Dynamic-channel-equalizer using in-line channel power monitor and electronic variable optical attenuator

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Abstract

We propose and demonstrate a polarization-insensitive dynamic-channel-equalizer (DCE) for compensating erbium-doped-fiber-amplifier (EDFA) amplified signals after dynamic optical add/drop. The DCE can be monolithically integrated on silicon-on-insulator (SOI) platform and is potentially low cost and compact. The DCE can compensate complicated gain slope shape, which may be generated in cascaded EDFAs or deliberate channel add/drop, based on individual channel equalization. Fifteen-decibel receiver sensitivity improvement at 10 Gb/s bit-error-rate (BER) measurement of $10^{-9}$ was achieved in the compensated channel by removing cross-gain-modulation generated by neighboring channel add/drop.

Keywords: Photodetector; Silicon waveguide; Optical amplifier

1. Introduction

The widespread deployment of erbium-doped-fiber-amplifiers (EDFA) in wavelength division multiplexing (WDM) networks is a potential problem for the future implementation of reconfigurable networks. Channels add/drop or transmission of optical bursts/packets, will lead to transient power fluctuations in EDFA-amplified signals. Gain tilt may be introduced when one or more channel(s) is/are dropped, and this can accumulate in a cascade of amplifiers to produce excessive power at one end of the spectrum, making the received signal exceed the dynamic range of receivers. Even if only a single channel is amplified by an EDFA, transient gain can occur [1]. The gain tilt may be compensated by gain-clamping [2], using a single variable optical attenuator within an EDFA [3], using the transfer characteristic of cascaded Mach–Zehnder filters [4] or acousto–optic filter [5]. More complicated changes in gain slope may be generated in cascaded EDFAs, from simulated Raman scattering (SRS), deliberate channel add/drop or uncontrolled changes from fiber breakage. For such changes individual channel equalization after wavelength demultiplexing, such as using thermo-optic attenuators [6] or MEMS [7] have been reported. One of the promising candidates to compensate gain transient without wavelength demultiplexing is based on envelope detection of optical bursts. For every input burst, the control circuit (consists of envelope detection, RF amplification and laser driver) generates an inverted envelope, which then modulates a control laser launching into the EDFA together with the input bursts [8]. However, the control wavelength should be different form the input wavelengths and part of the EDFA gain bandwidth is reserved for the control wavelength.

In this paper, we propose and demonstrate a polarization-insensitive-dynamic-channel-equalizer (DCE) using an electronic variable optical attenuator (EVOA) and in-line channel power monitor (ICPM) [9] for transient compensation and detection, respectively. Although the subsystem complexity is increased due to the need of an ICPM and an EVOA for individual wavelength channel,
the DCE can be monolithically fabricated on a single SOI wafer, and is thus compact and stable. In this scheme, there is no wavelength reservation and the whole EDFA gain bandwidth can be used when compared with [8]. Also, there is no laser source, laser driver and modulation in the control circuit. As each wavelength channel has an EVOA, this can provide further flexibility for individual channel amplitude equalization in WDM networks [10]. Gain transient suppression of 7 dB was observed in a single EDFA-amplified channel. Receiver sensitivity improvement of 15 dB at 10 Gb/s BER of $10^{-9}$ without error-floor was achieved in the compensated channel by compensating the gain fluctuation generated by the add/drop of a neighboring channel.

2. Proposed architecture

The proposed architecture of the DCE is shown in Fig. 1. The EDFA amplified WDM signals are wavelength demultiplexed by an arrayed waveguide grating (AWG). Each wavelength channel is detected by an ICPM [9], which is based on helium ion implanted silicon waveguides to detect below-bandgap wavelengths (C-band) and tap out some optical power to provide electrical control signal to the EVOA, which then equalizes the amplitude fluctuation of the signal by adjusting its optical attenuation using current injection [11]. The control circuit consists of an RF amplifier to amplify the detected electrical signal to drive the EVOA and a threshold decision module to equalize the transient with the rest of the optical signal. An optical delay is used between the ICPM and EVOA to match with the processing latency of the control circuit. As the typical lifetime of EDFA falls between 100 and 350 $\mu$s [1], a slow speed control circuit can be used. Finally, different channels are multiplexed by another AWG. Monolithic integration of the AWG and EVOA has already been demonstrated [12]. The ICPM provides the same function as a waveguide tap coupler and a hybrid-integrated photodiode (PD) to realize in-line power monitoring. Fig. 2(a) and (b) show the schematic functionality required of a conventional channel power monitor using a waveguide tap coupler and a hybrid-integrated PD, and the proposed ICPM based on helium ion implantation, respectively. Fig. 2(c) is the photograph of the SOI ICPM. By using different implantation doses and annealing durations, we can obtain different responsivity of the ICPM [9].

