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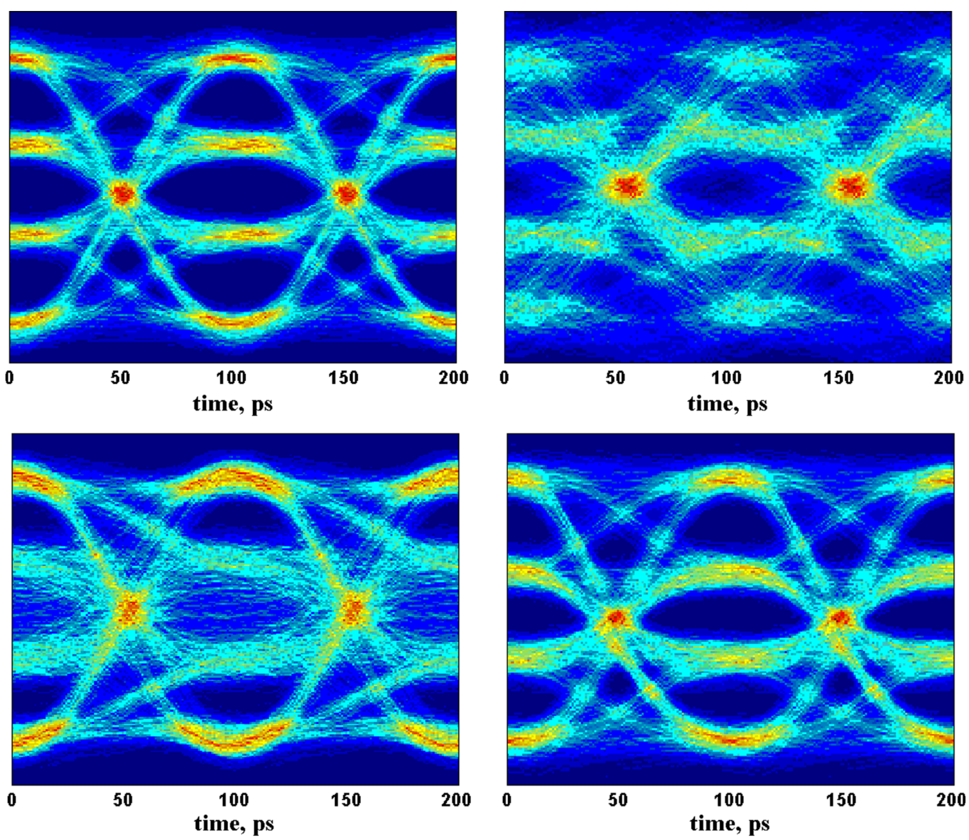

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Joint Fiber and SOA Impairment Compensation Using Digital Backward Propagation

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Abstract: An electronic scheme for joint postcompensation of fiber and semiconductor optical amplifier (SOA) impairments based on coherent detection and digital backward propagation is proposed and demonstrated. A 10-GBd amplitude-phase-modulated transmission system was demonstrated experimentally using semiconductor optical amplification. The Q-factor of the received signal was improved by 5 dB with simultaneous fiber and SOA impairment compensation in the electrical domain.

Index Terms: Amplitude-phase-shift keying, semiconductor optical amplifiers, impairment compensation.

