Journal of the Optical Society of Korea
Vol. 19, No. 4, August 2015, pp. 371-375

ISSN: 1226-4776(Print) / ISSN: 2093-6885(Online)
DOI: http://dx.doi.org/10.3807/JOSK.2015.19.4.371

Equivalent Optical Bandwidth of Reflective Electro-Absorption Modulator Based Optical Source with a Broadband Seed Light for a 2.5 Gb/s and Beyond Signal Transmission

Chul Han Kim*

School of Electrical and Computer Engineering, University of Seoul, Seoul 130-743, Korea

(Received March 3, 2015 : revised June 23, 2015 : accepted June 23, 2015)

The impact of equivalent optical bandwidth on the performance of a system using a reflective electro-absorption modulator (R-EAM) based optical source has been experimentally evaluated with signals operating at 2.5 Gb/s and beyond. The equivalent optical bandwidth of our source with a broadband seed light was simply adjusted by using a bandwidth tunable optical filter. From the measurements, we have estimated the required equivalent optical bandwidth of our source for an error-free transmission (@ bit-error-rate of 10^{-12}) and a forward error correction (FEC) threshold of 2×10^{-4}.

Keywords : Passive optical network, Reflective electro-absorption modulator, Broadband light source, Wavelength division multiplexing
OCIS codes : (060.0060) Fiber optics and optical communications; (060.2330) Fiber optics communications

I. INTRODUCTION

For the cost-effective implementation of high-capacity passive optical networks (PONs) operating at 10 Gb/s and beyond, a reflective electro-absorption modulator (R-EAM) based optical source has been considered as an attractive solution, since it could provide a wide modulation bandwidth as well as a low chirp [1-4]. In many previous studies, a wavelength-specific optical source has been mainly used as a seeding source for the R-EAM based optical source. However, it has been well known that a broadband light source (BLS) would be a more cost-effective seed source than wavelength-specific sources especially for the colorless wavelength-division multiplexed (WDM)-PON systems [5-6]. Thus, in order to demonstrate the feasibility of the R-EAM based optical source with a BLS seed, we have evaluated the effect of various noises, such as excess intensity noise (EIN) within a BLS, chromatic dispersion of transmission fiber and in-band crosstalk, on the performance of an R-EAM based system [7]. In our previous study, we found that the equivalent optical bandwidth of our BLS seeded R-EAM optical source should be wider than 1 nm to achieve an error-free transmission of a 1.25 Gb/s signal. For the case of a 10 Gb/s signal, we have estimated that the equivalent optical bandwidth of a BLS seeded R-EAM source should be increased to be wider than 10 nm for the error-free transmission. This estimation is based on the fact that the signal-to-noise ratio (SNR) of a BLS based optical source is determined by the ratio of optical bandwidth and electrical bandwidth [8-10]. However, in our previous study, we used only a few different optical bandwidths of BLS seeded R-EAM optical source, due to the limited availability of an optical bandpass filter (OBPF) at that time. Therefore, we have just estimated the equivalent optical bandwidth of an R-EAM based optical source especially for the error-free transmission of a 10 Gb/s signal. Recently, many wavelength and bandwidth tunable filters have been demonstrated and commercially available [11]. Using one of these bandwidth tunable filters, we can easily adjust the equivalent optical bandwidth of R-EAM based optical source with a BLS seed. Thus, in this paper, we have evaluated the impact of equivalent optical bandwidth of an R-EAM based optical source on the system's performance with various equivalent optical bandwidths and signals operating at 2.5 Gb/s and beyond. At first, we have re-confirmed that the equivalent optical bandwidth of our BLS seeded R-EAM optical source should be wider than 1 nm for a 1.25 Gb/s signal error-free transmission (@ bit-error-rate (BER) of 10^{-12}). In the case

*Corresponding author: chkim@uos.ac.kr
Color versions of one or more of the figures in this paper are available online.

of a 2.5 Gb/s signal, the equivalent optical bandwidth should be increased to be wider than ~2.7 nm for the error-free transmission. For a 10 Gb/s signal, no error-free transmission was achieved mainly due to the un-equalized output spectrum of our BLS seeded R-EAM optical source. Only BER floor at 10^{-5} was observed with an equivalent optical bandwidth of ~5 nm. Thus, from this BER floor level and wide equivalent optical bandwidth requirement, we believe that our BLS seeded R-EAM optical source could be used for the implementation of a 10 Gb/s signal transmission system with a conventional forward error correction (FEC) technique [12] as well as a proper dispersion compensation scheme.

