All-Optical Regeneration for Ultra-Long Fiber Links and its Prospects for Future Applications with New Modulation Formats

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Abstract: We will discuss all-optical regeneration technologies in ultra-long fiber communication links and investigate prospects for spectrally efficient modulation formats. Future modulation schemes with novel re-generation techniques will also be discussed.

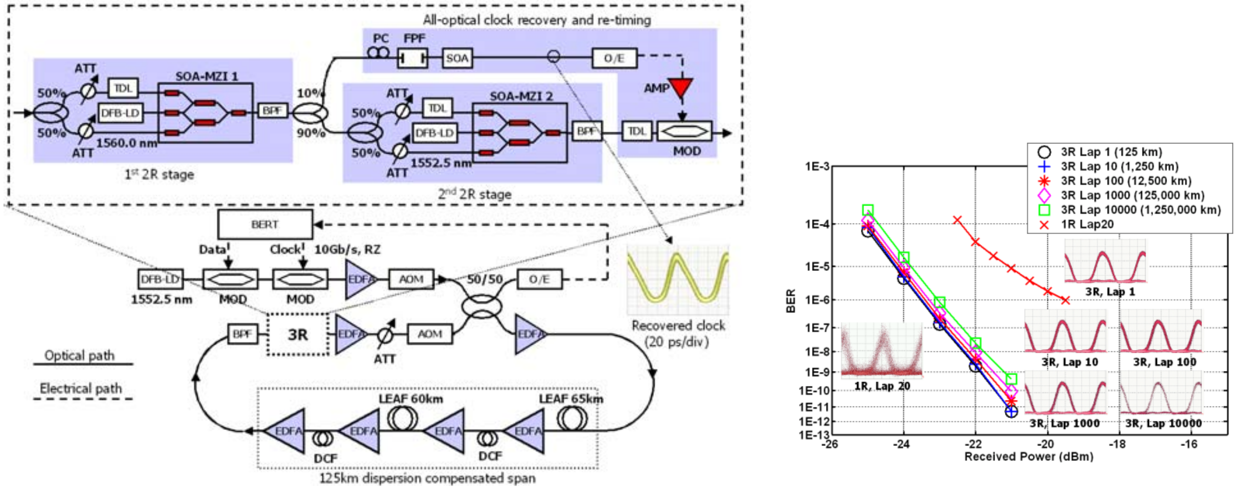
OCIS codes: (060.4510) Optical communications;

1. Introduction

All-optical regeneration in ultra-long fiber links can potentially bring significant cost savings due to reduced power and size requirements, especially at high-data rates, where electronics suffer power inefficiency and high electro-magnetic interference in multi-channel configuration. Today's optical regenerators typically include high-speed electronics with optical-to-electrical and electrical-to-optical interfaces as included in each 'card' for each wave-length. Thus ultra-long fiber link transmission system will include many such cards for as many wavelengths included in a system repeated many times over the long haul. Thermo-electric coolers (TEC) alone in such systems are repeated 2~3 times the product of the number of wavelengths and the number of repeaters. All-optical regenera-tion with photonic integration on an InP platform or even photonic-electronic integration on a silicon CMOS platform can realize orders of magnitude reduction in power consumption, and at the same time allow miniaturiza-tion in multi-channel packages without concerns for EMI. Optical regenerators involving passive optics, lasers, and regeneration units can all be realized on an InP or similar material platform(s) to achieve monolithic or hybrid integration on a single TEC. Since there are no real concerns for EMI between optical carriers in such optical components or waveguides, the packaging can utilize relatively dense packing or even overlapped packing exploit-ing parallelism of optics. The recent demonstration of 1.25 million km fiber transmission with 10,000 hops of all-optical regeneration [1] is one of the examples. More importantly, multi-channel regeneration blocks can be inte-grated on a single monolithic platform on a single TEC in a single package. Utilizing advanced all-optical regeneration using such a multi-channel packaging can be a disruptive technology reducing the power and size footprint by two orders of magnitude or better. On the other hand, recent efforts in ***spectrally-efficient advanced modulation format*** transmission has focused on high-datarate and repeaterless transmission using exploiting For-ward-Error-Correction (FEC) and Digital Signal Processing (DSP). While such high-speed electronics are power hungry and costly, ultra-long reach repeaterless distance achievable at high data rates is extremely attractive. Indeed, recent demonstrations have led to repeaterless transmission of 107 Gb/s on DQPSK over 504 km field fiber [2] using DSP and FEC. Hence, the next frontier for all-optical regeneration is to support advanced modulation formats with multi-level coding in amplitude and phase. This paper reviews progress of all-optical regeneration and its future prospects for long haul communications using spectrally-efficient data formats.

