# Simultaneous DPSK demodulation and wavelength conversion scheme for Rayleigh backscattering noise mitigation in WDM-PON

**Hanlin Feng (冯翰林)*, Shilin Xiao (肖石林), Lilin Yi (义理林), Zhao Zhou (周 钊), Jie Shi (史 杰), and Tao Qi (戚 涛)**

*State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China*

**Corresponding author: fenghanlin@sjtu.edu.cn*

Received July 25, 2012; accepted September 4, 2012; posted online January 21, 2013

We propose a scheme for mitigating Rayleigh backscattering noise and demodulating differential phase-shift keying (DPSK) signals in wavelength-division-multiplexed passive optical networks (WDM-PONs) with injection-locked Fabry-Perot laser diodes (FP-LDs). Signal demodulation and wavelength conversion are simultaneously realized on the basis of the frequency deviation and red shift of longitude modes in the FP-LDs. Experimental results demonstrate that the demodulation and wavelength conversion of 2.5-Gb/s DPSK signals are achieved. A power penalty of about 1.6 dB at a bit error rate of $10^{-9}$ is measured after transmission over 25-km single mode fiber.

*OCIS codes:* 060.0060, 060.5060, 230.7405.
*doi: 10.3788/COL201311.020607.*

Under the growing demand for broadband services and network convergence, wavelength-division-multiplexed passive optical networks (WDM-PONs) have received considerable attention because of their huge bandwidths and flexible network architectures. Under existing technical conditions, cost remains the primary constraint to WDM-PON development. Various schemes for colorless optical network units (ONUs) have recently been proposed to realize cost-effective PON systems[1,2]. These schemes include external light injection locking[3], self-seeding[4], and different formats of remodulation schemes[5,6]. According to present research, optical filter devices have the advantages of low cost, reliability, and manufacturability; such devices include semiconductor thin film filters[7] and computer-controlled fiber Bragg grating (FBG)[8]. In particular, these commercial devices may have very low temperature dependence, making them suitable for WDM-PON deployment. Many studies indicate that differential phase-shift keying (DPSK) signals exhibit higher receiver sensitivity and nonlinear tolerance than do traditional intensity modulation signals[9−11]; however, a Mach-Zehnder delay interferometer (MZDI) must be deployed in each ONU, which further increases costs[12]. Interferometric crosstalk, including Rayleigh backscattering (RB) noise, can also severely degrade upstream performance when a single feeder fiber is deployed[13]. RB noise can be effectively avoided by a dual fiber transmission scheme[14], but this scheme fails to satisfy the requirements for cost-effectiveness.

In this letter, we propose a DPSK demodulation and wavelength conversion scheme for WDM-PONs, in which a single commercial Fabry-Perot laser diode (FP-LD) with low-cost FBG is used. Upstream and downstream wavelengths are physically separated by wavelength conversion to mitigate reflection noise. The converted wavelength passes through a tunable optical filter (TOF) and is then split by an optical coupler. One split beam serves as the downstream receiving signal, and the other beam is launched into a reflective semiconductor optical amplifier (RSOA) as seeding light. We measure the bit error rate (BER) performance of 2.5-Gb/s downstream data with 1.25-Gb/s upstream data in single-fiber bidirectional transmission over 25-km single mode fiber (SMF). The proposed scheme effectively eliminates RB noise.

As depicted in Fig. 1, the FP-LD originally self-seeds at wavelength $\lambda^*$. When an external injection locking DPSK signal $\lambda$ exists, the FP-LD is in a locked state at wavelength $\lambda$ and the self-seeding condition at wavelength $\lambda^*$ is mismatched because of the red shift of cavity modes. The stable locking range of the FP-LD is only $f_1$ GHz. However, every phase shift in the DPSK signal produces a frequency deviation of $f_2$ GHz due to the sudden rise time of differential intensity data. A frequency deviation of $f_2$ GHz is considerably larger than the locking range of $f_1$ GHz. Therefore, the phase shift destroys the locking condition at wavelength $\lambda$ and induces self-seeding recovery at wavelength $\lambda^*$. When optical power is received at wavelength $\lambda^*$, the DPSK signal can be detected by wavelength conversion.

