Adjacent crosstalk suppression in a colorless WDM passive optical network

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Abstract: We propose and experimentally demonstrate a novel wavelength-division-multiplexed passive optical network (WDM-PON) scheme for the suppression of adjacent crosstalk arising from the wavelength misalignment in arrayed waveguide gratings (AWGs) between a central office (CO) and a remote node (RN). The adjacent crosstalk suppression is achieved by allocating two different bands to adjacent channels of the AWGs by utilizing interleavers and WDM filters. The transmission performance of the proposed scheme was measured at a 155 Mb/s data stream, and error free transmission with a power penalty less than 0.7 dB was successfully achieved in case of AWG misalignment of 0.3 nm.

OCIS codes: (060.2330) Fiber optics communications; (060.4250) Networks

References and links

1. S. -J. Park, C. -H. Lee, K. -T. Jeong, H. -J. Park, J. -G. Ahn, and K. -H. Song, "Fiber-to-the-Home Services Based on Wavelength-Division-Multiplexing Passive Optical Network," J. Lightwave Technol. **22**, 2582-2591 (2004).
2. Z. Xu, Y. J. Wen, W. -D. Zhong, C. -J. Chae, X. -F. Cheng, Y. Wang, C. Lu, and J. Shankar, "High-speed WDM-PON using CW injection-locked Fabry-Pérot laser diodes," Opt. Express **15**, 2953-2962 (2007).
3. H. D. Kim, S.-G. Kang, and C.-H. Lee, "A low-cost WDM source with an ASE injected Fabry–Pérot semiconductor laser," IEEE Photon. Technol. Lett. **12**, 1067–1069 (2000).
4. D. J. Shin, Y. C. Keh, J. W. Kwon, E. H. Lee, J. K. Lee, M. K. Park, J. W. Park, Y. K. Oh, S. W. Kim, I. K.Yun, H. C. Shin, D. Heo, J. S. Lee, H. S. Shin, H. S. Kim, S. B. Park, D. K. Jung, S. Hwang, Y. J. Oh, D. H.Jang, and C. S. Shim, "Low-cost WDM-PON with colorless bidirectional transceivers," J. Lightwave Technol. **24**, 158-165 (2006).
5. E. H. Lee, Y. C. Bang, J. K. Kang, Y. C. Keh, J. S. Lee, and D. H. Jang, "Uncooled C-band wide-band gain lasers with 32-channel coverage and -20-dBm ASE injection for WDM-PON," IEEE Photon. Technol. Lett. **18**, 667-669 (2006).
6. D. K. Jung, S. K. Shin, H. G. Woo, and Y. C. Chung, "Wavelength-tracking technique for spectrum-sliced WDM-PON," IEEE Photon. Technol. Lett. **12**, 338-340 (2000).
7. A. Tervonen, P. Ohman, A. Pietilainen, O.-P. Hiironen, and M. Oksanen, "Control of wavelength alignment in WDM-PON," Electron. Lett. **39**, 229-230 (2003).
8. A. J. Ticknor, B. P. McGinnis, T. tarter, and M. Yan, "Efficient passive and active wavelength-stabilization techniques for AWGs and integrated optical filters," in Proc. Optical Fiber Communication Conference, Anaheim, CA, paper NTHL3 (2005).
9. C. R. Doerr and K. Okamoto, "Advances in silica planar lightwave circuits," J. Lightwave Technol. **24**, 4763-4789 (2006).
10. D. J. Shin, D. K. Jung, H. S. Shin, S. B. Park, H. S. Kim, S. H. Kim, S. H. Hwang, E. H. Lee, J. K. Lee, Y.S. Oh, and Y. J. Oh, "AWG misalignment tolerance of 16 ×155 Mb/s WDM-PON based on ASE-injected FP-LDs," in Proc. Optical Fiber Communication Conference, Anaheim, CA, paper JWA54 (2005).

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11. K. Lee, S. B. Lee, J. H. Lee, Y. -G. Han, S. -G. Mun, S. -M. Lee, and C. -H. Lee, "A self-restorable architecture for bidirectional wavelength-division-multiplexed passive optical network with colorless ONUs," Opt. Express **15**, 4863-4868 (2007).
12. R. D. Feldman, "Crosstalk and loss in wavelength division multiplexed systems employing spectral slicing," J. Lightwave. Technol. **15**, 1823-1831 (1997).
13. Y. S. Jang, C. –H. Lee, and Y.C. Chung, "Effects of crosstalk in WDM systems using spectrum-sliced light sources," IEEE Photon. Technol. Lett. **11**, 715–717 (1999).
14. S. Cao, J. Chen, J. N. Damask, C. R. Doerr, L. Guiziou, G. Harvey, Y. Hibino, H. Li, S. Suzuki, K.-Y. Wu, and P. Xie, "Interleaver technology: comparisons and applications requirements," J. Lightwave. Technol. **22**, 281-289 (2004).