3. Experiment, results and discussion

In this section, three separate experiments were performed to evaluate the DCE when operated in one, two and multiple wavelength channels. Firstly, a single channel gain transient compensation was performed (only $\lambda_0$ present in Fig. 1). A 10 kHz optical square pulse, with extinction ratio (ER) of 10 dB, experienced gain transients after being amplified by an EDFA (gain of $24 \pm 27$ dB) as shown in Fig. 3 (uncompensated curve). The distorted optical signal was then passed through the DCE for transient detection. The responsibility of the ICPM prepared by using implantation dose of $1 \times 10^{12}$ cm$^{-2}$ followed by annealing...
at 200 °C for 45 min was 64 mA/W. The speed and the polarization dependent loss (PDL) of the ICPM are 20 MHz and 0.2 dB, respectively. The electrical signal from the ICPM was fed to a control circuit, which then provides a feed-forward signal to the EVOA for transient suppression. The EVOA can provide attenuation of about 40 dB with 50 mA applied current. Fig. 3 shows the oscilloscope traces of the EDFA-amplified optical signal detected by the ICPM and the transient suppressed signal detected by a 32 GHz PIN PD at the output of the EVOA. Both the ICPM and the PIN were connected to a 40 GHz digital sampling oscilloscope for capturing the traces. The transient of the EDFA-amplified channel after the EVOA was reduced from 8 dB to 0.8 dB.

Secondly, we tested the equalization of gain transients induced by optical add/drop. The experiment consisted of launching optical square pulses (\(\lambda_0\)) of \(ER = 10\) dB and a continuous-wave (CW) signal (\(\lambda_1\)) into an EDFA via a 3 dB fiber coupler. At the output of the EDFA, the two channels were then wavelength demultiplexed by a 100 GHz channel spacing AWG, which had 3 dB bandwidth of 50 GHz and PDL of 0.5 dB. The CW signal suffered from power fluctuation of 0.42 dB introduced by the cross-gain-modulation from the neighboring channel. The power fluctuation at \(\lambda_1\) channel was detected by the ICPM and compensation by the EVOA reduced the power fluctuation to 0.08 dB. Fig. 4 shows the oscilloscope traces of the \(\lambda_1\) channel suffering from the crosstalk generated by the neighboring \(\lambda_0\) channel before and after compensation by the EVOA. The compensated signal was detected by a 32 GHz PIN PD at the output of the EVOA.

We then evaluated the BER performance of the DCE by modulating the \(\lambda_1\) channel using a Mach–Zehnder modulator to produce a 10 Gb/s NRZ signal, pseudo-random binary sequence (PRBS) of \(2^{31} - 1\). The 10 Gb/s NRZ signal was launched into the EDFA together with the 10 kHz optical square pulse (\(\lambda_0\)) of \(ER = 10\) dB via a 3 dB fiber coupler. BER measurements (Fig. 5) were performed using optically pre-amplified receiver, formed by an EDFA, followed by an optical bandpass filter [to remove the out-of-band amplified-spontaneous emission (ASE)] and a PIN photodiode. For the uncompensated signal, power fluctuations was observed in the \(\lambda_1\) channel generated by the neighboring \(\lambda_0\) channel, as shown in the eye-diagram [inset a of Fig. 5], and an error-floor was observed at BER of \(10^{-9}\). Fifteen-decibel receiver sensitivity improvement was observed in the compensated case. No error-floor appeared.

![Fig. 4. Cross-gain-modulation removal by the DCE.](image)

![Fig. 5. BER measurements of \(\lambda_1\) channel without and with signal compensation by the DCE. Inset: eye-diagram of \(\lambda_1\) channel (a) without and (b) with the DCE compensation.](image)

![Fig. 6. Optical spectra of (a) four EDFA-amplified channels with nearly equal amplitude, (b) the three survival channels after one of the channels is dropped, and they experienced different gain, (c) the three survival channels were equalized in amplitude by the EVOA.](image)
in the compensated signal. The receiver sensitivity improvement is due to the removal of the power fluctuations as shown in inset b of Fig. 5.