1. Introduction

Coherent detection and digital signal processing (DSP) have changed the landscape for optical communication in recent years [1]. Chromatic dispersion and polarization-mode dispersion can now be compensated in the digital rather than the optical domain [2]. Furthermore, fiber nonlinearities can be potentially compensated using DSP [3]. It should be pointed out that the combination of coherent detection and DSP can compensate not only fiber impairments but the imperfection of hardware components in coherent optical communication as well [4]. Imperfections and impairments of active optical components can also be potentially compensated using coherent detection and DSP. We have previously demonstrated digital impairment compensation for the semiconductor optical amplifier (SOA) [5]. The SOA is a potential substitute for the erbium-doped fiber amplifier (EDFA) for optical transmission, especially in metro systems, due to its low cost, compactness and ultrawide gain spectrum. It also enables long-distance transmission in other spectral windows, such as the 1310-nm transmission window, where there is no mature amplification technology. A few transmission experiments using SOAs have been demonstrated in the 1310- and 1550-nm windows [6]–[9]. In such systems, high signal (launching) power is desired to counter the rapid degradation of the signal-to-noise ratio (SNR) at the receiver due to accumulated amplified spontaneous emission (ASE) noise of SOAs along the link. However, SOAs will be saturated at high launching powers, and the signals will suffer from SOA impairments including the data pattern effect, self-gain modulation, self-phase modulation, and interchannel crosstalk effects such as cross-gain modulation and four-wave mixing in wavelength-division multiplexing (DWM). In [5], electronic SOA impairment compensation was experimentally demonstrated for an amplitude-modulated system in which 1) direct detection was employed, and 2) only amplitude distortion introduced by SOA was compensated. This was possible because that transmission system was operated near the zero-dispersion

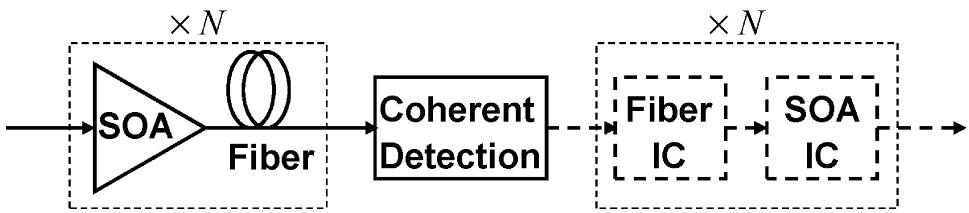


Fig. 1. Fiber-optic transmission using SOAs and electronic postcompensation of SOA and fiber impairments. IC: impairment compensation.

wavelength for relatively short distances. In more general cases, optical signals are modulated in both the amplitude and phase, and the optical signals will also be distorted by fiber impairments such as chromatic dispersion and the Kerr nonlinear effect. In this paper, we propose joint compensation of fiber and SOA impairments in the digital domain and experimentally demonstrated impairment compensation of an amplitude- and phase-modulated transmission system, where coherent detection is employed, and both the amplitude and phase distortions induced by the SOA and fiber are compensated simultaneously.

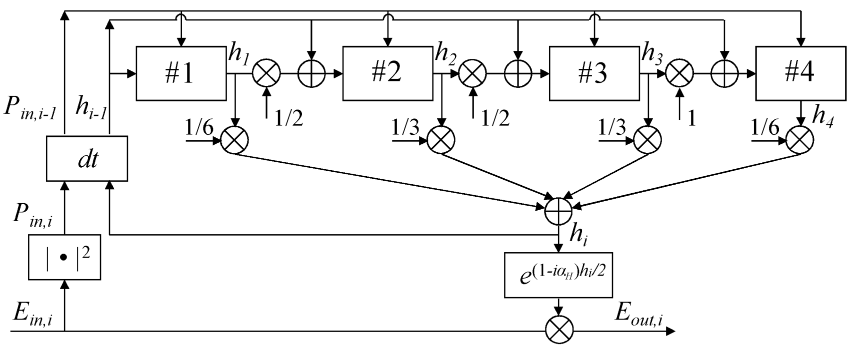
2. Principle of Joint Fiber and SOA Impairment Compensation

Fig. 1 shows the schematic diagram of an N-span fiber-optic transmission system using SOAs and electronic fiber and SOA impairment compensations. At the end of the transmission link, the received optical signal is first converted to the baseband signal by coherent detection, and then, fiber impairment compensation and SOA impairment compensation are implemented in the electrical domain in the reverse order to the their forward propagation. Both fiber impairment compensation and SOA impairment compensation are based on digital backward propagation. The fiber impairment compensation is implemented by solving the nonlinear Schrödinger equation (*NLSE*) numerically using the split-step Fourier method, and the corresponding DSP implementation has been depicted in [3]. The equations for SOA impairment compensation are described as follows [5]:

