Long reach DWDM-PON with 12.5 GHz channel spacing based on comb source seeding

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A long reach dense wavelength division multiplexing passive optical network (DWDM-PON) with 12.5 GHz channel spacing is proposed and experimentally demonstrated. An optical frequency comb source is used to provide the multi-wavelength seeding light, while reflective semiconductor optical amplifiers (RSOAs) are installed in both optical line terminal (OLT) and optical network units (ONUs) as colorless transmitter. The experimental results show that the bi-directional transmission for 1.2 Gbit/s data rate is achieved over 80 km single mode fiber (SMF).
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Wavelength division multiplexing passive optical network (WDM-PON) has been widely acknowledged as an attractive solution of access network to meet the bandwidth demand and provide multi-service integration[1]. With the fast increasing number of terminals, lower channel spacing of PON system is desired to accommodate large number of users with relatively low cost[2]. In addition, the scope of PONs is geographically extended up to nearly 100 km, thus the consolidation of metro and access networks can be realized to reduce network maintenance cost and energy consumption[3,4]. Hence, long reach dense WDM-PON (DWDM-PON) for more users with reductive channel spacing is considered as an attractive candidate for future next generation-PON3 systems[5].

To substantially reduce the operation cost and alleviate the inventory management issue, it is highly desirable to utilize colorless optical transmitters based on seeding light injection technology in DWDM-PONs, such as Fabry-Perot laser diodes (FP-LDs) and reflective semiconductor optical amplifiers (RSOAs)[6-8]. U. R. Duarte et al have demonstrated a DWDM-PON system with 100 GHz grid and 20 km reach. The self-seeding RSOAs are used as the downstream transmitter in OLT, while the ROSA is also used for upstream re-modulation in ONUs[7]. Another 25 GHz spaced DWDM-PON system with 60 km fiber reach has been proposed based on the RSOA injected by spectrum sliced amplified spontaneous emission (ASE) source[8]. The key limiting factors for long distance transmission are the intensity noise of the spectrum sliced ASE light and optical back reflection. Larger linewidth light sources exhibit much greater intensity noise (amplitude noise), which deteriorates the transmission performance[8,9]. Therefore, distributed feedback (DFB) laser has been employed in PON systems to mitigate intensity noise[10,11]. But these schemes induce added cost to users due to infeasible share of laser sources.

In this paper, a long reach DWDM-PON with 12.5 GHz channel spacing is proposed and experimentally demonstrated. Experimental results show that 80 km upstream and 150 km downstream SMF transmissions can be supported by the proposed system.

Fig.1 depicts the architecture of the proposed DWDM-PON system. In OLT, the comb source generates multi-wavelengths with 12.5 GHz spacing. A band-pass filter (BPF) filters out 2*N* wavelength channels, with *N* channels for upstream and the other *N* for downstream. After being amplified by the following erbium doped fiber amplifier (EDFA), the 2*N* channel seeding wavelengths are separated by a red-blue coarse wavelength division multiplexer (CWDM), with red part for downstream and blue part for upstream. After passing through a circulator and arrayed waveguide grating (AWG1), all the downstream seeding wavelengths are injected into the RSOAs for wavelength locking and downstream data modulation. The downstream signals multiplexed by AWG1 are coupled with upstream seeding light by an optical coupler (OC), and then boosted by an EDFA before entering the SMF.

In remote node (RN), the cyclic routing AWG3 is used to de-multiplex both the downstream signals and upstream seeding light for each ONU. In ONU, a red-blue CWDM is used for splitting upstream seeding light and downstream signals. The seeding wavelength is injected into the RSOAs for wavelength locking and upstream modulation. The upstream signals are multiplexed by AWG3 in RN and transmitted through SMF. In OLT, the

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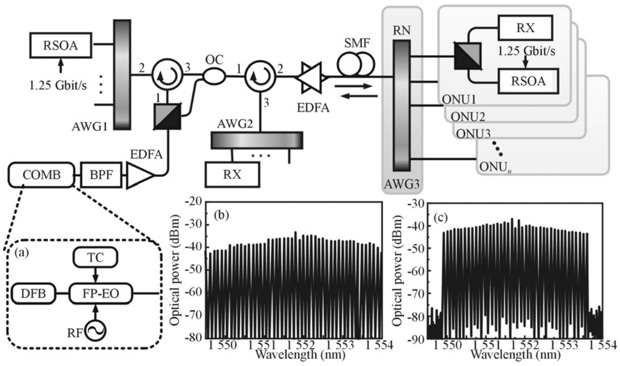
upstream signals are pre-amplified by an EDFA and de-multiplexed by AWG2 before entering the receivers.



