Performance Supervision for Multiple Optical Amplifiers in WDM Transmission Systems Using Spectral Analysis

K. Chan, C. K. Chan, F. Tong, and L. K. Chen

***Abstract*—In this letter, we proposed and experimentally demonstrated a novel supervisory scheme to monitor the working status of multiple optical amplifiers in a wavelength-division-multiplexing transmission link. An optical feedback loop with unique loop length is added around each inline optical amplifier to create monitoring signal at a common supervisory wavelength. By analyzing the RF spectra of the common supervisory wavelength at the receiver end, any failed optical amplifier in the transmission link can be identified.**

***Index Terms*—Fault detection, optical amplifiers, optical fiber communication.**

I. Introduction

NOWADAYS, the role of optical layer in telecommunication network infrastructure is getting more and more important. The optical layer no longer only provides mere point-to-point transmission pipes, but can also incorporate many networking functions such as routing, switching and performance monitoring. In a wavelength-division-multiplexing (WDM) transmission link, multiple inline erbium-doped fiber amplifiers (EDFAs) are usually employed to improve the transmission span and signal quality. To ensure reliability of data delivery through such WDM transmission links, the working status of all the inline EDFAs have to be monitored in a real time manner. Thus, a simple but effective EDFA supervisory scheme is highly desirable to identify any degraded or failed ones, and thus appropriate remedy can be made timely to restore the system transmission. Several methods [1]–[5] have been previously proposed. They include applying low-frequency pilot-tone modulation on pump lasers [1]; using optical time-domain reflectometry [2], [3]; and using fiber Bragg gratings with amplified spontaneous emission [4], [5]. In this letter, we propose and demonstrate an EDFA supervisory scheme, which is simple and scalable. The identifiers for all EDFAs are generated all-optically and share the same supervisory wavelength channel. By analyzing RF spectra of the common supervisory channel at the end of the transmission link, the multiple superimposed EDFA identifiers can be easily resolved and thus the working status of all in-line EDFAs can be monitored continuously.

Manuscript received September 4, 2001; revised January 7, 2002.

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Publisher Item Identifier S 1041-1135(02)03230-5.

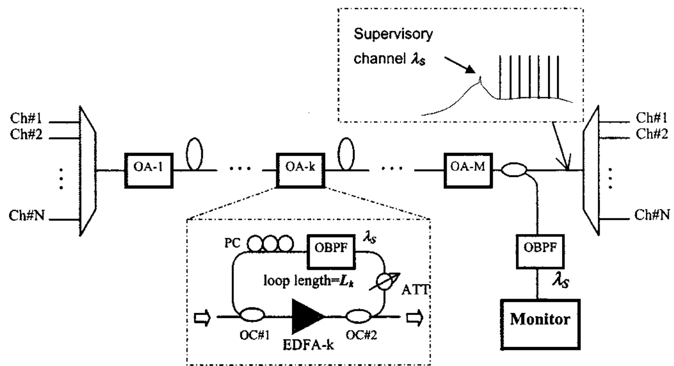

Fig. 1. A WDM transmission system with multiple inline EDFAs implemented with our proposed EDFA supervisory scheme. OA: Optical amplifier. OBPF: Optical bandpass filter. OC: Optical coupler. PC: Polarization controller. ATT: Optical attenuator.