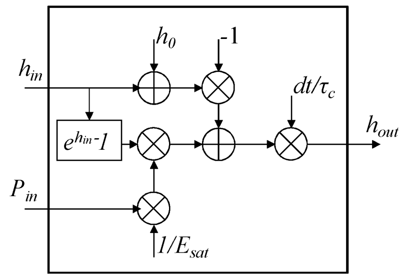
$$\left(1+\tau_c\frac{d}{dt}\right)h(t)=h_0-\frac{|E_{in}(t)|^2}{P_{sat}}(exp[h(t)]-1) \quad (1)$$

$$E_{out}(t)=E_{in}(t)exp[(1-i\alpha_H)h(t)/2] \quad (2)$$

where $E_{\rm in}(t)$ is the electrical field of the signal after fiber impairment compensation and the input for SOA impairment compensation; $h(t)$ is the loss coefficient to be solved for SOA impairment compensation; τ_c is the effective carrier lifetime of SOA and depends on the average power of the input signal; and $h_0=-\ln G_0$, where G_0 is the small signal gain of the SOA. $P_{sat}=E_{sat}/\tau_c$, where E_{sat} is the saturation energy of the SOA. Equation (1) can be solved numerically by the fourth-order Runge–Kutta method, and then, the electrical field of the signal after the SOA impairment compensation $E_{\rm out}(t)$ can be expressed by (2), where α_H is the chirp factor of the SOA. Through (1) and (2), both amplitude and phase distortions from SOA are compensated. The corresponding implementation of the algorithm is described in Fig. 2, where $E_{in,i}$ is the electrical field of the input signal at ith sampling point; $P_{in,i}$ and $P_{in,i-1}$ are the powers (intensities) of the input signal at the $(i-1)$th and the ith sampling point, respectively; h_i and h_{i-1} are the corresponding loss coefficients for the SOA impairment compensation; $E_{out,i}$ is the electrical field of the recovered signal at the ith sampling point; and dt is the sampling interval. The implementation of the subblock #1 to #4 in Fig. 2(a) is shown in Fig. 2(b). Similar to the proposed fiber impairment compensation in [3], the SOA impairment compensation consists of basic multiplications, summations, and exponential calculations, and thus, the fiber and SOA impairment compensations can be implemented jointly in digital domain using DSP or application-specific integrated circuits (ASIC) with multiplication-accumulation



(a)



(b)

Fig. 2. (a) Block diagram for the implementation of SOA impairment compensation. (b) Block diagram for subblocks #1 to #4 in (a).

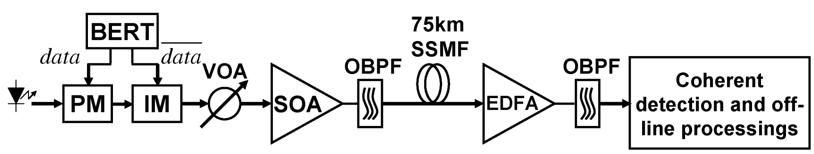


Fig. 3. Experimental setup for 4-APSK transmission with joint fiber and SOA impairments compensation. BERT: bit-error-ratio tester; PM: phase modulator; IM: intensity modulator; VOA: variable optical attenuator; OBPF: optical bandpass filter.

(*MAC*) units and lookup tables. The proposed algorithm for SOA impairment compensation is rather effective. The required calculations for compensating SOA impairments of one sample of the input signal include merely 25 multiplications, 22 summations, and seven lookups.

3. Experimental Setup

Fig. 3 shows the experimental setup for a four-level amplitude-phase-shift keying (4-APSK) transmission experiment over 75-km standard single-mode fiber (SSMF) with joint fiber and SOA impairment compensations. An optical 10-Gb/s binary phase-shift keying (BPSK) signal was first generated by phase-modulating a 1550-nm DFB laser with an electrical 10-Gb/s $2^{31}-1$ pseudo-random binary sequence (PRBS) non-return-to-zero (NRZ) data from a bit-error-ratio tester (BERT). Then, the optical 10-GBd or 20-Gb/s 4-APSK signal was generated by intensity modulating the optical 10-Gb/s BPSK signal with a complementary electrical 10-Gb/s NRZ data from the BERT. A 100-bit delay was introduced between the two complementary electrical NRZ signals for decorrelation. When both the phase modulator and the intensity modulator were properly biased, the optical 4-APSK signal had two amplitude levels (1, 3) and two phase levels (0, π). A 1550-nm low-tensile-strained bulk SOA having a noise figure of $\sim$7 dB was used as a booster amplifier, followed by an optical bandpass filter

