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A cost-effective ultra-dense WDM PON system with speed of 12.5 Gbit/s and channel spacing of 12.5 GHz*

MU Hong-qian (牟宏谦)**, **WANG Mu-guang (王目光), and JIAN Shui-sheng (简水生)**
Key Laboratory of All Optical Network and Advanced Telecommunication Network of EMC, Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

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A cost-effective ultra-dense wavelength-division-multiplexed passive optical network (UD-WDM PON) with speed of 12.5 Gbit/s and channel spacing of 12.5 GHz is proposed and demonstrated. The distributed feedback (DFB) lasers modulated in 4-level pulse amplitude modulation (4-PAM) format are used for downstream links, and the reflective semiconductor optical amplifiers (RSOAs) together with an optical frequency comb modulated in quadrature phase shift keying (QPSK) format are used for upstream links. We can achieve the error-free transmission of the upstream signals with speed of 12.5 Gbit/s even after 20 km single-mode fiber (SMF). The power penalty obtained by using the frequency comb generator instead of a tunable laser is around 0.5 dB. By using 11 DFB lasers and a set of intensity and phase modulators, it is possible to provide the seed light for 297 optical network units (ONUs) within the C-band.

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Wavelength-division-multiplexed passive optical network (WDM PON) has been widely regarded as the most promising future access solution of 10 Gbit/s data to each subscriber[1,2]. To provide broadband services to a large number of subscribers cost-effectively, the ultra-dense WDM PON (UD-WDM PON) has attracted increasing attention[3,4]. There also have been some efforts to develop the high-speed (>10 Gbit/s) UD-WDM PON in the future optical access networks[5-7]. However, most of these networks may not be cost-effective enough for the practical deployment. Ref.[8] starts with a practical 10 Gbit/s, 10 GHz spaced UD-WDM PON by using an optical frequency comb generator to provide the seed light for reflective semiconductor optical amplifiers (RSOAs) at the optical network units (ONUs)[9], while the downstream signals are generated by using directly-modulated distributed feedback (DFB) lasers in 4-level pulse amplitude modulation (4-PAM) format[10]. The feasibility of the proposed UD-WDM PON is demonstrated by the error-free transmission of 10 Gbit/s quadrature phase shift keying (QPSK) upstream signal, which is spaced at 10 GHz.

In this paper, we propose and experimentally demonstrate a cost-effective 12.5 GHz spaced UD-WDM PON operating at a per-wavelength speed of 12.5 Gbit/s for both upstream and downstream signals. The downstream signals are transmitted by using directly-modulated DFB lasers in 4-PAM format and direct-detection receivers, while the upstream signals are transmitted by utilizing the RSOAs directly modulated in QPSK format and inexpensive coherent receivers developed in the access networks. To the best of our knowledge, it is the first time to improve the spectral efficiency by decreasing the wavelength spacing of the adjacent comb spectra for the WDM-PON networks which use optical frequency comb as WDM sources.

Fig.1 shows the configuration of the proposed 12.5 GHz spaced UD-WDM PON system which provides symmetric 12.5 Gbit/s services to each subscriber. To accommodate the 12.5 Gbit/s signals in the channel spacing of 12.5 GHz, it is inevitable to utilize the multi-level modulation format. In this network, we assume that the downstream links are implemented by using directly-modulated DFB lasers in 4-PAM format at the optical line terminal (OLT) and direct-detection receivers at the ONUs. On the other hand, for the cost-effectiveness, the upstream links must be implemented by using colorless light sources. Thus, we assume that the upstream links are implemented by directly modulating RSOAs in QPSK format at the ONUs and utilizing inexpensive coherent receivers at the OLT. However, for the use of RSOAs, it is necessary to provide the seed light to each ONU. For this purpose, instead of using a bank of DFB lasers at the OLT, we assume to utilize an optical frequency comb generator composed of an intensity modulator and a phase modulator. In this case, the maximum number of the generated comb lines is limited by the modulation index of the

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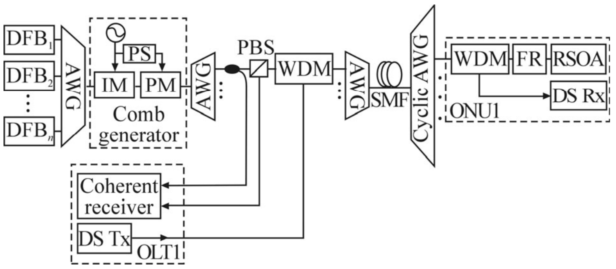
** E-mail: hongqianmu@bjtu.edu.cn

phase modulator. However, this number can be substantially increased by applying the outputs of additional DFB lasers operating at different wavelengths into the same modulator. Thus, by using an optical comb generator, we can reduce the number of DFB lasers which are required to provide the seed light to every ONU by the maximum number of the frequency comb lines achievable by using one DFB laser together with a set of phase and intensity modulators. In the remote node, a cyclic arrayed-waveguide grating (AWG) can be utilized to support both the upstream and downstream signals operating in the different wavelength bands.