The architecture of the proposed WDM-PON system with an injection-locked FP-LD is shown in Fig. 2. In our scheme, a commercially available FP-LD is used as both

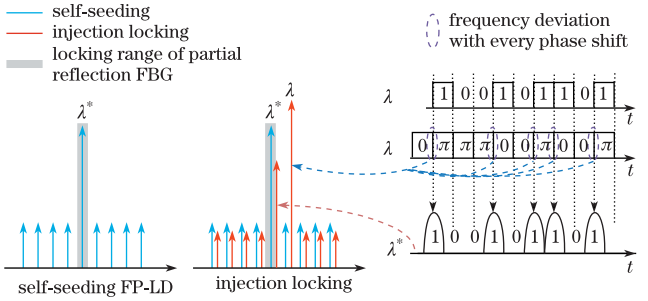


Fig. 1. Principle of DPSK demodulation and wavelength conversion.

 

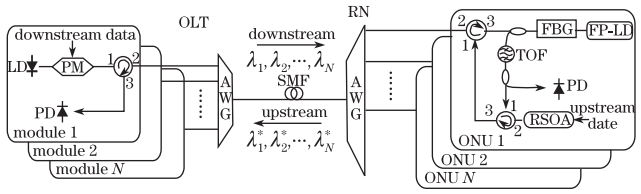


Fig. 2. Proposed system architecture.

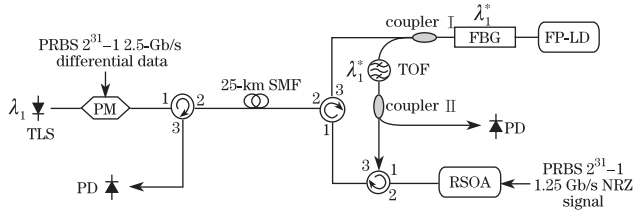


Fig. 3. Experimental setup.

a DPSK signal detector and wavelength converter. This way, the recovered intensity data can be transferred to another cavity mode for upstream transmission, thereby mitigating RB noise. In an optical line terminal (OLT), downstream data are modulated on continuous wave (CW) light $\lambda_i$ by a phase modulator. The multiplexed wavelengths are transmitted to a remote node (RN) after transmission over 25-km optical fiber. Optical carriers are then demultiplexed and routed to different ONUs. In each ONU, a FBG-based self-seeding FP-LD is driven by an externally injected downstream wavelength. Because a sudden phase shift in DPSK signals can cause frequency deviation in optical carriers, the unstable injection locking state in the FP-LD caused by downstream DPSK signals results in intensity fluctuations. Furthermore, phase information is converted into intensity data from cavity mode $\lambda_i$ to $\lambda_i^*$ through the destroyed self-seeding condition at wavelength $\lambda_i^*$. Converted wavelength $\lambda_i^*$ is filtered by a TOF and subsequently split by a 50:50 optical coupler. One split beam is detected by a photo detector (PD) to recover downstream data. The other beam is sent to the RSOA as seeding light to remodulate upstream non-return-to-zero (NRZ) data. To satisfy the requirements for wavelength independence, both the FBG and TOF have tunable functions that can flexibly change the central wavelength. These functions ensure the colorless characteristic of ONUs.

We first investigate the performance of the proposed DPSK signal demodulation and wavelength conversion scheme in WDM-PONs with injection-locked FP-LDs. In the experimental setup (Fig. 3), the input wavelength $\lambda_1$ (1 543.68 nm) is generated by a tunable laser source with a power of 6 dBm, modulated with pseudo-random binary sequence (PRBS) with a length of $2^{31}-1$. After propagating through 25-km SMF and two circulators, the signal is transmitted to a self-seeding FP-LD. This FP-LD is in an injection locking state at wavelength $\lambda_1^*$ (1 542.27 nm), which corresponds to one longitude mode with a peak power of 3 dBm and side mode suppression ratio of nearly 50 dB (Fig. 4(a)). The bias current and operating temperature of the FP-LD can be controlled to a wide wavelength tuning range up to 30 nm (from 1 530 to 1 560 nm).

