System Impairments and Performance Implications of ASE Seeded WDM PON Systems

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Abstract: Systematic analysis of various impairments in ASE seeded WDM PONs is presented and transmission performance limitations are determined in this paper. From a system perspective, characteristics of colorless transmitters are optimized for larger transmission distance.

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

1. Introduction

Wavelength division multiplexing passive optical network (WDM PON) is a promising solution for future broadband access services [1]. In WDM PONs, each optical network unit (ONU) will be served by a dedicated wavelength channel to communicate with the central office or the optical line-terminal (OLT). Hence, WDM PON can provide a logic point-to-point connection with dedicated bandwidth, transparent protocol, data security and guaranteed quality of service. A major technical challenge in WDM PONs is low-cost colorless ONUs. Colorless ONUs can work across all the WDM channels, so as to solve the inventory problem and provide better OAM (operation, administration and maintenance) for service providers. Two widely used colorless lightsource for WDM PONs are injection locked FP (IL FP) lasers and reflective semiconductor optical amplifiers (RSOAs) [2]. In WDM PON systems using IL FP lasers or RSOAs, the upstream transmission of colorless ONU transmission is usually achieved by injecting an ASE (amplified spontaneous noise) seed light from OLT. ASE seeded WDM PON has been demonstrated in various experiments, and the impact of Rayleigh backscattering has been investigated in previous work [3]. However, to the best of our knowledge, a thorough analysis on the performance limitations of ASE seeded WDM PON systems have not been done in the literature. It is necessary to fully understand system performance of ASE seeded WDM PONs before large scale deployment.

In this paper, we start with a systematic analysis of various impairments in ASE seeded WDM PONs in section 2. Then the system performance in term of OSNR (optical signal-to-noise-ratio) and dispersion limitations is analyzed in details in section 3, and the transmission distance of ASE seeded WDM PONs can be deduced so as to provide a general guide line for service providers deploying WDM PONs. Furthermore, system performance implications of RSOA and IL FP laser characteristics are investigated so that RSOA and IL FP laser design can be optimized from a system perspective. Finally, section 4 concludes the paper with a summary on the performance of ASE seeded WDM PONs.

2. System impairments in ASE seeded WDM PONs

In WDM PONs, both downstream and upstream could use ASE seeded colorless transmitters. However, the performance bottleneck is in the upstream direction due to the large loss experienced by the seeded signal from OLT to ONUs. Hence, our analysis will focus on the upstream direction, and for downstream, similar analysis can be done. In the upstream transmission, a number of interferences could degrade the system performance, including Rayleigh backscatterings of the ASE seed and the upstream signal, ASE noise from the seed and colorless transmitters, and discrete reflection of the seed and the upstream signal due to abrupt refractive index changes at connectors and other components along the fiber link. In addition, fiber loss and dispersion also impose system performance limitations. Since the discrete reflection in the fiber link can be minimized with proper construction of fiber infrastructure, this term will be neglected in the following analysis. Considering all the system impairments, the transmission limits of ASE seed WDM PONs is determined by optical power budget, dispersion limit and OSNR of the received signal. Furthermore, the transmission limits also depends on the characteristics of the colorless transmitters. In the following, we will discuss the Rayleigth backscattering noise and intensity noise (from ASE seed and colorless transmitter) in WDM PONs using IL FP lasers and RSOAs respectively.

(a) WDM PONs using IL FP lasers

When ASE seed is filter by AWG (arrayed waveguide grating) and injected into an IL FP laser, the IL FP laser will lase under a single mode with wavelength determined by the injection wavelength and its cavity modes. Meanwhile, the relative intensity noise from the seed will be amplified in the IL FP laser cavity and transmitted back toward OLT. The intensity noise contribution from the seed light can be written as

$$P_{RIN} = \tfrac{1}{4} P_n G e^{-2\alpha L} \alpha_{AWG}^2 \tag{1}$$

where P_n is the intensity noise of the filtered ASE seed, G is the gain of IL FP laser, $\exp(-\alpha L)$ is the loss of the fiber with a length of L, α_{AWG} represent the insertion loss of the AWG. For the 1/4 coefficient on the right hand side, 1/2 comes from intensity modulation and 1/2 comes from polarization dependence gain of IL FP laser. The intensity noise P_n depends on the relative intensity noise of the ASE seed, and it is proportional to the power of the ASE seed, $P_n = kP_{seed}$. For external injected noise, IL FP laser can be considered as a reflective FP cavity with gain, and the gain spectrum can be derived as