1. Introduction

A wavelength-division-multiplexed passive optical network (WDM-PON) has recently attracted a lot of attention due to easy upgradability for large bandwidths and network flexibility [1,2]. In WDM-PON, key components are optical sources generating WDM channels and multi/demulti-plexer to multi/demulti-plex the WDM channels. Thus, the wavelength alignment among the sources, a multiplexer, and a demultiplexer is essential. Especially, the amplified spontaneous emission (ASE)-injected Fabry-Perot laser diode (FP-LD) has opened the commercial possibility as a low-cost transmitter with its automatic wavelength locking to the arrayed waveguide grating (AWG) passband [3-5], i.e., making it "colorless". Therefore, in the WDM-PON employing ASE-injected FP-LDs, the wavelength alignment between the source and a multiplexer is automatically solved. For the wavelength alignment between the multiplexer and the demultiplexer, there have been approaches such as wavelength-tracking techniques controlling the temperature of the AWG at a central office (CO) to compensate the thermal drift (~ 10 pm/°C) of the AWG at a remote node (RN) [6,7]. This requires a constant power consumption of a few Watts and complicated setup. But recently, various kind of AWG configurations to achieve athermal operation have been reported [8,9]. To date, compared to conventional AWGs, the temperature-dependent wavelength change has been reduced from 0.95 to 0.05 nm in the 0-85°C range.

However, even if we adopt athermal AWGs, when the RN is located in the harsh temperature environment such as from -40°C to +85°C, there may be still unacceptable wavelength drift. Extrapolating from the Fig. 12 in the reference [8], the maximum wavelength shift may be around 70 pm in the -40~85°C temperature range. Assume that target wavelength accuracy of the athermal AWG is around +/- 100 pm in both waveband, then the maximum wavelength misalignment can be 270 pm in the temperature range of -40 ~ +85°C. In particular, since the output of the ASE-injected FP-LDs are sensitive to overlap conditions between the injected ASEs and FP-LD spectra in a colorless WDM-PON, the crosstalk from the adjacent channels may result in significant performance degradation in WDM transmission at high bit rates [10].

In this letter, we propose a novel architecture for suppressing the adjacent crosstalk in a partially colorless (In fact, it requires two different type of ONUs), bidirectional WDM-PON employing ASE-injected FP-LDs and experimentally demonstrate its feasibility. As a consequence, a partially colorless WDM-PON operating over wide temperature range of -40 to 85°C can be realized. In our proposed architecture, the adjacent crosstalk signals were removed by assigning the odd/even channels in such a manner that odd/even channels belong to different wavebands and placing the different spectrum transmitting WDM filters in front of the odd /even channel receivers. Our experimental demonstration is carried out at a data rate of 155 Mb/s over a 20 km standard single mode fiber (SMF).

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2. Proposed self-restorable network architecture

Figure 1 shows the proposed WDM-PON architecture employing ASE-injected FP-LDs. It includes four broadband light sources (BLSs), two interleavers, four 2×N AWGs, a plurality of transceivers at CO, and a plurality of ONUs. A- and B-band BLSs are separated by a free spectral range (FSR) of the AWG and are injected into the CO transmitters which provide downstream signals. Similarly, C- and D-band BLSs are used for injection lights to upstream transmitters. Note that the channel wavelength allocation of interleavers is identical to that of the AWGs. The input light into the interleaver is divided into odd and even channels. The odd and even channel lights are divided again at (A+D)/(B+C) band WDM filters. Here the (A+D)/(B+C) filter can be realized by combining three common band-pass filters or by a single multilayer thin film filter if the bandwidth of the filter is less than 120 nm. Thus, the light is divided into four groups according to its spectrum band and corresponding channel number as described in Fig. 1. The B-band downstream and C-band upstream signals are connected to ONUs through the odd index ports of the AWG3, while the A-band downstream and D-band upstream signals are connected to the even index ports of AWG. In contrast, in case of AWG4 A- and D-band signals are connected to its even ports, and B- and C-band signals are to its odd ports.

