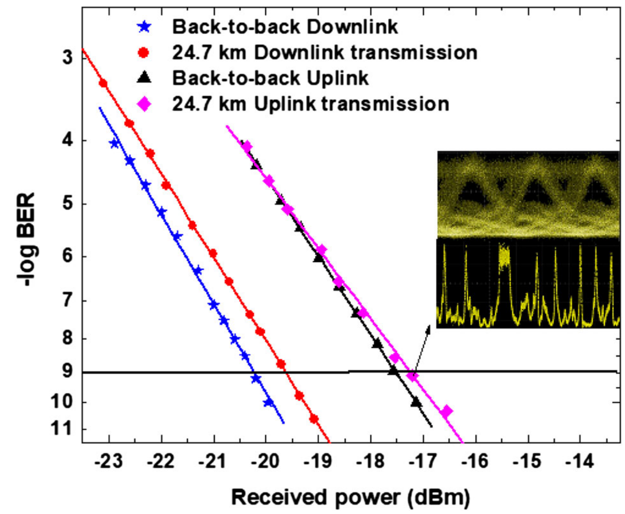

Figure 4. Experimentally measured BER curves for back-to-back (B2B) down link, 24.7 km downstream transmission, (B2B) uplink after data erase and rewrite and 24.7 km wavelength reuse with EDFA gain saturation, insert: measured eye diagram and data pattern for the reused wavelength over 24.7 km upstream transmission fibre link fibre.

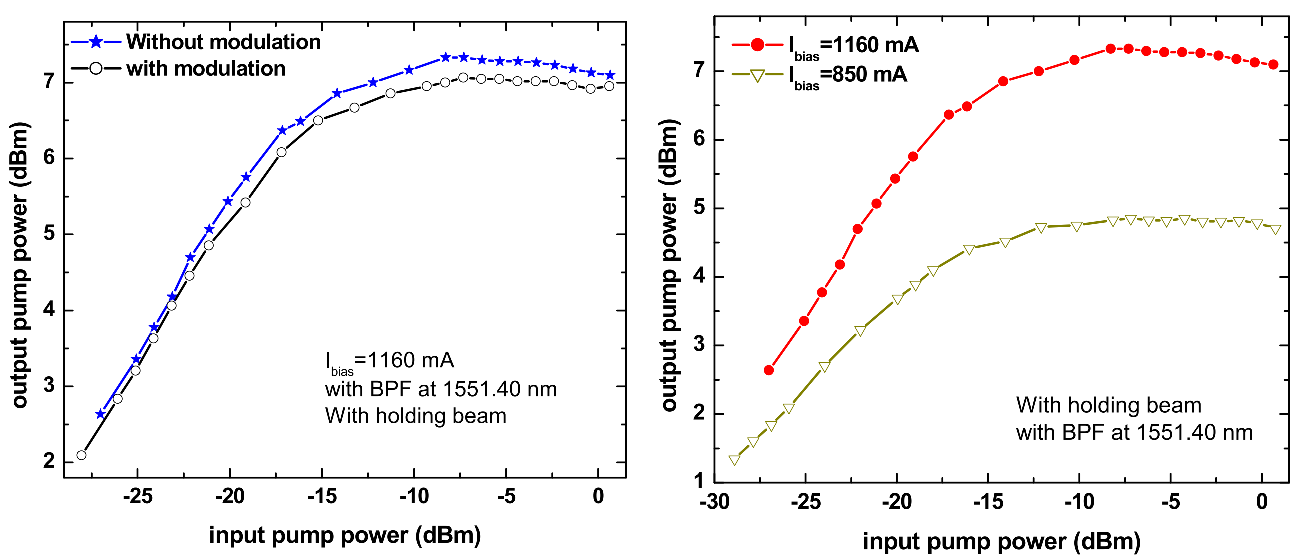

Figure 3. Experimentally measured EDFA output power at 1551.40 nm as a function of input optical power at different bias current (left), EDFA output power at 1551.40 nm as a function of input optical power with and without modulation at bias current of 1160 mA (right).