$$G = \frac{R_2 \cdot (1-R_1)^2 \cdot G_s}{1 + R_1 R_2 G_s - 2\sqrt{R_1 R_2}\sqrt{G_s}\cos(2\beta L)} \tag{2}$$

where G_s is the single pass gain of IL FP laser cavity, R_1 and R_2 are the reflectivities of the front facet and back facet respectively, and β is the propagation constant of the active region waveguide in the FP laser. Since the FP laser is in lasing mode, the lasing wavelength (a cavity mode) experience largest gain and the gain for the lasing wavelength is actually equal to the cavity loss, that is, the maxim cavity gain (at lasing wavelength) is $G_m = 1/ R_1R_2$.

The intensity noise of an IL FP laser can be determined by integrating its noise power spectral density $S_{FP}(\omega)$,

$$S_{FP}(\omega) = \frac{2}{\pi\sigma} N_{ph} R_{ASE} \int_{-\infty}^{\infty} \left|H(\omega)\right|^4 \Big/ [(\omega - \varpi)^2 + \Omega^2]\Omega d\omega \qquad (3)$$

where N_{ph} represents the photon density in the FP cavity, R_{ASE} is the ASE injection rate, and σ is the spectral overlap factor determined from the overlap integral between the spectral shape of the spectrum sliced ASE and the frequency response of the FP cavity [4]. ϖ denotes the shift of the resonance frequency induced by the carrier density depletion due to ASE injection, and $\Omega = (\gamma - G)/2$, where G is the gain and γ is the cavity loss. $H(\omega)$ is the transfer function of a small signal modulation response given by $H(\omega) = \omega_R^2 \big/ (\omega_R^2 - \omega^2 + j\gamma_d\omega)$, where ω_R is the relaxation oscillation frequency and γ_d is the damping factor. ASE injection rate is proportional to the seed power, $R_{ASE} = k_cP_{seed}$, where k_c is the coupling coefficient.

Rayleigh backscattering of the seed light is given by

$$P_{seed\_scattering} = SP_{seed} \qquad \text{and} \qquad S = CP_{seed}(1 - e^{-2\alpha L})\alpha_S \big/ 2\alpha \qquad (4)$$

where S is the Rayleigh backscattering coefficient, α_s is the fiber scattering coefficient, and C is the fiber recapture coefficient of the scattered light [5].

Similarly, Rayleigh backscattering create a noise power travels back toward the IL FP laser. When the Rayleigh backscattering of the upstream signal enters IL FP laser, it is amplified, modulated and redirected to OLT. This amplified and modulated Rayleigh scattering, in turn, will produce Rayleigh scattering, which will be amplified and modulated again by IL FP laser. The process will continues infinitely. Summing up all the amplified Rayleigh scattering power, one has

$$P_{sig\_scattering} = P_{tx} e^{-\alpha L} \alpha_{AWG} \sum_{n=1}^{\infty} [SG_m / 2]^n = P_{tx} e^{-\alpha L} \alpha_{AWG} \frac{SG_m / 2}{1 - SG_m / 2} \qquad (5)$$

where P_{tx} is the transmitted power from the IL FP laser, G_m is the IL FP cavity gain for the upstream wavelength.

(b) WDM PONs using RSOAs

In WDM PONs using RSOAs, the intensity noise contribution from ASE seed is given by

$$P_{RIN} = \tfrac{1}{2} P_n G e^{-2\alpha L} \alpha_{AWG}^2 \qquad (6)$$

where G is the gain of the RSOA, and the 1/2 coefficient comes from modulation. The intensity noise from RSOA is

$$P_{ASE} = \tfrac{1}{2} h\nu F_n G B_o e^{-\alpha L} \alpha_{AWG} \qquad (7)$$

where h is the plank constant, ν is the optical carrier frequency, F_n is the noise figure of RSOA, B_o is the optical bandwidth of AWG channel. Note that intensity modulation contributes to a coefficient of 1/2 in the above equation.