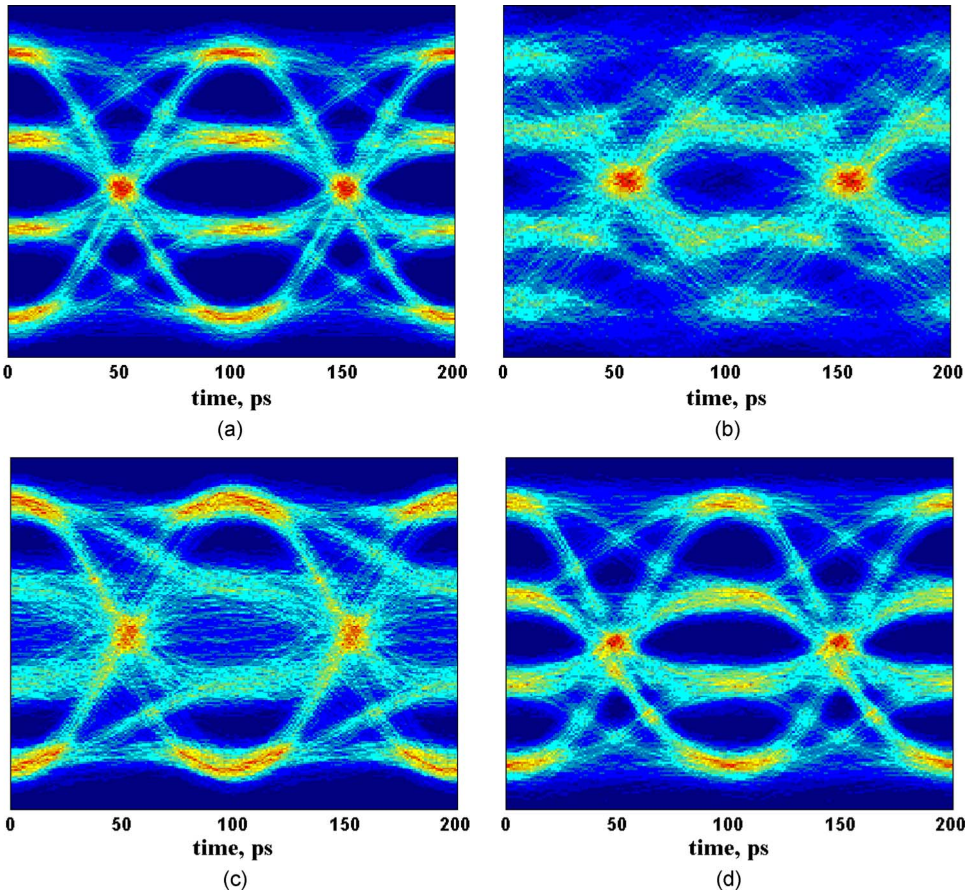


Fig. 4. Eye diagram of the 4-APSK signal. (a) Back-to-back; (b) after SOA and 75-km SSMF without fiber and SOA impairment compensations; after SOA and 75-km SSMF; (c) with only fiber impairment compensation; (d) with both fiber and SOA impairment compensations. (*y*-axis: amplitude, a.u.).