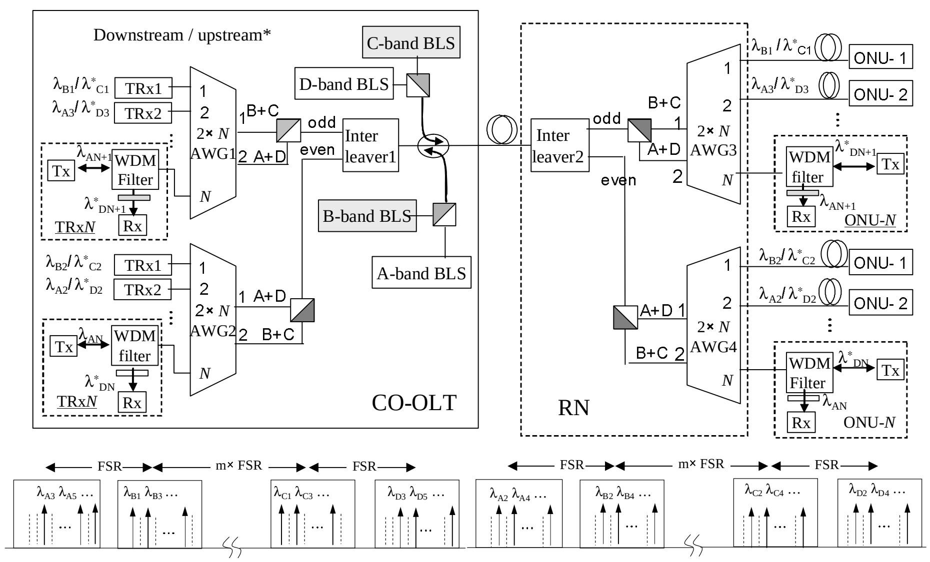

Fig. 1. Proposed network architecture and wavelength assignment. A- and B-band for downstream wavelengths; C-and D-band for upstream wavelengths (OLT: Optical line terminal, RN: Remote node, ONU: Optical network unit).

Now consider the procedure of injecting BLSs into the downstream transmitters. A- and B-band BLSs are delivered to interleaver1 through a directional coupler. In this case, BLS light output from the odd port of the interleaver1 is demultiplexed depending on its wavelength at the AWG1 via a (B+C)/(A+D) WDM filter. The B- and A-band lights are thus assigned to the odd and even index ports of the AWG1, respectively as shown in Fig. 1. In the same way, BLS light output from the even port of interleaver1 is demultiplexed at the AWG2. Thus, A- and B-band are assigned to the even and odd index ports, respectively unlike the case of the AWG1. Therefore, the wavelengths of FP-LDs at CO are allocated as shown in Fig. 1 depending on the AWG output port indexes. Downstream channels from FP-LDs are multiplexed at each AWG (AWG1, AWG2), and then combined again at interleaver1. The multiplexed downstream signal is transmitted to the remote node (RN) through an optical

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fiber. The interleaver2 located at the RN divides the multiplexed downstream signal into two groups like the interleaver1 at the CO. The divided downstream output signals at the odd port of interleaver2 are demultiplexed depending on their wavelength and band at the AWG3. In this case, B-band odd channel downstream signals arrive at the ONUs connected to the odd index ports of the AWG3. In addition, a B-band pass filter is installed in the front of the optical receiver to efficiently prevent the adjacent crosstalk. Similarly, A-band odd channel signals are delivered to the receiver through A-band pass filter located at the ONUs connected to the even ports of the AWG3.

On the other hand, output signals from the even port of interleaver2 are demultiplexed at the AWG4 (In this case, A- and B-band are assigned to the even and odd channels, respectively). Therefore, it enables us to prevent the crosstalk due to adjacent channel signals by adding an appropriate band pass filter in front of the receiver, since wavelengths of adjacent channels are in the different waveband. Likewise, the operation of the upstream transmission using C- and D- band BLSs is same to that of the downstream transmission. As a result, the bidirectional adjacent crosstalk free operation is achieved even though wavelengths are incompletely aligned in AWGs between at the CO and the RN when the operating temperature range of the RN is varied from -40 to 85°C. It may be noted that the number of users supported by 2 x N AWG is N, thus the network supports 2N users.

3. Experimental results

As is known, the amount of the wavelength misalignments between AWGs at CO and RN increase with the operating temperature range. Since the temperature oven operating over wide temperature range was not available, we constructed an experimental setup as shown in Fig. 2 in order to prove the concept of the proposed WDM-PON using ASE-injected FP-LDs for adjacent crosstalk suppression.