2. All-Optical Regeneration

We concentrate our discussions on 2R and 3R regeneration (reamplification, reshaping, and retiming) for all-optical regeneration with prospects for achieving such regeneration in both amplitude and phase (real and imaginary) domains. All-optical regeneration helps mitigate accumulation of noise, but it does not reduce the bit-error-rate by itself at a single stage, thus the regenerator spacing is an important parameter. For amplitude modulation, semicon-ductor optical amplifier (SOA)-based Mach-Zehnder interferometers have been popularly adopted for data rates up to 40 Gb/s. For data rates beyond 40 Gb/s, ultrafast mechanisms in optical fibers or polarization rotation in SOAs are commonly used. Optical regeneration and wavelength conversion often use identical mechanisms since they both exploit a three-port architecture involving input, output, and control (or probe) signals. In optical regeneration, however, wavelength conversion should be avoided to maintain its channel wavelength over the transmission distance. Two-step wavelength conversion or directional-coupler based regenerators are used to achieve this re-quirement. All optical regeneration schemes for amplitude-modulated signals induce some amount of unintended amplitude-to-phase crosstalk, which will induce jitter [3]. This is particularly pronounced for SOA based regenerators involving optical carrier dynamics. Thus regeneration with retiming will be essential for optical regeneration at high data rates. Figure 1 (a) shows an experimental setup of 1.25 million km transmission experiment for 10 Gb/s RZ-OOK modulation format involving SOA-MZI stages for 2R regeneration, fiber Fabry-Perot with SOA for all-optical clock recovery, and a pulse carver for retiming. In the future all-optical pulse carver can be implemented. Figure 1 (b) shows resulting BER and eye diagram indicating excellent performance up to 1.25 million km [3].



(a) (b)

Figure 1 (a) Experimental setup for evaluating the optical 3R regenerator in a 125 km fiber recirculation loop; DFB-LD: DFB laser diode, Mod: LiNbO3 optical modulator; BERT: Bit-error-rate tester; EDFA: Erbium-doped fiber amplifier; AOM: Acoustic optical modulator; O/E: Optical-to-electrical converter; DCF: Dispersion-compensating fiber; BPF: Band-pass filter; ATT: Variable attenuator; TDL: Tunable delay line; SOA-MZI: Semiconductor optical amplifier based Mach-Zehnder interferometer; PC: Polarization controller; FPF: Fabry-Perot filter; SOA: Semiconductor optical amplifier; AMP: RF amplifier. (b) BER measurement results and eye-diagram evolution for transmission distance from 125 km to 1,250,000 km with 3R regeneration and 2,500 km transmission with 1R regeneration[3].