(OBPF) to remove the out-of-band ASE noise. At the injection current of 120 mA, the SOA had a small signal gain of 23.5 dB and 3-dB saturation output power of 4.0 dBm. The OBPF had a 3-dB bandwidth of 1 nm and insertion loss of 1.4 dB. A variable optical attenuator was used to control the power into the SOA, thus launching power into fiber. The measured loss of the 75-km SSMF was 17.7 dB. An EDFA operating in the power mode was used as a preamplifier, followed by another 1-nm OBPF to remove the extra ASE noise. Since the APSK signal is phase-modulated, coherent detection has to be used. The coherent receiver consists of an optical local oscillator, a 90° optical hybrid, photodetectors, and electrical preamplifiers. After coherent detection and at different input powers to the SOA, both in-phase and quadrature components of the electrical fields of the received optical signals were sampled and recorded at 40-GSa/s or 4-Sa/Symbol by analog-to-digital converters (ADCs) with a resolution of 8 bits in a real-time sampling oscilloscope. The signal powers at the output of the SOA and the end of the fiber were also measured using an optical power meter. Fiber and SOA impairment compensations were implemented offline in the software domain.

4. Experimental Results

Fig. 4(a) shows the back-to-back eye diagram of the 10-GBd 4-APSK signal after coherent detection and phase estimation. Four Amplitude levels were clearly observed. Fig. 4(b) shows the eye diagram of the received signal without fiber and SOA impairment compensations when the input power to SOA was -20 dBm. The signal was distorted significantly by SOA and fiber impairments

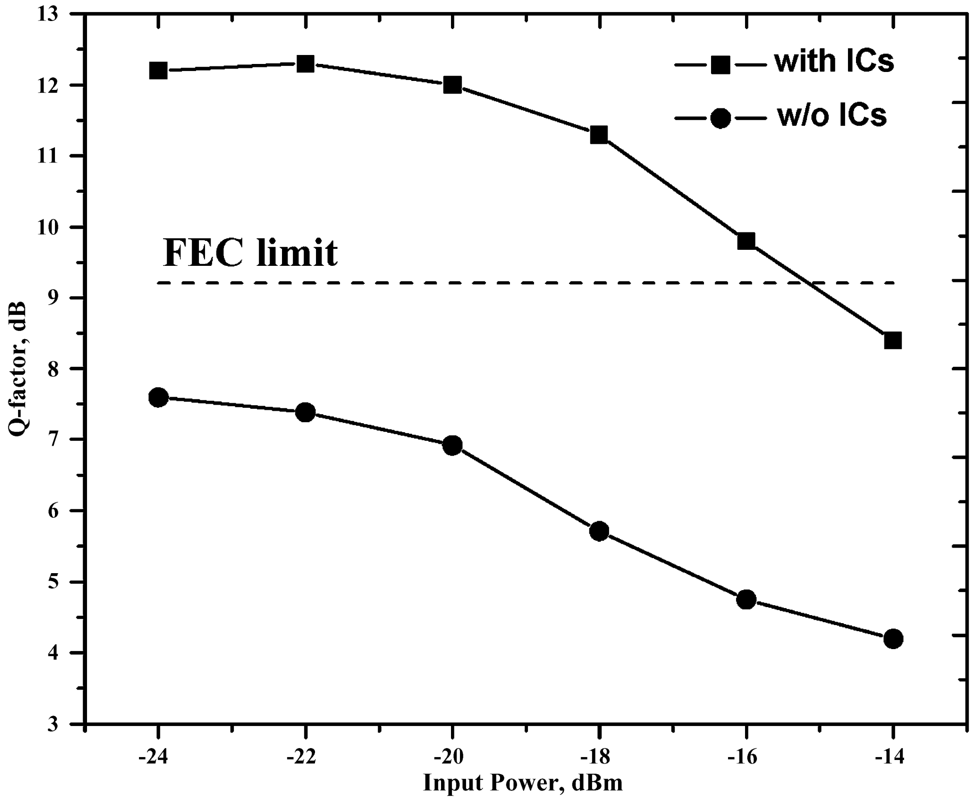


Fig. 5. Q-factor of the received 4-APSK signal versus input power to SOA.

such as data pattern effect and chromatic dispersion. To compensate the fiber impairment effectively, a step size of 15 km was used in solving *NLSE*. The eye diagram of the received signal after fiber impairment compensation is shown in Fig. 4(c). The improvement compared with the signal in Fig. 4(b) was mainly because fiber dispersion was compensated. Fig. 4(d) shows the eye diagram of the signal after both fiber and SOA impairment compensation. It had four clean amplitude levels, similar to the back-to-back signal indicating both amplitude and phase distortions induced through the fiber and SOA were compensated effectively.