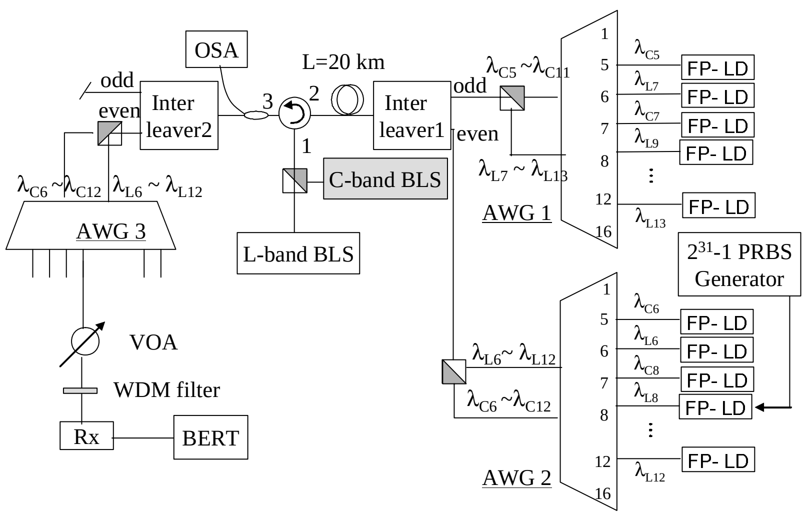

Fig. 2. Experimental setup (BLS: Broadband light source, OSA: Optical spectrum analyzer, VOA: Variable optical attenuator, Rx: Receiver, BERT: Bit error rate tester).

Experiments are conducted for the only upstream transmission with 16 WDM channels due to limited availability of only C- and L-band BLS source. The feeder fiber was a 20 km long single mode fiber. Two BLSs are generated from erbium-doped fiber amplifiers. The front facets of FP-LDs are anti-reflection coated for efficient ASE injection. The channel

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spacing and 3-dB bandwidth of AWGs were 100 GHz and ~0.4 nm, respectively. The even and odd channels were combined with a 100/200 GHz interleaver1, having a 3 dB bandwidth of 107 GHz and a ~1.5 dB insertion loss. In this embodiment, both interleavers had a free spectral range of 200 GHz coinciding with a channel spacing of the WDM signal and the center frequencies were matched to those of AWGs connected through WDM filters. The wavelength misalignment between CO-AWG and RN-AWG (AWG1 & AWG2) was controlled by a thermo-electric cooler (TEC) attached to the AWG3 while the temperature of AWG1 and 2 was fixed.

In this experiment, a main channel was channel no.8 connected to AWG2. Thus, the FP-LDs in the main and adjacent channels were directly modulated with 2^{31}-1 pseudorandom bit sequences at 155 Mb/s to measure bit error rate (BER). Figure 3 shows the spectra of 16 multiplexed upstream signals. The injected ASE power into the FP-LDs is around –12 dBm. The different power and spectral shape of each channel is attributed to the fact that output power of ASE-injected FP-LDs are sensitive to the front facet reflectivity and the detuning condition between the lasing wavelength of FP-LD and injected ASE wavelength [11]. Upper solid and dotted lines in Fig. 3 are the spectra of odd and even port of the interleaver, respectively. As described previously, the adjacent crosstalk signals are in the different band (Here, in the C-band). Thus it is easy to eliminate the adjacent crosstalk by adopting L-band pass filter in front of the receiver.

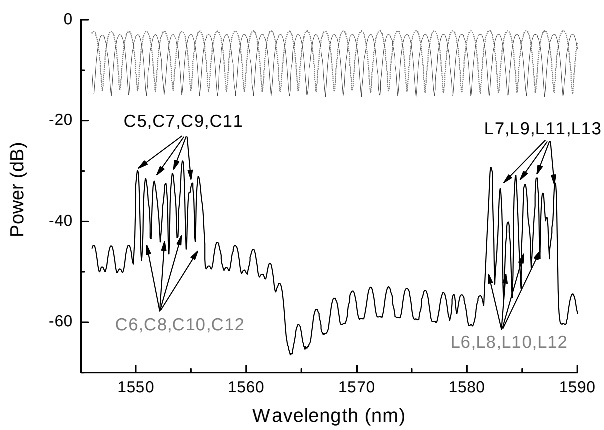

Fig. 3. Measured spectra. Lower solid line: spectrum of 16 multiplexed signals, upper solid line: odd port of interleaver, upper dotted line: even port of interleaver.

The bit error rate (BER) performance was measured at the several misalignment conditions. Figures 4(a) and 4(b) shows the BER curves in a conventional scheme [1] and our newly proposed scheme, respectively. It can be seen that in the conventional WDM-PON, we have a BER floor of ~10^{-10} at misalignment of larger than 0.2 nm, as a consequence of adjacent channel crosstalk, while in our proposed scheme, we obtain error free transmission with a power penalty of less than 0.7 dB even at misalignment of 0.3 nm.