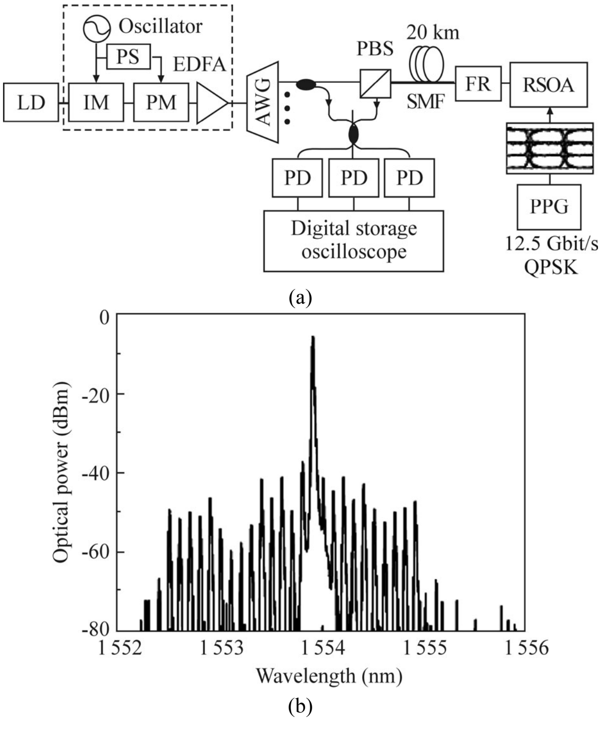


DS Tx: downstream transmitter; DS Rx: downstream receiver; IM: intensity modulator; PM: phase modulator; PS: phase shifter; PBS: polarization beam splitter; AWG: arrayed-waveguide grating; FR: Faraday rotator

Fig.1 Configuration of the proposed 12.5 GHz spaced UD-WDM PON system with speed of 12.5 Gbit/s

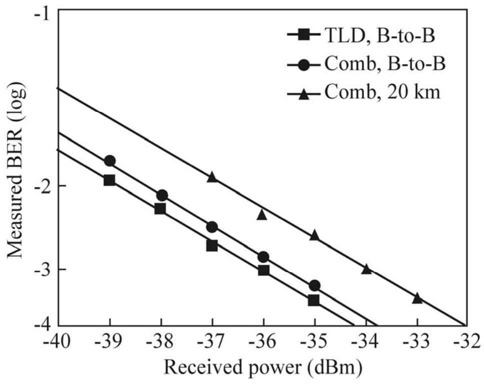
Fig.2(a) shows the experimental setup for the upstream link of the proposed 12.5 Gbit/s, 12.5 GHz spaced UD-WDM PON. The upstream link is implemented by using directly modulated RSOAs at 12.5 Gbit/s in QPSK format and inexpensive coherent receivers. The seed light for these RSOAs is provided by using an optical comb generator. For generating the 12.5 GHz spaced frequency comb, we inject the output of a tunable laser into a set of intensity and phase modulators. A 12.5 GHz sinusoidal signal is applied to these modulators, and a phase shifter is used for the synchronous modulation. The modulation index of the phase modulator is 11, and we can obtain more than 30 comb lines spaced at 12.5 GHz at the output of the comb generator. One of these combs is selected by an AWG and then sent to a TO-can packaged RSOA in the ONU, and the adjacent spectral lines are suppressed by more than 30 dB by AWG, as shown in Fig.2(b). The optical power of the comb line incident on the RSOA is set to be –12 dBm. This RSOA is directly modulated with 4-level electrical signal to generate the 12.5 Gbit/s QPSK signal. The modulated signal is then sent to the OLT and detected by using a self-homodyne receiver. This receiver utilizes an inexpensive 3×3 coupler as the 120° optical hybrid[11]. A portion of the spectrum-sliced comb line by AWG is used as the local oscillator. The optical power of the local oscillator incident on the coherent receiver is set to be 1 dBm. There is no need to utilize the expensive polarization-diversity receiver because we stabilize the polarization state of the 12.5 Gbit/s upstream signals by placing a Faraday rotator in front of the RSOA at the ONU[12]. Fig.2(c) shows the measured bit-error rate (BER) curves of the 12.5 Gbit/s upstream signals obtained by using either the spectrum-sliced frequency comb or a tunable laser as the local oscillator as well as the seed light for the RSOA. The power penalty caused by using the frequency comb instead of the tunable laser is measured to be as small as 0.5 dB in the back-to-back (B-to-B) experiment. Furthermore, the error-free performance for this 12.5 Gbit/s QPSK signal can be achieved even after the transmission over 20 km-long SMF with a power penalty of less than 2 dB. In order to investigate the impact of the optical signal-to-noise ratio (OSNR) on the performance of the uplink, the BER curves are measured with different optical power of the seed light incident on the RSOA, while the optical power of the local oscillator is set to be 0 dBm, as shown in Fig.3. When the optical power of the seed light incident on the RSOA is set to be –3 dBm, the receiver sensitivity is measured to be around –35 dBm at BER of 10^{-4}. As the optical power incident on the RSOA is decreased, the receiver sensitivity is accordingly degraded due to the decreased OSNR. However, even if the seed power to the RSOA is decreased to be –20 dBm, the error-free B-to-B transmission can still be realized with a receiver sensitivity of around –29 dBm at BER of 10^{-4}.