AWG: array waveguide grating; BPF: band pass filter; RX: receiver; OC: optical coupler; TC: temperature controller; FP-EO: Fabry-Perot electro-optic modulator

Fig.1 Architecture of the proposed DWDM-PON system: (a) Inner structure of the comb source; (b) Spectrum of partial comb source output; (c) Spectrum of the filtered out 40-channel seeding light for downstream

Fig.1(a) shows the structure of optical frequency comb source, which consists of a DFB laser, a temperature controller (TC), a radio frequency (RF) source and a Fabry-Perot electro-optic (FP-EO) modulator. The FP-EO modulator is driven by 12.5 GHz RF signal. After modulation, a large number of channels with 12.5 GHz spacing (0.1 nm) are generated. The partial spectrum of optical frequency comb is measured by an optical spectrum analyzer (OSA) with 0.015 nm resolution, as shown in Fig.1(b).

Following the configuration shown in Fig.1, an experiment is set up for evaluating the performance of this proposed DWDN-PON system. Since the used AWG doesn't have cyclic property, we conduct the upstream and downstream experiments separately. The output wavelength and power of DFB laser are set as 1 549.6 nm and 0 dBm, respectively.

For downstream, the number of AWG output ports N corresponds to 40, so 40 channels with 1 549.6 nm center wavelength and 0.1 nm spacing are filtered out by BPF, as illustrated in Fig.1(c). Then the seeding light is injected into RSOAs in OLT for downstream signal modulation. Due to limited modulation bandwidth, the modulation rate of RSOA is typically 1.25 Gbit/s[7,8]. In our experiment, all the ROSAs are directly modulated by 1.25 Gbit/s pseudo random binary sequence (PRBS) data with word length of $2^{31}-1$. The multiplexed downstream signals are boosted to 10 dBm by an EDFA.

For upstream, the 40 channel seeding light signals centered at 1 555.1 nm are also filtered out in OLT, and then assigned to each ONU for upstream signal modulation. Before de-multiplexing in OLT, an EDFA is employed to pre-amplify the upstream signals. The avalanche photodiodes (APDs) are used in both ONU and OLT to detect the signals, and the received electrical signals are observed and analyzed by an oscilloscope.

In this proposed DWDM-PON, the seeding light is provided by the comb source instead of spectrum sliced ASE. As the linewidth of light source will affect the RSOA's injection property and the transmission performance[12], we compare the linewidths of optical comb source and sliced ASE source. Fig.2 depicts the output spectra of our employed comb source and 5 ASE channels sliced by a 12.5 GHz AWG. The measured linewidth of comb source is 0.017 nm, obviously narrower than that of the sliced ASE light.

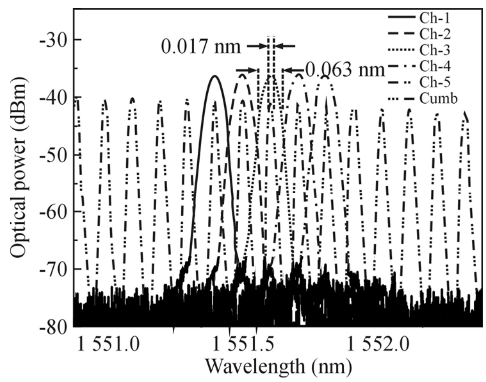


Fig.2 Experimental spectra of comb source output and stacked 5-channel sliced ASE by 12.5 GHz AWG

To investigate the influence of seeding light linewidth on the transmission performance, a simulation test system shown in Fig.3 is set up by VPI Transmission Maker. A tunable DFB laser generates the seeding light with different linewidths. Then the seeding light is injected into RSOA through a circulator. The RSOA output signal with 1.25 Gbit/s PRBS modulation rate transmits through an 80 km SMF. The spectra and eye diagrams are both observed by the signal analyzer in simulation. The simulation results are shown in Fig.4(a)—(e). It is observed from Fig.4(a) that with seeding light linewidth increasing from 1 MHz to 1 GHz, the output spectrum of injection-seeded RSOA is obviously broadened. Moreover, the noise floor is gradually increasing from −25 dBm to −15 dBm with the broadening of linewidth. Broadened optical spectrum intensifies the chromatic dispersion and deteriorates the transmission performance. As a result, gradually deteriorated eye diagrams caused by intensity noise of carrier are observed in Fig.4(b)—(e). Therefore, the employed comb source has better performance than the spectrum sliced ASE source for long reach fiber transmission in the DWDM system based on injected RSOAs.