II. RESULTS AND DISCUSSION

Figure 1 shows the apparatus for the performance evaluation of R-EAM based PON system. An amplified spontaneous emission (ASE) light from a BLS implemented with an erbium-doped fiber amplifier (EDFA) was spectrally-sliced at the center wavelength of 1550 nm with an optical bandwidth tunable filter, and then launched into an R-EAM via a 3-ports circulator. The R-EAM was used to modulate the spectrum-sliced BLS output with a non-return-to-zero (NRZ) pseudo-random bit sequence (PRBS) of length 2^{31}-1 operating at 1.25 Gb/s, 2.5 Gb/s or 10 Gb/s. The bias and modulation voltages of the R-EAM were set to be -1.2 V and ±1.5 V, respectively. The 3-dB RF bandwidth of the R-EAM was ~8 GHz, which was wide enough to generate up to 10 Gb/s signal. The insertion loss of the R-EAM including a circulator insertion loss was measured to be ~10 dB. The modulated signal was amplified with a second EDFA for the compensation of this R-EAM insertion loss. The amplified signal was then passed through an OBPF having a 3-dB optical bandwidth of ~18 nm. The measured output spectrum of the OBPF was shown in the inset of Fig. 1. From the measured spectrum, we confirmed that the OBPF had a quite flat passband around ~1550 nm. Finally, the main portion of the signal was detected by use of an optical receiver to evaluate the back-to-back performance of the system, while the small portion was directed to an optical spectrum analyzer (OSA) for the measurement of optical source bandwidth. A lightwave clock/data receiver (HP83446A) was used to detect a 1.25 Gb/s and a 2.5 Gb/s signals while a receiver implemented with a PIN-preamplifier and a limiting amplifier in our lab was used for a 10 Gb/s signal. Especially, for a 1.25 Gb/s signal detection with a OC-48 optical receiver, an electrical filter having a 3-dB bandwidth of 940 MHz was externally connected at the data output of the receiver.

At first, in order to confirm the performance of our optical bandwidth tunable filter, optical spectra of our BLS seeded R-EAM optical source with different 3-dB filter bandwidths were measured with an OSA. Figure 2 shows various optical spectra of our R-EAM source measured with an OSA resolution of 0.1 nm at the receiver side after passing through a second OBPF. Even though the optical spectra of our source were measured after two cascade filters, the output spectra were mainly determined by a bandwidth tunable filter due to the wide flat passband of a second OBPF (shown in Fig. 1). The 3-dB source bandwidth of the BLS seeded R-EAM source could be easily changed from 0.2 nm to 4.0 nm. Previously, we have found that the performance of a BLS seeded PON system could be estimated properly with an equivalent optical bandwidth rather than with a 3-dB optical bandwidth [7, 10]. Thus, we have calculated the equivalent optical bandwidths of our BLS seeded R-EAM optical source with the measured optical spectra shown in Fig. 2, and summarized the results in Table 1. As it can be seen in Table 1, the 3-dB bandwidth and equivalent bandwidth of our BLS seeded R-EAM optical source were almost identical at narrow bandwidth regions (@<1.2 nm of 3-dB bandwidth). However, the difference between two bandwidths was increased as the

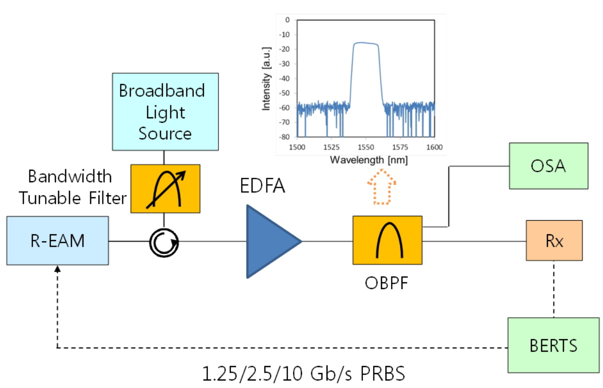

FIG. 1. Apparatus used for the performance evaluation of a transmission system using an R-EAM based optical source with a BLS seed. Acronyms are receiver, Rx; and bit-error-rate test sets, BERTs.