Figure 5 shows the power penalties measured at a 10^{-9} BER as a function of AWG misalignment for the conventional scheme and for the proposed scheme. In Fig. 5, the symbols represent the measured data and the lines are calculated values. In the conventional WDM-PON, the optical power penalty in dB from incoherent crosstalk is calculated as [12, 13]

$$\Delta P = -10 \cdot \log (1- 1/\chi)$$

where χ is the crosstalk.

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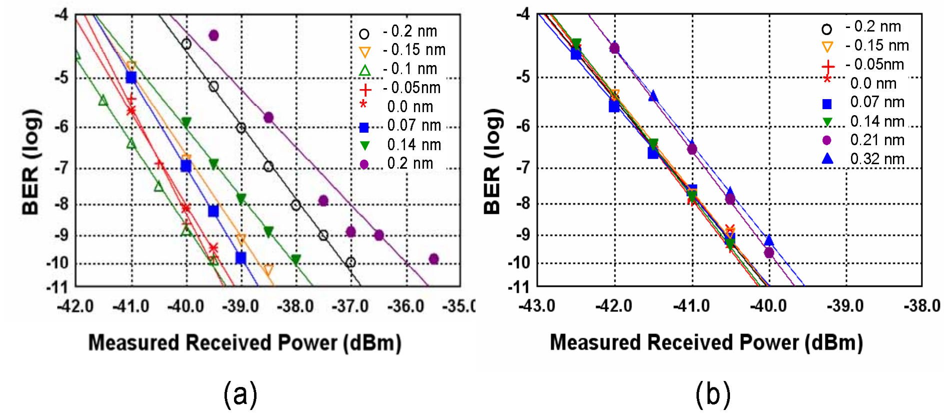

Fig. 4. BER measurements. (a). Conventional WDM-PON. (b). Proposed WDM-PON. The parameters in the graph are AWG wavelength misalignments.

As previously stated, wavelength misalignment of 0.3 nm corresponds to RN temperature range of -40°C to 85°C. Therefore our proposed scheme should be operable in the wide RN temperature range of -40°C~85°C. However, there exists a received power reduction due to misalignment of AWGs between at the CO and the RN. In our experiment, the received power reduction was about 4 dB at the 0.3 nm misalignment.

To test the effect of the thermal dependence of interleavers on the system performance, we also controlled the interleaver2 temperature. The results have shown that 0.34 nm wavelength misalignment between interleavers, corresponding to more than 140°C shift in temperature in case of interleaver having thermal stability of 1 pm/°C and wavelength accuracy of +/-100 pm in C and L bands, did not cause any penalty (Note that with recent advances in fused fiber design and improved manufacturing process, commercial optical interleavers having thermal stability of less than 1 pm/°C are available [14]). Therefore it is not necessary to control the temperature of interleavers.

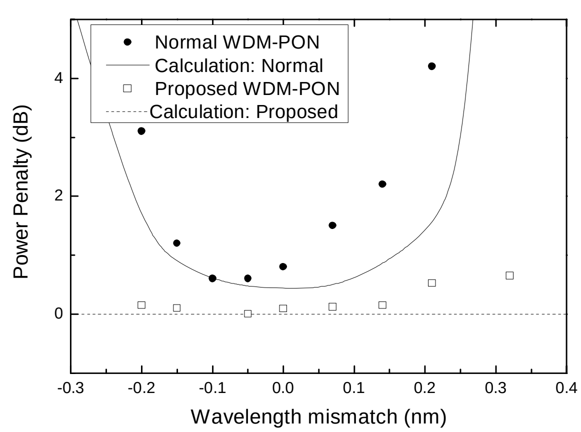

Fig. 5. Power penalty. The circle and rectangle represent data for conventional and proposed scheme, respectively. The solid line is calculated value for conventional scheme restoration states.

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4. Conclusion

We have proposed and experimentally demonstrated a novel adjacent crosstalk eliminated WDM-PON. By allocating two different bands to adjacent channels of the AWGs with help of interleavers and WDM filters**,** adjacent crosstalk free operation was achieved although wavelengths were misaligned in two AWGs. The experimental results show that wavelength misalignment of 0.3 nm induces less than 0.7 dB power penalty on the receiver sensitivity in the 100 GHz channel spacing WDM-PON. We believe that this proposed scheme is a promising candidate for wide RN temperature range from -40°C to 85°C, since it can tolerate the incomplete alignment of wavelength channels between at AWGs at the CO and the RN.

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