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Experimental demonstration of all-optical 2R regeneration at 10 Gb/s In a novel MMI-SOA based device

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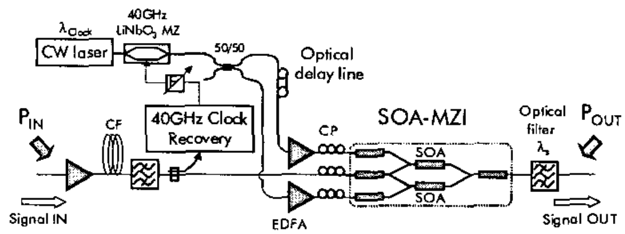


TuN1 Fig. 3. Experimental set-up of the 40 Gbit/s all-optical regenerator based on SOA-MZI-induced synchronous modulation.

vides a noise/jitter-free signal pulse train at the input of the first conversion stage (i.e. first MZ-SOA). Note that output wavelength can differ or not from the input one with an inverted polarity or not. Moreover, this structure is compatible with both RZ and NRZ formats.

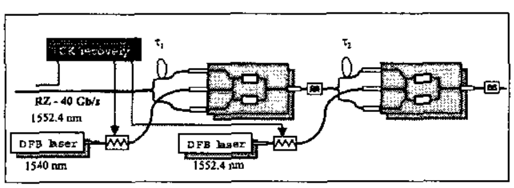
Using the 3R regenerator the basic layout of which is shown in fig. 4, Optical Regeneration at 40 Gbit/s was successfully demonstrated by means of the penalty-free cascade of more than 100 regenerators,[23] as illustrated on fig. 5. In this experiment, both MZ-SOA devices were used in differential mode,[24] as to improve the regenerator speed of operation. Based on the same concept of Wavelength Conversion for Optical 3R Regeneration, many 3R devices have been proposed[25] and validated at rates up to 84 Gbit/s,[26] but with cascadability issue still to be demonstrated.

Other key-point concerns the investigation of all-optical clock recovery circuits, which represent key elements for the completion of all-optical integrated structures. Such devices can be based on a self-pulsating (SP) DFB laser which have been shown to operate either at high bit rate (40 Gbit/s)[27] or with a very fast locking time (less than 2 ns). This last feature of SP laser paves the way for the fabrication of regenerators operating in asynchronous regime, as first validated at 10 Gbit/s through loop experiments.[28]

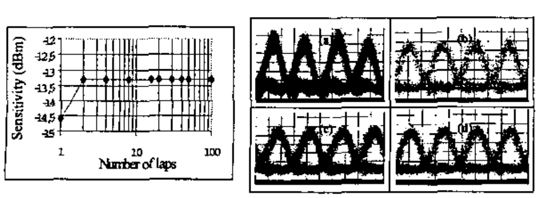
Conclusion

In this paper, two complementary techniques for Optical 3R Regeneration implementation have been described. The first one is based on Synchronous Modulation and is dedicated to ultra long-haul transmission applications. It was shown to be fully compatible with Dispersion Management, allowing a 4 × 40 Gbit/s transmission over 10,000 km representing the only reported WDM transmission over such long distance with 40 Gbit/s line-rate to date. Key results have also been reported as to further illustrate the potential of this technique. The second approach is based on Wavelength Conversion and uses the nonlinear transfer function resulting from the cascade of two SOA-based Mach-Zehnder interferometers. Its regenerative properties have been demonstrated at 40 Gbit/s through loop experiment and burst mode operation was assessed at 10 Gbit/s.

Optical 3R Regeneration at higher bit rate was also considered through a possible evolution towards pure all-optical processing based on new clock recovery devices and optically-controlled interferometers such as SOA-MZI devices. Further developments of such all-optical devices associated with 3R concepts should soon lead to new classes of 40 Gbit/s-based- undersea systems and terrestrial networks with multi-terabit capacities.



TuN1 Fig. 4. Structure of the 40 Gbit/s SOA-based 3R regenerator



TuN1 Fig. 5. (left) Evolution sensitivity & (right) 40 Gbit/s eye diagram evolution: (a) B-to-B, (b) 1 lap, (c) 10 laps, (d) 100 laps.

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TuN2 2:30 pm

Experimental demonstration of all-optical 2R regeneration at 10 Gb/s in a novel MMI-SOA based device

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1. Introduction

All-optical regeneration will be a key functionality in future high-speed networks, since the detrimental effects of ASE- and jitter accumulation, as well as fiber dispersion, will put a strict limit on the size of the network.[1] The ideal regenerator would be an all-optical device capable of performing 3R regeneration on a number of WDM channels simultaneously. However, this would require temporal synchronization of all the channels, as well as a regeneration scheme very tolerant towards power level and cross-talk.[2] These issues may be solved in the future, but until then regeneration will have to be performed on each channel separately. This puts very stringent requirements on the physical size and power consumption of each regenerator, if they are to be integrated on a single chip. In most of the regeneration schemes reported so far, e.g. using all-active Michelson (MI) or Mach-Zehnder (MZI) interferometers, simultaneous wavelength conversion to a CW or clock signal is an inherent property.[3] This is an advantage in a scenario where wavelength conversion is required anyway, but if the conversion is not desirable, an additional wavelength converter is needed to return to the original input wavelength.[3] This complicates integration, and increases the physical size of the device considerably. So-called pass-through 2R regeneration schemes, in which wavelength conversion is not performed, have been demonstrated at up to 40 Gb/s using the MI and MZI.[4] In these schemes the data signal does not interact with additional signals, which means that a CW or clock source can be avoided at the input, and a filter is no longer needed at the output. This greatly reduces complexity and enables integration of a large number of regenerators for use in parts of the network where wavelength conversion is not necessary.