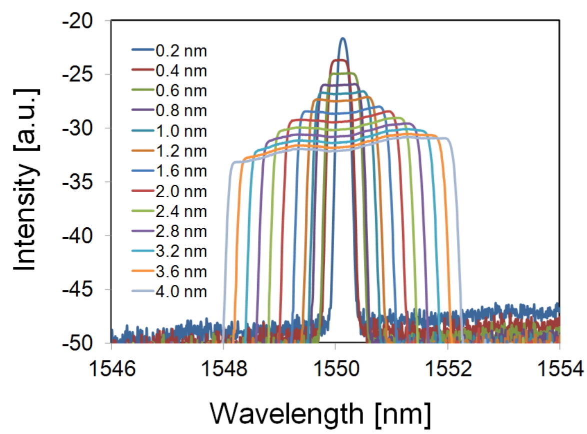

FIG. 2. Optical spectra of our BLS seeded R-EAM optical source with various 3-dB bandwidths. Each spectrum was measured with an optical spectrum analyzer located at a receiver side.

TABLE 1. Estimated equivalent optical bandwidths and measured optical powers of our BLS seeded R-EAM optical source with various 3-dB optical bandwidths

3-dB BW [nm]	Equivalent BW [nm]	Power [dBm]	3-dB BW [nm]	Equivalent BW [nm]	Power [dBm]
0.20	0.22	-18.31	2.00	1.76	-15.96
0.40	0.42	-17.49	2.40	2.06	-15.94
0.60	0.61	-17.06	2.80	2.35	-15.87
0.80	0.80	-16.87	3.20	2.67	-15.82
1.00	0.99	-16.64	3.60	2.98	-15.76
1.20	1.16	-16.50	4.00	3.30	-15.69
1.60	1.48	-16.32			

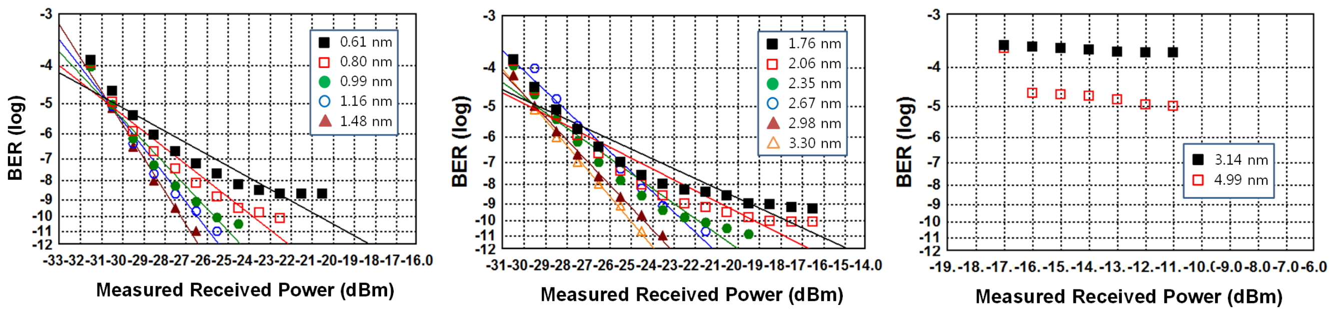

FIG. 3. Measured BER curves with various equivalent optical bandwidths using (a) a 1.25 Gb/s signal, (b) a 2.5 Gb/s signal and (c) a 10 Gb/s signal.

3-dB bandwidth increased. This was mainly due to the un-equalized output spectrum of EDFA based BLS. Another feature in the measured optical spectra of our BLS seeded R-EAM source was that the power spectral density of the measured spectrum at wider bandwidth was lower than that at narrower bandwidth, as shown in Fig. 2. Thus, total power of each spectrum-sliced BLS output was measured with an optical power meter at the receiver side and summarized in Table 1 as well. The total powers with 0.2 nm and 4.0 nm of 3-dB source bandwidth were measured to be -18.31 dBm and -15.69 dBm, respectively. Thus, the input power into an optical receiver was increased by ~2.6 dB when the 3-dB source bandwidth was increased from 0.2 nm to 4.0 nm.