II. Supervisory Scheme

Fig. 1 shows a WDM transmission link with M inline EDFAs. To facilitate monitoring the working status of all the EDFAs, identifying tags are generated all-optically to label individual EDFAs. This is done by applying an optical fiber loop of unique fiber length around each EDFA to feed a small portion of output power back to the amplifier's input. In this way, an external fiber feedback cavity is formed around each EDFA. An optical bandpass filter is added within the fiber loop to select the monitoring wavelength, which is chosen to be the same for all EDFAs and lies outside the transmission band for data wavelengths. This common monitoring wavelength among all EDFAs is regarded as the supervisory wavelength (λ_s). The optical power of the supervisory wavelength at each EDFA is carefully adjusted, using optical attenuators, to keep the feedback cavity below the lasing threshold, in order to achieve better power stability and avoid excessive amplifier gain consumption. At each EDFA, the respective feedback signal, in RF domain it comprises a train of cavity modes with unique mode spacing due to the chosen unique fiber loop length. This unique characteristic serves as an identifying tag for the respective EDFA. For example, if the fiber loop length for k th EDFA is L_k, the generated cavity mode spacing will be $S_k = c/(nL_k)$ where c is the light velocity and n is the refractive index in fiber. Such identifying tag is denoted as E_k $(k \in 1{:}M)$. In the case that all EDFAs are working properly, these identifying tags generated at the EDFAs are superimposed together onto the supervisory wavelength as they

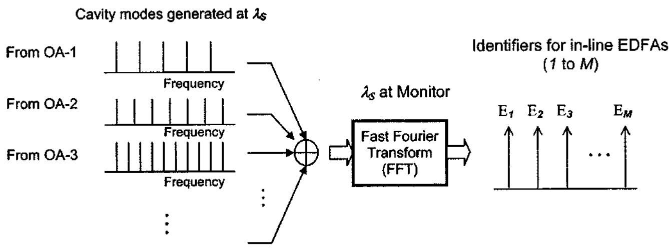

Fig. 2. Operation principle of our proposed EDFA supervisory scheme.

pass along the transmission link. All M identifying tags for the EDFAs will be present at the receiving end. The individual identifying tags E_k $(k \in 1{:}M)$ can be easily differentiated by applying fast Fourier transform (FFT) to the obtained RF spectra. This can be performed simply by using a personal computer or a digital signal processing module at the receiving end. Each resultant identifying tag will be represented by a distinctive peak in the output FFT waveform as illustrated in Fig. 2.

For a healthy system, all M identifying tags E_k $(k \in 1{:}M)$ for the EDFAs will be present on λ_s at the monitor unit. However, when one of EDFAs, say EDFA-r, has degraded output power, the respective identifying tag E_r will have weaker intensity comparing to the healthy system. It is because the cavity gain is reduced in the feedback cavity at EDFA-r, thus reduces the intensity of the respective cavity modes. In the case that EDFA-r is failed, the input power to EDFA-$(r+1)$ will be drastically reduced which leads to excessive gain in the feedback cavity at EDFA-$(r+1)$. Thus, lasing occurs at λ_s and the power of the cavity modes with mode spacing S_{r+1} is strongly enhanced. This enhanced λ_s then, in contrast, reduces the cavity gain at all the following EDFAs, and thus, suppresses their cavity modes. Therefore, only the identifying tag E_{r+1} will be present in the output FFT waveform at the monitor unit. In general, absence of all but only one identifying tag E_r implies failure in EDFA-$(r-1)$.

III. Experiment

The experimental setup was similar to Fig. 1 with three inline EDFAs. Optical attenuators with 12-dB attenuation were used to simulate fiber spans of 50 km. An optical data channel (λ_D) at 1545 nm was modulated with 10-Gb/s pseudorandom binary sequence (PBRS) nonreturn-to-zero (NRZ) data and was injected to EDFA-1. The launch power was -7 dBm to simulate the multichannel scenario. The gain of each EDFA was about 12.5 dB. At each EDFA, a feedback fiber loop of unique length was formed and the OBPF was centered at the common supervisory wavelength λ_s, which was chosen to be 1533 nm. Individual cavity loss was carefully adjusted such that the ring laser cavity was biased below the lasing threshold. Its value should be smaller than the small-signal amplifier gain and larger than the amplifier saturated gain. Cavity modes of different mode spacings were formed at EDFA-1, EDFA-2, and EDFA-3 and the corresponding mode spacings were measured to be 4.5, 3.7, and 2.8 MHz, respectively. The cavity modes are superimposed on the supervisory wavelength λ_s while