The Rayleigh backscattering of the ASE seed can be determined from eq. (4). The Rayleigh backscattering of the upstream signal is also an infinite process, and its total power is given by

$$P_{sig\_scattering} = \frac{1}{2} GP_{seed} e^{-2\alpha L} h_{AWG} \frac{SG/2}{1 - SG/2} \qquad (8)$$

3. System performance of ASE seeded WDM PONs

The performance of ASE seeded WDM PONs is limited by three factors: power budget, OSNR and fiber dispersion. Among these, power budget is not the major limiting factor from our simulations and experiments. Fiber dispersion is not a limiting factor for WDM PONs with IL FP lasers running at 1.25 Gb/s or 2.5 Gb/s, because a well-locked FP laser operates in a single mode and its linewidth is about 0.1nm [4]. In WDM PONs with RSOAs, fiber dispersion limits is

$$|D| L\sigma_{sig} \le 0.25T_b \qquad (9)$$

Where D denotes the fiber dispersion coefficient, T_b represents the bit period, and σ_{sig} is the spectral width of the transmitted signal. For ASE seeded WDM PON using RSOAs, the spectral width of the upstream signal is roughly equal to the effective bandwidth of the AWG channel.

As different intensity noise powers in ASE seeded WDM PONs has been derived in section 2, OSNR can be easily derived from the ratio of the received signal power and total noise power. For WDM PONs with RSOAs, the received signal power at OLT is

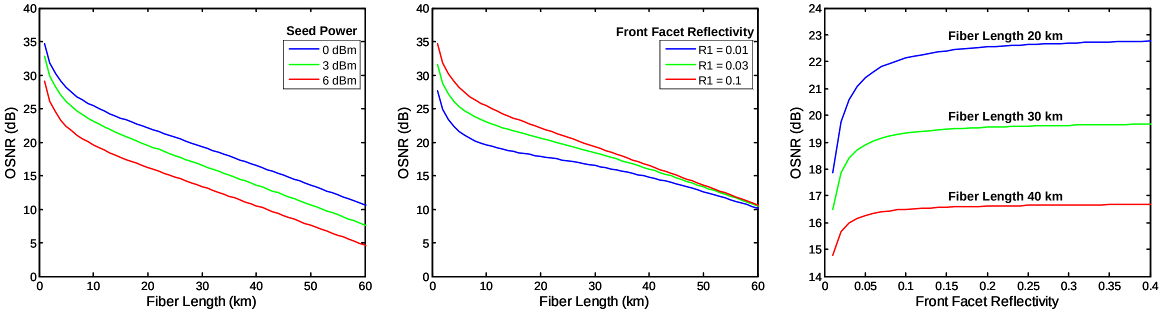
$$P_{sig} = \tfrac{1}{2} G \cdot P_{seed} \cdot e^{-\alpha L} \alpha_{AWG}^2 \qquad (10)$$

For WDM PONs with IL FP lasers, the received signal power at OLT is

$$P_{sig} = \tfrac{1}{2} P_{tx} \cdot e^{-\alpha L} \alpha_{AWG} \qquad (11)$$

where is the transmitted power P_{tx} from IL FP lasers is mostly determined by the biasing current, and it shows weak dependence on the injected power, as long as FP laser is operating in single mode and the injected power is not excessive.

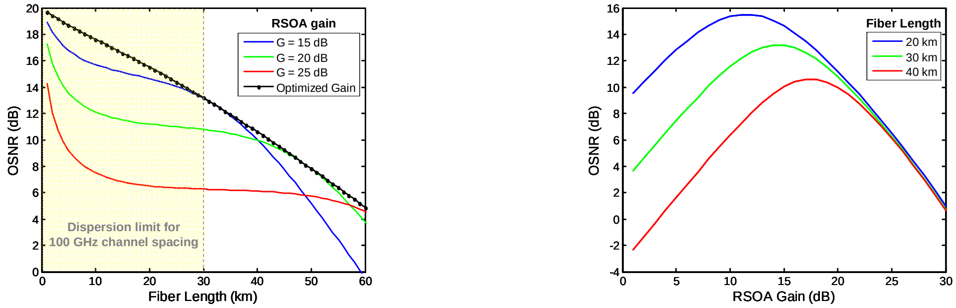
Fig. 1(a) shows the simulation results for OSNR as a function of fiber length for WDM PONs using IL FP lasers. The OSNR depends also on the seed power. When the FP laser is well-locked, larger seed power leads to worse OSNR because of larger intensity noise and Rayleigth backscattering. Fig. 1(b) shows the OSNR vs fiber length for different front facet reflectivity and Fig. 1(c) shows the OSNR as a function of front facet reflectivity at a given fiber length. With larger front facet reflectivity, OSNR improves because the IL FP laser has a stronger filtering effect on the intensity noise of the seed