Figure 3 shows the measured BER curves with various equivalent optical bandwidths of our BLS seeded R-EAM optical source. In order to confirm our previous result reported in [7], a 1.25 Gb/s signal was first used for the BER measurement with five different equivalent optical bandwidths, as shown in Fig. 3(a). With the equivalent optical bandwidths of 0.61 nm and 0.80 nm, BER floors were observed at 2×10^{-9} and 7×10^{-11}, respectively. We also found that the BER floor levels were increased to be 1×10^{-5} and 1×10^{-7} with the equivalent optical bandwidths of 0.22 nm and 0.42 nm, respectively. The error-free transmission (@ BER of 10^{-12}) of a 1.25 Gb/s signal was achieved with the equivalent bandwidth of >0.99 nm, which was agreed well with our previous result [7]. Then, the BER curves with a 2.5 Gb/s signal using our BLS seeded R-EAM source were also measured with six different equivalent bandwidths, as shown in Fig. 3(b). With the equivalent optical bandwidths of 1.76 nm, 2.06 nm and 2.35 nm, the BER floors were observed at 6×10^{-10}, 8×10^{-11}, and 2×10^{-11}, respectively. For the case of a 2.5 Gb/s signal, the BER floors at 2×10^{-4}, 4×10^{-6}, 1×10^{-7}, 7×10^{-9} were also observed with the equivalent optical bandwidths of 0.42 nm, 0.80 nm, 1.16 nm and 1.48 nm, respectively. We found that the error-free transmission of a 2.5 Gb/s signal with our BLS seeded R-EAM source was achieved with the equivalent optical bandwidth of > 2.67 nm, as shown in Fig. 3(b). For the case of a 10 Gb/s signal transmission, only BER floors at 2×10^{-4} and 1×10^{-5} were observed with the equivalent optical bandwidth of 3.14 nm and 4.99 nm, as shown in Fig. 3(c). Since our EDFA based BLS had an un-equalized output spectrum, it was impossible to increase the equivalent optical bandwidth of our R-EAM source to be wider than 5 nm. However, using a conventional forward error correction (FEC) scheme, we believe that a 10 Gb/s signal transmission system could be implemented with our BLS seeded R-EAM optical source even with this BER floor level. The use of FEC scheme might increase the required equivalent optical band-

TABLE 2. Required equivalent optical bandwidths of our BLS seeded R-EAM optical source for the error-free transmission and the FEC threshold (@ BER=2×10^{-4}).

	1.25 Gb/s	2.5 Gb/s	10 Gb/s
Error-Free Transmission	0.99 nm	2.67 nm	10~20 nm (estimation)
FEC Threshold (@ 2×10^{-4})	0.16 nm	0.42 nm	3.14 nm

width of our source slightly, depending on the size of FEC overhead and the electrical filter bandwidth used in optical receiver.

Table 2 summarizes the required equivalent optical bandwidths of our BLS seeded R-EAM optical source for the error-free signal transmission with three different data rates. The equivalent optical bandwidths which meet a FEC threshold of 2×10^{-4} were also summarized in Table 2. The required equivalent optical bandwidths of our R-EAM based optical source for a 2.5 Gb/s signal were approximately 2.7 times wider than those for 1.25 Gb/s signal in both error-free transmission and FEC threshold cases. From these required equivalent optical bandwidths of our BLS seeded R-EAM source, the required signal-to-noise ratios (SNRs) of both 1.25 Gb/s and 2.5 Gb/s signals could be estimated easily with the receiver electrical bandwidths [7-8]. For example, the required SNRs for the error-free signal transmission were calculated to be 21.5 dB and 23.6 dB with a 1.25 Gb/s and a 2.5 Gb/s signals, respectively. These required SNRs were a little bit higher than 18 dB reported in [8] for the error-free (@ BER of 10^{-14}) transmission. We believe that this increase in the required equivalent optical bandwidth was mainly due to low extinction ratio of our BLS seeded R-EAM source (which was measured to be less than 9 dB). For the case of a 10 Gb/s signal, the required equivalent optical bandwidth was measured in only the FEC threshold case, which was 19.6 times wider than that for a 1.25 Gb/s signal. This required equivalent bandwidth of our source for a 10 Gb/s signal is about 2 times wider than our expectation. We believe that this difference was mainly due to the low extinction ratio of our transmitter as well as the performance variation of our optical receiver. For reference, the receiver sensitivities of our receivers at a BER of 10^{-9} for a 1.25 Gb/s, a 2.5 Gb/s and a 10 Gb/s signals with an external cavity laser seeded R-EAM optical source were measured to be -27.6 dBm, -26.7 dBm and -12.6 dBm, respectively. From the results, we found that the receiver sensitivity, especially for a 10 Gb/s signal, was much higher than usual. Thus, we conclude that the required equivalent optical bandwidth of our source for a 10 Gb/s signal could be reduced as long as the performances of both optical transmitter and receiver would be optimized.