The 30-GHz frequency deviation range induced by the 16.5-ps rise time of differential intensity data results in an unstable injection locking state; that is, frequency deviation that corresponds to every phase shift in wavelength $\lambda_1$ occurs. If deviation is larger than locking range, the FP-LD becomes unlocked. Given that the phase remains constant, no frequency deviation is observed and the FP-LD is in a stable locking state. The locking and unlocking states in longitude mode $\lambda_1$ can be converted into intensity data. On the basis of this principle, mode $\lambda_1^*$ is suppressed to a certain level (suppression ratio, ~17 dB) and the peak power of longitude mode $\lambda_1$ is 5.8 dBm when DPSK signal $\lambda_1$ is injected at an adjacent wavelength near dominant mode $\lambda_1^*$ (Fig. 4(b)). Unlike the original longitude mode, external injection locking introduces a 0.1-nm red shift, consequently destroying the wavelength alignment on FBG. When longitude mode $\lambda_1$ is unlocked, mode $\lambda_1^*$ returns to a locking state. In this manner, every phase shift is converted into intensity data from mode $\lambda_1$ to mode $\lambda_1^*$.

We then investigate the transmission properties of the proposed WDM-PON system. A specific analysis of downstream and upstream BER performance is carried out to verify the application of the DPSK signal demodulation and wavelength conversion scheme. The total transmission loss is 13 dB, including that generated by 25-km SMF transmission. A pre-amplified PD is used as a receiver in the ONU. Unlike the MZDI, the FP-LD measures a power penalty of 1.6 dB at a BER of $10^{-9}$ (Fig. 5(a)). This result is due to the decreased extinction ratio (about 2.1 dB) and additional noise from the loop back structure in the ONU. As shown in Fig. 5(b), when the same wavelength is used for upstream transmission, the eye diagram is severely distorted and the BER cannot reach the lowest requirement of $10^{-9}$. Through wavelength conversion by the self-seeding FP-LD, however, downstream wavelength $\lambda_1$ and upstream wavelength $\lambda_1^*$

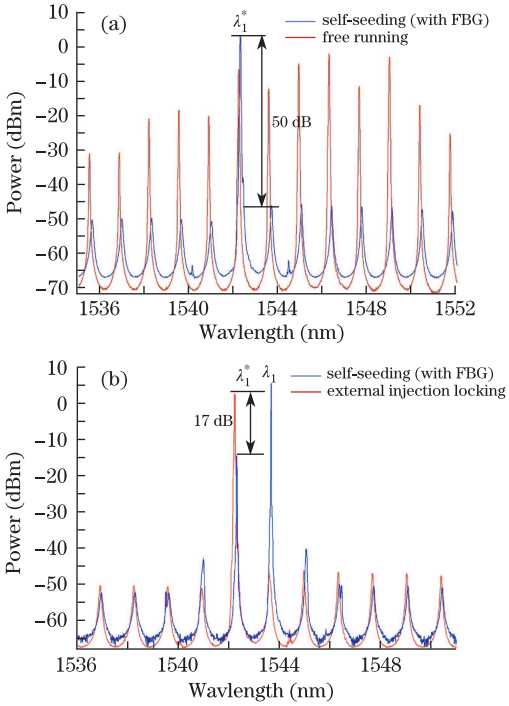


Fig. 4. Optical spectra. (a) Self-seeding at mode $\lambda_1^*$ with a free running state of FP-LD; (b) external injection locking at mode $\lambda_1$ with self-seeding state.