In this paper we show the first dynamic measurements at 10 Gb/s on a novel type of all-optical pass-through type 2R regenerator based on an all-active 2 × 2 multimode interference coupler (MMI-SOA). The device is very compact compared to the MZI 2R regenerator and has a digital-like transfer function,[5] which enables a more effective noise suppression in the logical zero level.

2. Principle of operation

As shown in Fig. 1a), the signal is launched into one of the inputs of the 2 × 2 MMI-SOA where it excites a subset of the eigenmodes supported by the wide waveguide. The excited eigenmodes will interfere as they propagate through the MMI, causing the lateral intensity pattern of the total excited field to produce periodic direct and mirrored self-images.[6] The propagation constants identifying the different eigenmodes depend on the lateral carrier density profile, which in turn is influenced by the input power. The length of the device is chosen such that, for input powers below the input saturation power, a mirrored self-image appears at the input of the cross-state exit-waveguide, causing all the signal power to be coupled out here. In other words the output field will interfere destructively at the input of the bar-state exit waveguide, and a minimum of power will exit through this port. As the input power is increased, the carrier density starts to saturate. This changes the real as well as the imaginary parts of the eigenmode propagation constants, causing a change of the relative phase relationship between the modes. As a result, the output field will evolve from interfering destructively at low input powers, to gradually interfere constructively in front of the bar-state exit waveguide. Accordingly, the amount of power coupled out of the bar-state waveguide increases with the input power, and since this increase is highly nonlinear, regeneration can be obtained.

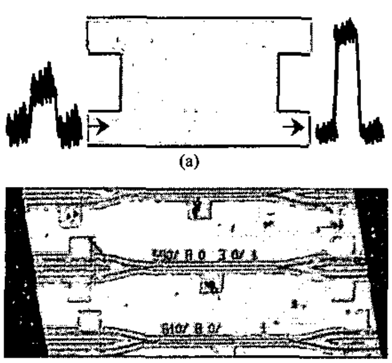
3. Static modeling, design, and characterization

To assist in the design of the MMI-SOA, a simulator based on the finite difference beam propagation method (FD-BPM) has been developed. It takes into account the inhomogeneous mode excitation by the ASE, as well as the lateral carrier diffusion in the active layer of the device. These effects are important since they influence the self-imaging properties of the MMI-SOA. Based on the modeling, it was concluded that the width of the input waveguides should be as large as 3 µm for an MMI width of 8 µm, to obtain a sufficiently tolerant MMI design. The MMI-SOAs were fabricated with an active region consisting of eight 8 nm thick compressively strained quantum wells. Additional details about the fabrication process can be found in.[5] In this reference a comparison of the simulated and measured transfer functions can also be found, and it was reported there that a static output extinction ratio (ER) of 22 dB could be achieved for an input ER of 7 dB.

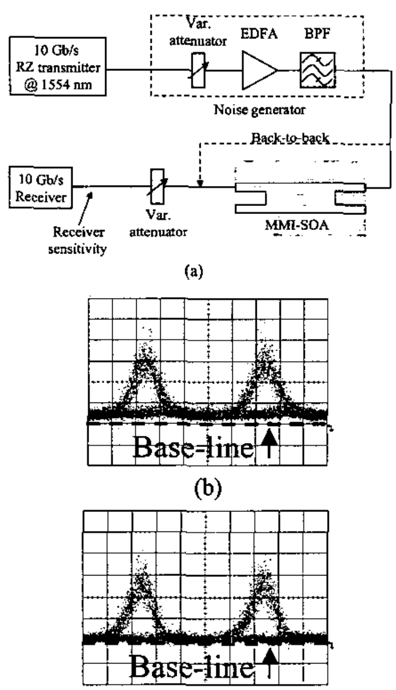
4. Dynamic measurements at 10 Gb/s

Dynamic measurements at 10 Gb/s were performed on an MMI-SOA with a length of 550 µm. Including the access waveguides, this makes the total structure only ~1.5 mm long. Fig. 2a) shows the experimental setup used in the measurements. The data signal is generated by modulating a 10 GHz pulse train from a gain-switched DFB laser, emitting at a wavelength of 1554 nm, with a PRBS sequence of word length $2^{31}-1$. The signal is first passed through a noise generator consisting of a variable attenuator followed by an EDFA and an optical bandpass filter. By controlling the amount of signal power launched into the EDFA, the output optical signal-to-noise ratio (OSNR) can be varied. The signal then traverses the MMI-SOA, using lensed fibers to couple the light in and out of the chip. Finally, the signal is detected in a pre-amplified receiver.