The comb generator is composed of an intensity modulator and a phase modulator. The outputs of a group of DFB lasers are combined by an AWG, and then injected into the comb generator. The output optical spectra of the comb generator are composed of a group of comb spectra. Both the group number and the wavelength spacing of the adjacent comb spectra depend on those of the DFB lasers. In order to efficiently utilize the output



(a)

(b)



(c)

Fig.2 (a) Experimental setup for the upstream link of the 12.5 Gbit/s, 12.5 GHz spaced UD-WDM PON; (b) Optical spectrum of the selected comb line at the output of the AWG; (c) BER curves of the upstream signals measured by using either a tunable laser or a comb line as the seed light incident on the RSOA

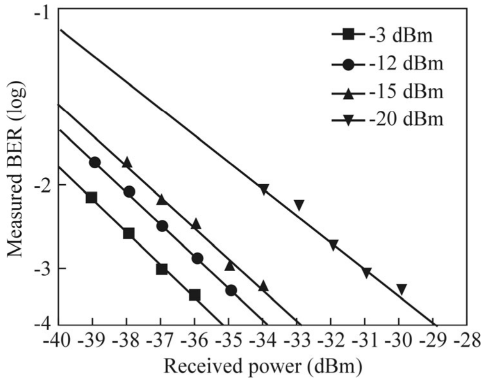
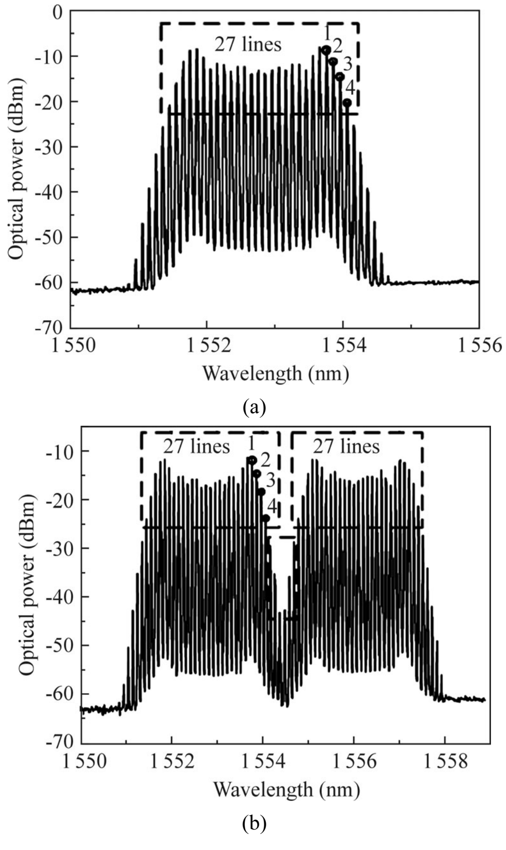