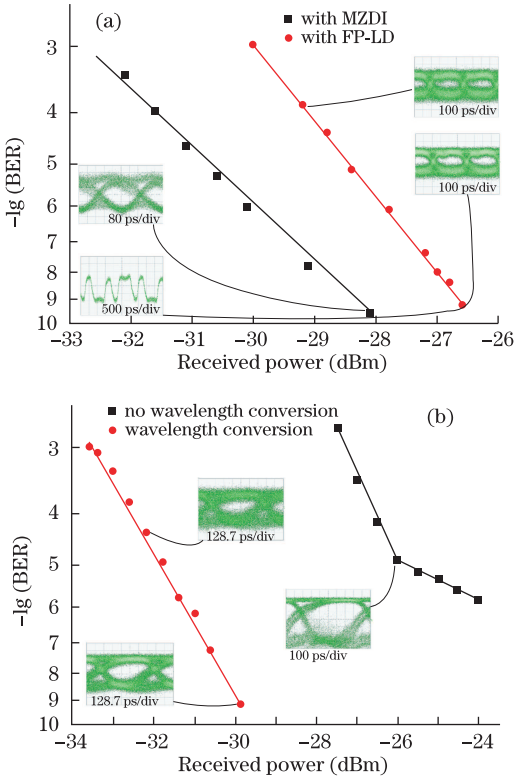


Fig. 5. BER performance, eye diagrams, and waveform. (a) Downstream; (b) upstream

are clearly distinguished, thereby effectively eliminating RB noise. Furthermore, the converted signals have a low extinction ratio. When the RSOA is operated in the gain saturation region, it can effectively erase all residual downstream data and remodulate upstream data. Thus, the eye diagram is clearly open and receiver sensitivity is about −30 dBm. When limited by the performance of a low-cost FP-LD, the highest speed for simultaneous DPSK signal demodulation and wavelength conversion is only 2.5 Gb/s. A speed of 10 Gb/s is realized by optimizing the physical parameters of the self-seeding FP-LD.

In conclusion, we propose a DPSK signal demodulation and wavelength conversion scheme based on a self-seeding FP-LD in a WDM-PON system. RB noise is effectively mitigated through wavelength conversion and differentiation between bidirectional wavelengths. For downstream signals, a power penalty of about 1.6 dB is experimentally measured at a BER of $10^{-9}$. The sensitivity of upstream transmission can reach –30 dBm without RB noise. The total working wavelengths can be increased by adjusting the bias current and operation temperature of the FP-LD. Such adjustments consequently upgrade transmission capacity.

This work was supported by the National "973" Project of China (Nos. 2010CB328205, 2010CB328204, and 2012CB315602), the National Natural Science Foundation of China (Nos. 60972032, 61090393, 61132004, and 60825103), and the National "863" Project of China.

## References

1. K. Iwatsuki and J. I. Kani, J. Opt. Commum. Netw. **1,** C17 (2009).
2. A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, J. Opt. Netw. **4,** 737 (2005).
3. N. Q. Thai, P. Besnard, L. Bramerie, A. Shen, C. Kazmierski, P. Chanlou, D. Guang-Hua, and J. C. Simon, IEEE Photon. Technol. Lett. **22,** 733 (2010).
4. E. Wong, L. K. Lun, and T. B. Anderson, J. Lightwave Technol. **25,** 67 (2007).
5. X. Jing and C. Lian-Kuan, IEEE Photon. Technol. Lett. **22,** 456 (2010).
6. R. Murano, W. F. Sharfin, and M. J. Cahill, in *Proceedings of OFC/NFOEC 2008* PDP32 (2008).
7. "PC Controlled tunable FBG," retrieved http://www.aos-fiber.com/eng/FBG/FBGen.html.
8. G. Bosco and P. Poggiolini, J. Lightwave Technol. **23,** 842 (2005).
9. K. Croussore, I. Kim, Y. Han, C. Kim, G. Li, and S. Radic, Opt. Express **13,** 3945 (2005).
10. G. Bosco, A. Coster, and V. Curri, in *Proceedings of ECOC 2006* 1 (2006).
11. X. Jing, C. Lian-Kuan, and C. Chun-Kit, IEEE Photon. Technol. Lett. **22,** 1343 (2010).
12. C. W. Chow and C. H. Yeh, Opt. Express **19,** 4970 (2011).
13. G. Talli, C. W. Chow, E. K. MacHale, and P. D. Townsend, J. Opt. Netw. **6,** 765 (2007).