(a) (b) (c)

Fig. 1 Simulation results for OSNR in WDM PONs using IL FP lasers. (a) OSNR as a function of fiber length for different seed powers; (b) OSNR vs fiber length for different front facet reflectivity of IL FP lasers (c) OSNR as a function of front facet reflectivity of IL FP lasers.

light, and the amplification for the Rayleigh backscattering of the upstream signal becomes smaller. On one hand, it is beneficial to increase the front facet reflectivity of IL FP lasers from system performance perspective; one the other hand, from device design perspective, it is typically to design IL FP lasers with small facet reflectivity [6], because smaller facet reflectivity makes it easier to coupling seed light into the cavity. Furthermore, smaller facet reflectivity also leads to larger band filling effect and hence broadened gain spectrum. In other words, the FP laser can operates in wider wavelength range and hence more WDM channels can be supported. Therefore, there is a design trade off for the front facet reflectivity from the perspectives of system performance and wavelength operating range.



(a) (b)

Fig. 2 Simulation results for OSNR in WDM PONs using RSOAs. (a) OSNR vs fiber length for different RSOA gain; (b) OSNR as a function of RSOA gain. The dispersion limit for 100GHz channel spacing is plotted as a shaded area in (a).

Fig. 2(a) presents the simulation results for OSNR as a function fiber length for WDM PONs using RSOAs. The simulation results showed that the OSNR depends strongly on RSOA. Fig. 2 (b) demonstrate that for a given fiber length, there exists an optimal value of RSOA gain to achieve the best OSNR performance. For small RSOA gain, the signal power is small, while for large RSOA, the Rayleigh backscattering of the upstream signal is also large. In both cases, the OSNR becomes worse. As the fiber length increase, the optimal value of RSOA gain increases. Therefore, it is necessary to optimize RSOA gain for different fiber lengths to achieve the best performance. The black curve in Fig. 2(a) shows the best OSNR for different fiber length with RSOA gain optimized. From the OSNR curve, the transmission limit for WDM PON using RSOA is about 30km is a BER = 10^{-10} is required. Similarly, the dispersion limit for the system is also about 30km for WDM PONs with 100GHz channel spacing (shaded area in Fig. 2(a)). In order to improve the transmission distance, electronic dispersion compensation can be used to combat fiber dispersion and forward error correct can be used to alleviate the impact of intensity noise on the system performance.

4. Conclusions

System impairments in ASE seeded WDM PONs, including ASE noise (from ASE seed and colorless lightsources) and Rayleigh backscattering (from ASE seed and upstream signals), are analyzed in this paper. OSNRs in the WDM PON systems are determined for colorless ONUs using IL FP lasers and RSOAs. The OSNR analysis and simulation results provided insights in the system performance and the performance implications of colorless transmitters. In WDM PONs using IL FP lasers, it is found that increasing front facet reflectivity of IL FP lasers could lead to a better OSNR performance. In WDM PONs using RSOAs, it is necessary to optimize the RSOA gain for a given fiber length to achieve the best system performance.

5. References

[1] A. Banerjee, et al, *Journal of Optical Networking*, vol. 4, issue 11, pp. 737-758 (2005).
[2] K. Iwatsuki, and J.-I. Kani, *Journal of Optical Communications and Networking*, vol. 1 , issue 4, pp. C17 - C24, 2009.
[3] C. Arellano, K.-D. Langer and J. Prat, *Journal of Lightwave Technology*, vol. 27, vol. issue 1, pp. 12-18, 2009.
[4] K.-Y. Park, and C.-H. Lee, *Journal of Quantum Electronics*, vol. 44, issue 3, pp. 209-215, 2008.
[5] W. V. Sorin, "Optical reflectometry for component characterization," in *Fiber Optic Test and Measurement*, Prentice-Hall, 1998.
[6] E. H. Lee, et al, *Photonics Technology Letter*, vol. 18, issue 3, pp.667-669, 2006.