III. SUMMARY

The performance of a BLS seeded R-EAM optical source has been experimentally evaluated with various equivalent optical bandwidths. A bandwidth tunable optical filter was used to implement our BLS seeded R-EAM optical source for the simple adjustment of the equivalent optical bandwidth. At first, we have re-confirmed that the equivalent optical bandwidth of the BLS seeded R-EAM optical source should be wider than 1 nm for the error-free transmission of a 1.25 Gb/s signal. For the case of a 2.5 Gb/s signal, the required equivalent optical bandwidth of our source was increased to be wider than 2.7 nm for the error-free transmission. However, no error-free transmission was achieved for a 10 Gb/s signal with our BLS seeded R-EAM source. This was mainly due to the un-equalized output spectrum of our BLS output. Thus, we believe that both FEC and dispersion compensation schemes should be adopted for the implementation of a 10 Gb/s signal transmission system even with a limited number of channels.

ACKNOWLEDGMENT

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (MEST) (NRF-2013R1A1A2005977).

REFERENCES

1. E. K. MacHale, G. Talli, P. D. Townsend, A. Borghesani, I. Lealman, D. G. Moodie, and D. W. Smith, “Extended-reach PON employing 10 Gb/s integrated reflective EAM-SOA,” in *Proc. Eur. Conf. Optical Communication (ECOC2008)* (Brussels, Belgium, Sep. 2008), Th.2.F.1.
2. G. Girault, L. Bramerie, O. Vaudel, S. Lobo, P. Besnard, M. Joindot, J.-C. Simon, C. Kazmierski, N. Dupuis, A. Garreau, Z. Belfqih, and P. Chanclou, “10 Gbit/s PON demonstration using a REAM-SOA in a bidirectional fiber configuration up to 25 km SMF,” in *Proc. Eur. Conf. Optical Communication (ECOC2008)* (Brussels, Belgium, Sep. 2008), P.6.08.
3. S.-C. Lin, S.-L. Lee, C.-K. Liu, C.-L. Yang, S.-C. Ko, T.-W. Liaw, and G. Keiser, “Design and demonstration of REAM-based WDM-PONs with remote amplification and channel fault monitoring,” J. Opt. Commun. Netw. **4**, 336-343 (2012).
4. Q. Guo and A. V. Tran, “Demonstration of 40-Gb/s WDM-PON system using SOA-REAM and equalization,” IEEE Photon. Technol. Lett. **24**, 951-953 (2012).

5. C.-H. Lee and S.-G. Mun, "WDM-PON based on wavelength-locked Fabry-Perot LDs," J. Opt. Soc. Korea **12**, 326-336 (2008).
6. B. W. Kim, "RSOA-based wavelength-reuse gigabit WDM-PON," J. Opt. Soc. Korea **12**, 337-345 (2008).
7. C. H. Kim, "Performance evaluation of reflective electro-absorption modulator based optical source using a broadband light seed source for colorless WDM-PON applications," Opt. Express **21**, 12914-12919 (2013).
8. J. S. Lee, Y. C. Chung, T. H. Wood, J. P. Meester, C. H. Joyner, C. A Burrus, J. Stone, H. M. Presby, and D. J. Y. DiGiovanni, "Spectrum-sliced fiber amplifier light source with a polarization-insensitive electroabsorption modulator," IEEE Photon. Technol. Lett. **6**, 1035-1038 (1994).
9. G. J. Pendock and D. D. Sampson, "Transmission performance of high bit rate spectrum-sliced WDM systems," IEEE J. Lightwave Technol. **14**, 2141-2148 (1996).
10. C. H. Kim, "Impact of various noises on maximum reach in broadband light source based high-capacity WDM passive optical networks," Opt. Express **18**, 9859-9864 (2010).
11. L. Chen, N. Sherwood-Droz, and M. Lipson, "Compact bandwidth-tunable microring resonators," Opt. Lett. **32**, 3361-3363 (2007).
12. ITU-T Recommendation G.975.1., Forward Error Correction for High Bit Rate DWDM Submarine Systems.