Finally, we evaluated the compensation of multiple channels and complicated gain-tilt compensation by using four EDFA-amplified channels at wavelengths of 1548.4 nm, 1550.9 nm, 1553.4 nm and 1555.7 nm. Here, the number of channels is limited by our EVOA, which is a four channels monolithic integrated device with characteristics as described in Section 2. Fig. 6(a) shows the optical spectrum, with resolution bandwidth of 0.01 nm, of the four wavelength channels with nearly equal amplitude after amplified by an EDFA. When the 1548.4 nm wavelength channel was dropped, the three survival channels experienced gain tilt as shown in Fig. 6(b). Fig. 6(c) shows the optical spectrum of the three survival channels which were individually equalized in amplitude by different EVOAs. The experimental results also suggest that the DCE can compensate more complicated gain slope, which may be generated in cascaded EDFAs, based on individual channel equalization.

We also perform a numerical analysis using VPI transmission Maker to assess the possible signal improvement after DCE compensation with different 10 Gb/s packet lengths and amplitude fluctuation, which is defined as $20 \log_{10} \left( \frac{U_{1\max}}{U_{1\min}} \right)$, where $U_{1\max}$ and $U_{1\min}$ are maximum and minimum values of ones, respectively. The EDFA carrier lifetime of $\sim 100$ µs and the electrical control circuit bandwidth of 200 kHz are used in the simulation. We evaluate the performance in terms of an eye opening factor (EOF), which is defined as $20 \log_{10} \left( \frac{U_{1\min} - U_{0\max}}{U_{1}} \right)$, where $U_{1\min}$ is minimum value of ones, $U_{0\max}$ is maximum value of zeros, $U_{1}$ and $U_{0}$ are the mean of ones and zeros, respectively. Fig. 7 shows that when the packet length decreases, the EOF improvement (EOF of compensated signal minus EOF of uncompensated signal) decreases because short packets experience less amplitude fluctuation due to the slow carrier lifetime of EDFA. At 0.5 dB EOF improvement window, the packet length is about 400 bits. Fig. 7 also illustrates that the proposed scheme can provide EOF improvement $>5$ dB at large packet lengths ($>1,500,000$ bits). We then modeled the transient compensation by the EVOA to the EDFA-amplified packet in the DCE. For every input packet, the control circuit will provide an electrical signal to control the attenuation of the EVOA according to the optical signal detected by the ICPM. Due to the limited frequency response of the control circuit ($\sim 200$ kHz), as well as the response of the ICPM (20 MHz) and the EVOA (3 MHz), the attenuation provided by the EVOA is dis-

![Fig. 7](image1)

EOF improvement by DCE compensation with different packet lengths and amplitude fluctuation of 10 Gb/s optical packets.

![Fig. 8](image2)

Traces of (a) attenuation provided by the EVOA, (b) input EDFA amplified and (c) compensated 10 Gb/s optical packet.
torted as shown in Fig. 8(a) when the EDFA-amplified packet is launched into the DCE as shown in Fig. 8(b). By positioning the attenuation peak to the transient peak of the optical packet with an appropriate delay, amplitude transient can be significantly removed as shown in Fig. 8(c). However, amplitude ripple can still be observed at the compensated signal, which agrees with experimental result shown in Fig. 3.

4. Conclusion

We propose and demonstrate a polarization-insensitive dynamic-channel-equalizer (DCE) based on the architecture of AWG-ICPM-EVOA-AWG. It can be monolithically fabricated on a SOI wafer, so it has the potential to be both compact and cost effective. We showed that the DCE can efficiently suppress gain transients from 8 dB to 0.8 dB in single channel condition (one EDFA per wavelength channel), hence, reducing the dynamic range of the receiver. To evaluate the effect of neighboring channel add/drop, 10 Gb/s BER measurements were performed and receiver sensitivity improvement of 15 dB was achieved in the compensated channel. Experimental results suggest that the approach is viable for the compensation of gain transient and per-channel equalization of complicated gain-tilt in reconfigurable DWDM systems. Numerical analysis illustrates that the proposed scheme can provide EOF improvement >5 dB at large packet lengths.

Acknowledgments

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References