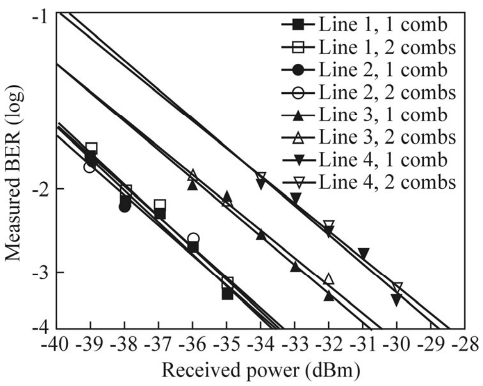
Fig.3 BER curves obtained at different optical power incident on the RSOA

optical spectra of the comb generator, the wavelength spacing of adjacent comb spectra should be set appropriately. Based on the experiment setup shown in Fig.2(a), two tunable lasers with wavelength spacing of 3.36 nm are combined by a 3 dB coupler, and then are injected into the comb generator. The output optical spectra are shown in Fig.4(a) and (b) by injecting either one laser or two lasers into the comb generator, respectively. For each comb spectrum, around 37 comb lines are generated, which can be analyzed as three regions separately, i.e., the left edge, the central flat region and the right edge. Because the optical power and the OSNR of the flat region are superior to those of both edges, the performance of the edges determines the maximum usable comb line number. At first, only the laser with the shorter wavelength is turned on. The first four spectral lines of the right edge of the comb spectrum, which are shown in line 1 to line 4 in Fig.4(a), are sliced by AWG and used as the seed light incident on the RSOA respectively, and a portion of the seed light is used as the local oscillator. From line 1 to line 4, the optical power is decreased, and the optical power of each local oscillator is measured to be 2.2 dBm, 0.5 dBm, –3.0 dBm and –4.8 dBm, respectively. Four solid block fitting lines in Fig.4(c) show the BER results for the B-to-B transmissions by using the four lines as the seed light incident on the RSOA, respectively. For the results of using line 1 and line 2, compared with the result of using the tunable laser as the seed light, the power penalties are less than 1 dB. However, for the results of using line 3 and line 4, compared with the result of using line 1, the power penalties are around 3 dB and 5 dB, respectively. And then the other laser with the longer wavelength is turned on as well. From Fig.4(b), it can be seen that the right edge of the left comb spectrum is overlapped with the left edge of the right comb spectrum, which can be viewed as intensity noise added to the left comb spectrum. The same four spectral lines of the left comb spectrum, namely line 1 to line 4, are used as the seed light incident on the RSOA respectively, and thus four hollow block fitting lines in Fig.4(c) show the BER results for the B-to-B transmissions. For each comb line, the BER characteristic here obtained by using both lasers is almost the same as the one obtained by using one laser. Therefore, it is possible to provide the seed light for 27 ONUs by using one DFB laser and a set of phase and intensity modulators. Moreover, by using 11 DFB lasers, the seed light for all ~297 ONUs within the entire C-band can be implemented.

A practical UD-WDM PON with speed of 12.5 Gbit/s and channel spacing of 12.5 GHz is proposed and demonstrated. For the cost-effectiveness, we propose to implement the downstream links by using DFB lasers



(b)



(c)

Fig.4 Output optical spectra of the comb generator obtained by injecting either (a) one laser or (b) two lasers into the comb generator; (c) BER curves of the upstream signals measured by using line 1–line 4 as the seed light incident on the RSOA, respectively

modulated in 4-PAM format and the upstream links by using RSOAs modulated in QPSK format and inexpensive self-homodyne receivers. To further enhance its cost-effectiveness, we also utilize an optical frequency comb generator to provide the seed light for these RSOAs instead of a large number of DFB lasers. We experimentally demonstrate the error-free transmission of the 12.5 Gbit/s upstream signals with channel spacing of 12.5 GHz, even after the 20 km-long SMF transmission. The power penalty obtained by using the frequency comb generator instead of a tunable laser is measured to be around 0.5 dB. We investigate the impact of the optical power incident on the RSOA experimentally, and find that the decrease of the optical power incident on the RSOA leads to the sensitivity degradation due to the decreased OSNR. By setting the wavelength spacing of the adjacent comb spectra at 3.36 nm, for each comb spectrum generated by injecting the output of one DFB laser into the comb generator, 27 comb lines can be used as the seed light for RSOAs. Thus by injecting 11 DFB lasers, it is possible to provide the seed light for 297 ONUs within the entire C-band.

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