For phase shifted keying (PSK) signals such as DPSK, phase-sensitive amplification schemes such as phase sensitive parametric amplification in nonlinear materials such as HNLF, Four-Wave-Mixing with spectral filtering, or phase modulation schemes using spectral filtering have been utilized. Figure 2 (a) shows the cross-phase modulation based optical 3R regeneration [4], and (b) and (c) show eye diagrams from the FWM based simultaneous regeneration of RZ-OOK and RZ-DPSK signals in a stream [5]. Recently

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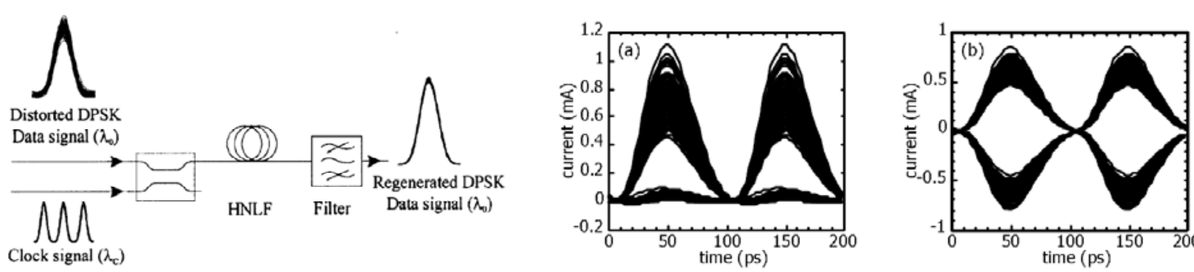

(a) (b) (c)

Figure 2 (a) 3R regeneration using cross-phase modulation based optical 3R regeneration [4], and (b) eye diagrams from the FWM based simultaneous regeneration of RZ-OOK and (c) RZ-DPSK signals in a stream [5].

However, none of these schemes support optical regeneration of arbitrary data modulation formats [6]. Recent studies on arbitrary waveform generation [7] [8] and measurement [9] give an interesting new direction for seeking all-optical regeneration for arbitrary data formats. Figure 3 shows arbitrary data formats [6]. In one of the configurations for OAWG, nested Mach Zehnder interferometer structure with limiting components can be implemented to realize high-fidelity optical regeneration for both in-phase and quadrature-phase components of the optical signal [10]. Normally such a nested MZI structure is used for multi-format modulations, but insertion of nonlinear element allows its application in arbitrary format all-optical regenerators. The details of the design, simulation results, and experimental results will be discussed.

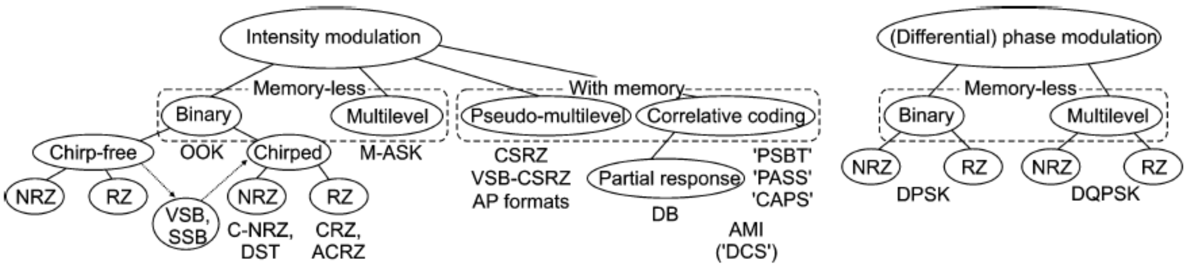

Figure 3 Classification of the most important intensity and phase modulation formats discussed in optical communications today. (N)RZ: (non)return to zero; VSB: vestigial sideband; SSB: single sideband; OOK: on/off keying; C-NRZ: chirped NRZ; DST: dispersion-supported transmission; (A)CRZ: (alternate) chirped RZ; CSRZ: carrier-suppressed RZ; AP: alternate phase; DB: duobinary; PSBT: phase-shaped binary transmission; PASS: phased amplitude-shift signaling; CAPS: combined amplitude phase-shift coding; AMI: alternate-mark inversion; DCS: DB carrier suppressed; M-ASK: multilevel amplitude-shift keying; DPSK: differential phase-shift keying; DQPSK: differential quadrature phase-shift keying. From[6]

4. Summary

We will review viable all optical regeneration techniques for ultra long haul communications, and will investigate methods to support future advanced modulation formats.

5. References

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