The dependence of the calculated Q-factor (average of the Q-factors of the three eyes) of the 4-APSK signal with and without fiber and SOA impairment compensation on the input power to the SOA is shown in Fig. 5. The effectiveness of fiber and SOA impairment compensation is limited by the ASE noise of SOA at low input powers and the imperfect SOA impairment compensation at high input powers, respectively. The optimum input power to SOA is -22 dBm with the Q-factor of 12.3 dB, which is $\sim$5 dB greater than that without fiber and SOA impairment compensation and well above the Q-factor level corresponding to the forward error correction (FEC) limit. At each input power to SOA, both carrier lifetime (τ_c) and chirp factor (α_H) of the SOA were optimized through global search by maximizing the Q-factor of the signals after fiber and SOA impairment compensations. Fig. 6 shows the optimized carrier lifetimes and chirp factors used for SOA impairment compensation at different input powers. It is noted that all the optimized carrier lifetimes and chirp factors are in the range of 80–200 ps and 4–7, respectively, which are the typical numbers of the conventional bulk SOAs [10].

5. Conclusion

Joint fiber and SOA impairment compensation has been proposed and experimentally demonstrated for an optical 10-GBd 4-APSK transmission system. The compensations of fiber and SOA

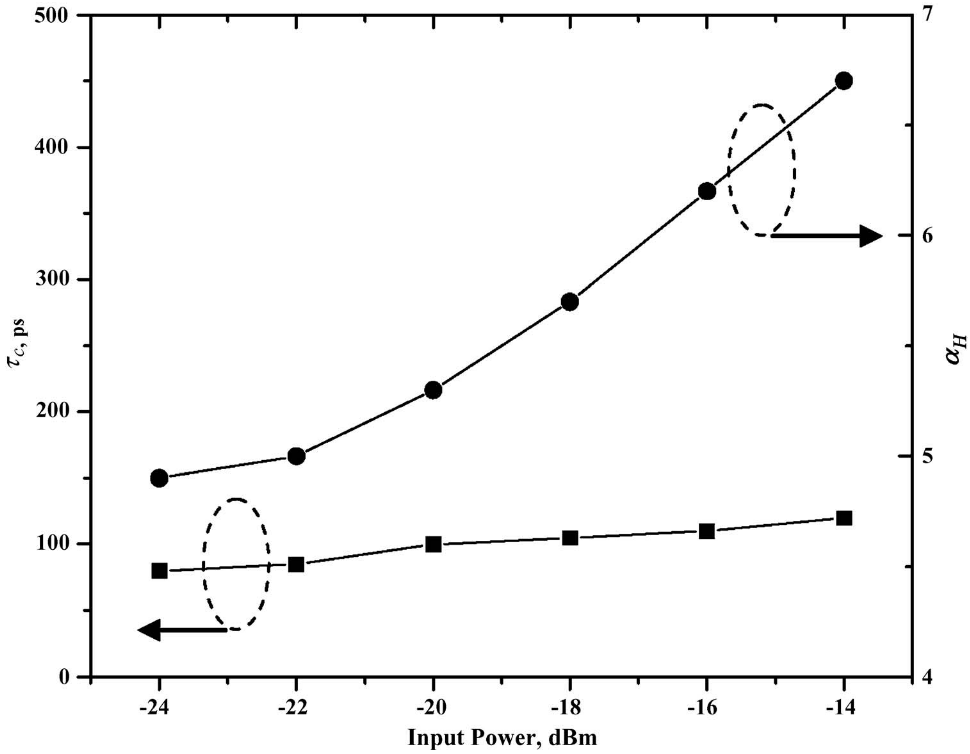


Fig. 6. Optimized τ_c and α_H versus input power to SOA.

impairments are both based on the digital backward propagation method and can be accomplished jointly in the electrical domain after coherent detection. Joint fiber and SOA impairment compensations can be realized by multiplications, summations, and exponential calculations and, thus, can be implemented using DSP technique in digital domain.

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