In this system, RSOA is employed as the modulator due to the low cost and large injection locking wavelength range. Since the seeding channels output from the comb have different power, the injection-locking property of RSOA is investigated with different seeding power. It is observed in Fig.5(a) that over about 40 dBm seeding power range, the output power of seeded RSOA fluctuates within 3 dB. For example, Fig.5(b) depicts the optical spectra of seeded RSOA with −20 dBm and −25 dBm seeding power, respectively. RSOA is well seeded in both the two cases. Moreover, 30-dB side-mode suppression ratio (*SMSR*) is observed, so that the inter-channel crosstalk is negligible. Therefore, the RSOA is available and applicative as a colorless transmitter in the proposed DWDM-PON system.

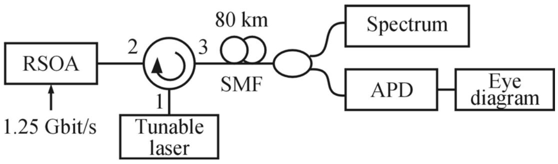


Fig.3 Simulation test system of spectrum

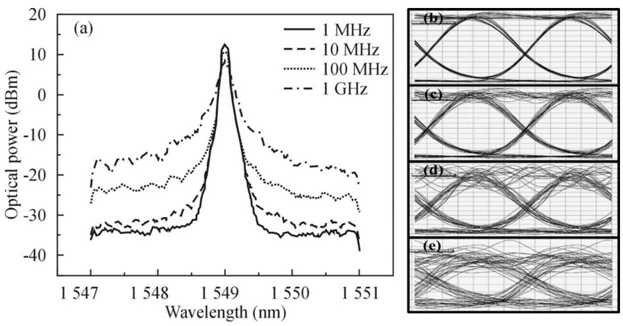
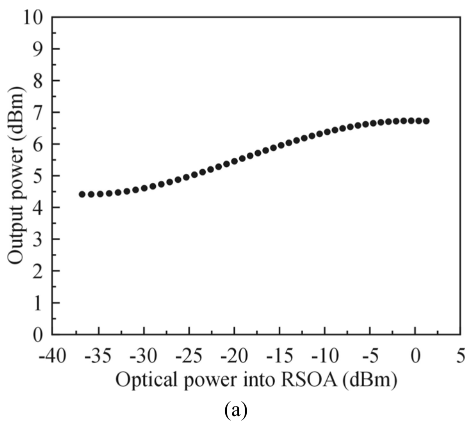


Fig.4 (a) Spectra of injection-seeded RSOA with different seed light linewidths; Eye diagrams for tested signals with (b) 1 MHz, (c) 10 MHz, (d) 100 MHz, and (e) 1 GHz linewidths of seeding light

The performance of downstream and upstream signals after various fiber length transmissions is evaluated. Fig.6(a) and (b) show the bit error rate (*BER*) performance and eye diagrams for upstream and downstream signals, respectively. For better sensitivity, an EDFA is employed as a preamplifier in OLT for upstream signals. Considering cost and performance tradeoff, the preamplifier is not used in RN or ONUs for downstream detection.

For upstream, with forward error correction (FEC), 80 km SMF transmission is achieved and about 13 dB power penalty is observed. Since the upstream seeding light and the modulated signals are carried in the same wavelength channel, the signal-to-noise ratio (*SNR*) drop



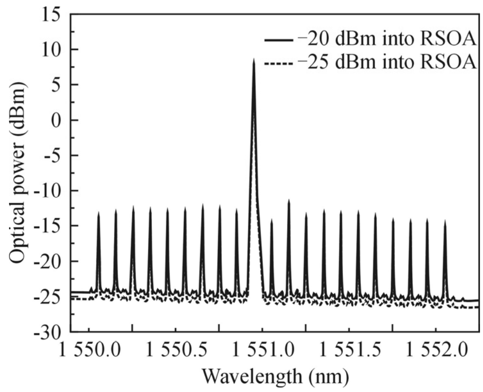


Fig.5 (a) Output power of RSOA with seeded injection versus its input power; (b) Optical spectra of injection-seeded RSOA with −20 dBm and −25 dBm input, respectively

caused by Rayleigh backscattering is the main factor that limits the upstream sensitivity and transmission reach. For downstream, error free transmission (*BER* at 10^{-10} level) is still achieved when the fiber length is less than 100 km. In 150 km case, we only achieve *BER* at 10^{-4} level due to the low optical received power. About 1 dB power penalty after 100 km and 1.5 dB power penalty after 150 km SMF transmission at FEC threshold (10^{-3})[13] are observed. These power penalties are mainly due to the slight fiber chromatic dispersion.