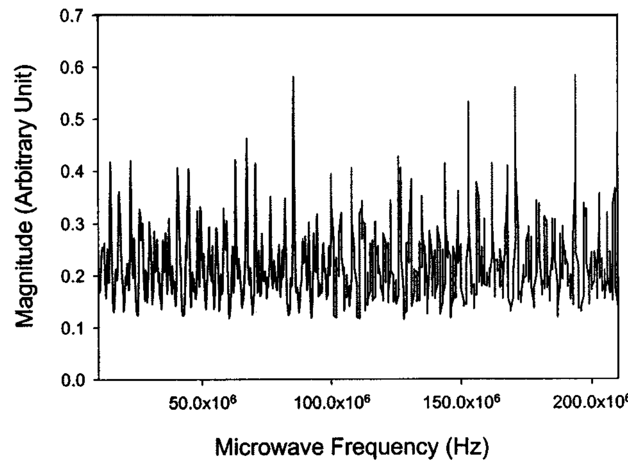

Fig. 3. RF spectrum of the surveillance channel. (center frequency: 110 MHz. Frequency span: 200 MHz. Resolution bandwidth: 100 kHz).

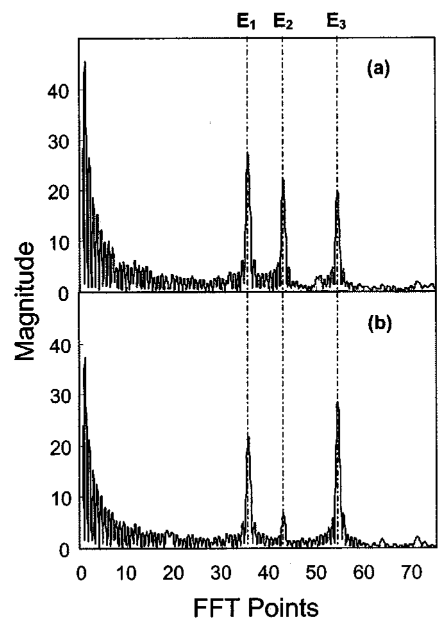

Fig. 4. FFT output waveforms from the RF spectra at the supervisory wavelength (a) healthy system and (b) EDFA-2 with reduced amplifier gain.

traversing through the transmission link. At the receiving end, the supervisory wavelength was filtered out at the monitor unit and was fed into an AC-coupled photodetector connected to an RF spectrum analyzer. Fig. 3 shows the RF spectra of λ_s, where the cavity modes formed on at all EDFAs were superimposed. We then applied FFT, using Matlab to the captured RF spectra for spectral analysis. For a healthy system, the FFT output consisted of three distinct peaks (identifying tags), E_1, E_2, and E_3, as shown in Fig. 4(a). In order to simulate an EDFA with degraded performance, we intentionally reduced the pump current to EDFA-2 such that the amplifier gain was reduced by 2 dB. The resultant FFT output waveform [see Fig. 4(b)] showed large attenuation in the tag E_2 due to the reduced gain in the feedback cavity of EDFA-2. On the contrary, the magnitude of the tag E_3 was enhanced slightly due to the reduced input signal power into EDFA-3, leading to a larger gain in its feedback cavity.

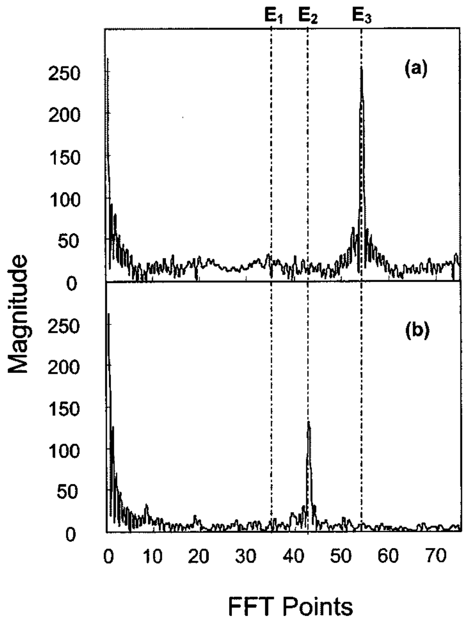

Fig. 5. FFT output waveforms from the RF spectra at the supervisory wavelength (a) EDFA-2 is failed and (b) EDFA-1 is failed.