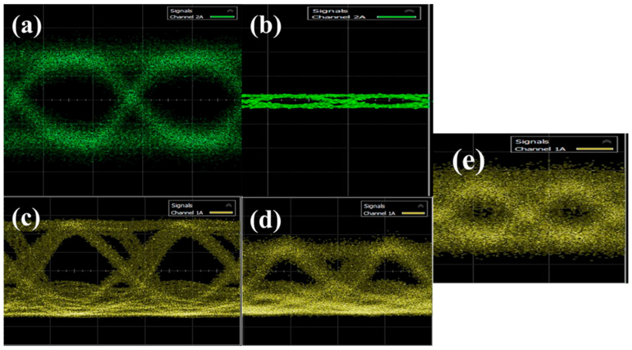

Figure 5. Experimentally measured eye diagrams at back-to-back (B2B) downstream analysis with ER = 6.2 dB (a), 24.7 km SMF downstream link transmission with ER = 4.2 dB (b), (B2B) analysis of upstream link after a successful data erase and rewrite with ER = 7.4 dB (c), 24.7 km upstream wavelength reuse transmission link with ER = 6.2 dB (d), a successfully data erased eye diagram with ER = 839.1 mdB.

attained an ER of 7.4 dB, while a 24.7 km upstream wavelength reuse transmission link achieved an ER of 6.2 dB as shown in Figure 5.

Intelligent optical network design and technological down selection are of great importance in meeting unique requirements of flexible access networks. Moreover, combined wavelength reuse and simultaneous distribution of both data and timing clock signals over shared network infrastructure significantly increases the network flexibility and efficiency at different optical network units (ONUs), without expensive optics investment. Other than the high-speed requirements, our proposed all-optical wavelength reuse technique with simultaneous upstream data and pulse-per-second (PPS) timing signal transfer, exploiting erbium-doped fibre amplifier (EDFA) gain saturation comply with strict budget cost and simplified maintenance, thus allowing for integration with flexible optical access networks. Our all-optical wavelength reuse technique concept is for the first time demonstrated using data rates of 8.5 Gbps per user channel due to its availability in our laboratory. However, much higher data rates and longer fibre transmission distances can still be supported in the same system where splitting ratio, reach, and aggregated capacity can be traded off against each other to maximize system performance potential.

Conclusion

This work has experimentally demonstrated the first all-optical wavelength reuse technique with simultaneous upstream data and pulse-per-second (PPS) timing signal transfer, exploiting erbium-doped fibre amplifier (EDFA) gain saturation. Extinction ratios of 6.2 and 4.2 dB have been achieved for back-to-back (B2B) downstream analysis and 24.7 km SMF downstream link transmission respectively. Moreover, a B2B analysis of upstream link after a successful data erase and rewrite have been shown to attain ER of 7.4 dB, while a 24.7 km upstream wavelength reuse transmission link achieved ER of 6.2 dB. A receiver sensitivity of −20.19 and −19.60 dBm have experimentally been achieved at BER = 10^{-9} for B2B analysis and 24.7 km downstream fibre transmission, respectively. Moreover, the jitter stability of the received pulse-per-second (PPS) clock signal after simultaneous carrier reuse and upstream transmission over 24.7 km fibre has been shown to remain below 1.01×10^{-08} and 6.64×10^{-08} ns at B2B analysis and 24.7 km transmission, respectively. Our proposed all-optical wavelength reuse technique with simultaneous upstream data and pulse-per-second (PPS) timing signal transfer, exploiting erbium-doped fibre amplifier (EDFA) gain saturation is a viable approach for realization of colourless optical network units in access networks with reduced cost and simplified maintenance.

Disclosure statement

No potential conflict of interest was reported by the authors.

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