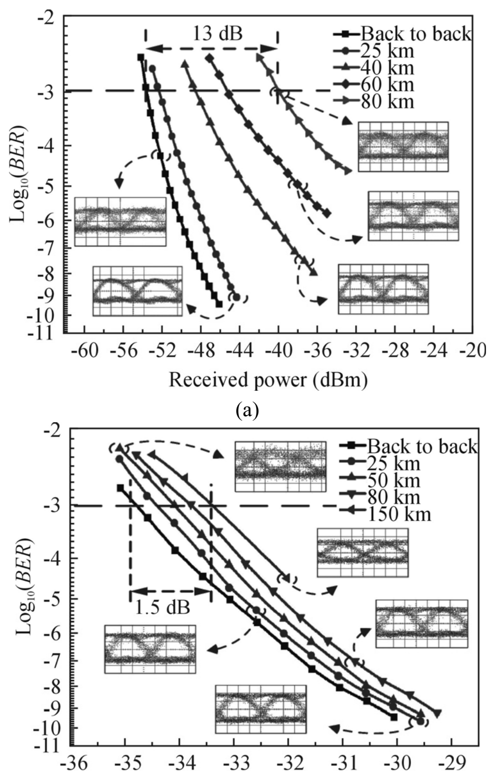


Fig.6 BER measurement results and eye diagrams for (a) upstream signal and (b) downstream signal with different fiber reaches

The power budget analysis of the proposed system is also carried out, as shown in Tab.1. In downstream direction and 80 km transmission case, the optical launching power after the EDFA is 10 dBm, and the total loss is 27 dB, including 80-km fiber attenuation (16.5 dB), the AWG insertion loss (7 dB) and the red-blue coarse WDM insertion loss (3 dB). The received sensitivity in 80 km SMF transmission at the FEC limit of *BER* of 10^{-3} is −33.5 dBm, as shown in Fig.6(b). So the calculated power margin for 80 km downstream transmission is 16.5 dB. For 150 km case, the power margin is 3.2 dB with the *BER* of 10^{-3}. In upstream direction, the RSOA has a saturated output power of 4.5 dBm, with the same insertion loss of 27 dB as downstream. The receiver sensitivity is −40 dBm at 10^{-3} level with a preamplifier employed at OLT. So the calculated upstream power margin for 80 km transmission with FEC is 17.5 dB. In a nutshell, the power margins for downstream and upstream transmissions in 80 km SMF case are 16.5 dB and 17.5 dB, respectively. It is shown that the proposed system can support at least 80 km transmission with FEC.

Tab.1 Power budget calculation for downstream and upstream signals

Element for power budget	Downstream	Upstream
Launching power after EDFA (dBm)	10	-
Injected power into RSOA (dBm)	-	−20
RSOA saturated output (dBm)	-	4.5
80-km SMF loss (dB)	16.5	16.5
Optical circulator insertion loss (dB)	0.5	0.5
$1\times N$ AWG insertion loss (dB)	7	7
Red-blue coarse WDM loss at ONU (dB)	3	3
Total insertion loss (dB)	27	27
Receiver sensitivity (dBm)	−33.5	−40
Power margin (dB)	16.5	17.5

We have proposed and experimentally demonstrated a cost-effective long-reach DWDM-PON based on the comb source seeding scheme for both upstream and downstream modulators. The experiment system sustains 40 upstream channels and 40 downstream channels with 12.5 GHz spacing, which are part of channels output from the comb source. The RSOA directly modulated by 1.25 Gbit/s data is configured as colorless transmitter on each channel in both upstream and downstream directions. Owing to the narrow linewidth of the seeding light generated by comb source, long reach transmission can be achieved. The experimental results show that the bi-directional transmission over 80 km SMF is achieved. This system could support more than 300 channels in C-band theoretically. Due to its capability and cost-effective property, the proposed architecture is valuable for practical DWDM-PON in future next generation-PON3 systems.

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