To simulate failure at EDFA-2, we turned off the current to the pump laser. The resultant FFT waveform of the captured RF spectra [see Fig. 5(a)] showed that the magnitude of tag E_3 is largely enhanced, while E_1 and E_2 were almost completely suppressed. This implied lasing had occurred in EDFA-3 as its input power was much weakened by the failed EDFA-2. Similarly, when EDFA-1 was simulated failed, only tag E_2 with largely enhanced magnitude was present in the resultant FFT waveform [see Fig. 5(b)]. Although we only demonstrated our scheme in 3-EDFA scenario, by carefully adjusting the cavity loss of the fiber loop around each EDFA so as to equalize the power of the RF cavity modes among all EDFAs, the scheme is still effective to monitor larger number of inline amplifiers in the system. In this way, failure in EDFA-k can be easily diagnosed by a single intense peak at tag E_{r+1} in the FFT waveform of the captured RF spectra at λ_s, and can also be easily differentiated from the case of degraded EDFA by following the diagnosis procedure.

```
for k = 1 to M
{ if I_k ≥ I_T
  then (output "EDFA-k is found failed"
 and goto end)
}
for k = 1 to M
{ if (I_k − T_k < 0 and I_{k+1} − T_{k+1} > 0)
  then (output "EDFA-k is found degraded"
 and goto end)
}
output "all EDFA's are in normal opera-
 tion"
end
```

where M is number of EDFAs in the transmission link; I_k $(k \in 1{:}M)$ is the magnitude of the identifying tag E_k;

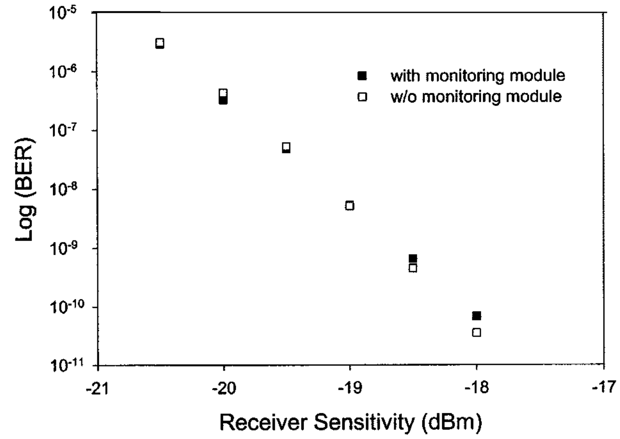

Fig. 6. Bit-error-rate performance with and without proposed monitoring module.

T_k $(k \in 1{:}M)$ is the initial magnitude of each identifying tag and I_T is the threshold value chosen to differentiate the case of lasing. In our scheme, it is assumed that no wavelength add–drop operation is present. Any change in FFT output due to possible wavelength add–drop can be recognized by monitoring the number of data wavelengths present at the receiver.

Besides, the nonintrusive nature of the proposed scheme has also been confirmed by the bit-error-rate measurement when an optical data channel carrying 10-Gb/s $2^{31} - 1$ PBRS NRZ data was sent down the transmission link under the proposed scheme. At receiving end, the data signal was extracted with Fabry–Pérot filter with 1-nm passband at 3-dB bandwidth. The results (see Fig. 6) showed that only negligible power penalty was obtained when the proposed monitoring scheme was applied to a healthy transmission link.

IV. Summary

We proposed and experimentally demonstrated a novel EDFA supervisory scheme for inservice fault identification. An identifying tag in form of cavity modes with unique mode spacing is generated all-optically at each EDFA. By constantly examining the intensities of all the identifying tags in the FFT output waveform at the monitor unit, the exact failed or degraded EDFA can be located without interrupting the existing data wavelength channels.

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