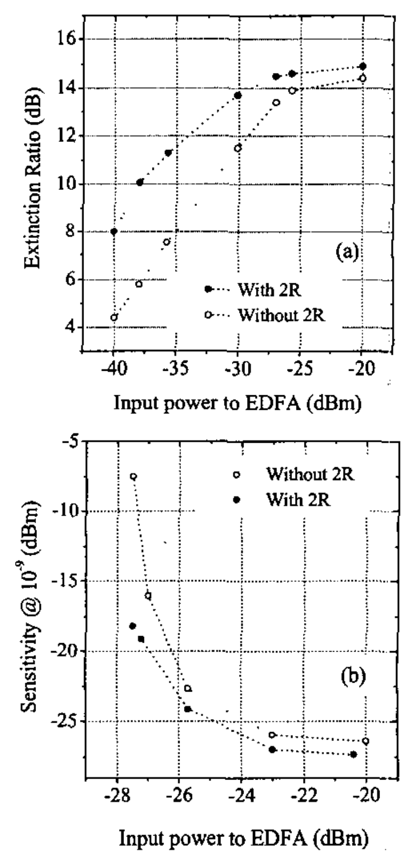
As the input power to the EDFA is decreased the OSNR obviously decreases. At the same time



TuN2 Fig. 1. (a) Schematic of device layout and operation principle, (b) photograph of chip



TuN2 Fig. 2. (a) Experimental setup for the 2R regeneration scheme using the MMI-SOA. The dashed arrow indicates the back-to-back setup. (b) Back-to back eye diagram of signal + added noise, and c) the same eye diagram using the MMI-SOA.



TuN2 Fig. 3. (a) Extinction ratio with and without the 2R regenerator, (b) Receiver sensitivity with and without 2R regenerator. Both as a function of input power to the noise generating EDFA.

the ER decreases, since the unmodulated ASE generated by the EDFA adds to the base-line of the signal. This is clearly seen in Fig. 2b), which shows an optical eye diagram withoutusing the MMI-SOA. Fig. 2c) shows the eye diagram of the same signal, after it has traversed the MMI-SOA, and a clear suppression of the zero-level is observed. In Fig. 3a) the ER of the signal is shown as a function of the input power to the EDFA, both with the MMI-SOA in the system (solid circles) and without it (hollow circles). The ER improvement obtained by using the MMI-SOA is observed to be significant.

The noise suppression capabilities of the MMI-SOA are demonstrated in Fig. 3b) where the receiver sensitivity is shown with (solid circles) and without regeneration (hollow circles), as a function of the input power to the EDFA. Clear signal regeneration is observed, which is a verification that noise suppression has taken place: from Fig. 3a) it is seen that an input power to the EDFA of −27.5 dBm gives rise to an ER of ~13 dB without regeneration and ~14.5 dB with regeneration. This modest ER improvement does not by itself give rise to any noticeable sensitivity improvement,[7] so it is clear that the improvement of more than 10 dB observed in Fig. 3b) is predominantly due to noise suppression.

5. Conclusions

We have shown the first demonstration of 2R pass-through regeneration of a 10 Gb/s data signal in an MMI-SOA. The measurements show extinction ratio improvement as well as sensitivity improvement. The latter is predominately due to noise suppression. The good high-speed performance, along with the compact and simple design, makes this a promising device.

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TuN3 **2:45 pm**

Novel Polarization-Insensitive Synchronous Modulator for 20 Gbit/s All-Optical Regeneration

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For high bit-rate long haul point to point transmission systems (20 Gbit/s and higher), 3R regeneration (Re-amplification, Re-timing and Re-shaping) might be soon required as a means to overcome physical limitations and hence to improve system margins and/or transmission distances. In that respect, the Optical Regeneration technique of Synchronous Modulation (SM) appears as a key technology for suitably controlling the signal characteristics but also to enhance or restore the signal-to-noise ratio.[1] Indeed, intensity synchronous modulation (IM) and narrow-band filtering have been demonstrated to both reduce timing jitter and to efficiently block noise accumulation, thus enabling error-free propagation over 10,000 km at high bit-rates.[2–3]

In this paper, we demonstrate for the first time the use of a Saturable Absorber[4] as an all-optical Synchronous Modulator. This all-optical regenerator is then implemented in a 20 Gbit/s regenerated loop transmission and is shown to enable error-free Dispersion Managed propagation over 10,000 km.

All-Optical Regenerator based on Saturable Absorber

Figure 1 shows the all-optical scheme for 20 Gbit/s 3R regeneration incorporating a semiconductor Saturable Absorber (SA).

The saturable absorber is a metalorganic vapor phase epitaxy-grown (MOVPE) structure including 9 InGaAs/InP quantum wells. It is inserted in a vertical cavity whose one side is an Ag mirror. The device is used in reflection mode thanks to a circulator. Intrinsic polarization-insensitive operation results from light input at normal incidence. Experimental characterizations have been conducted to evaluate the polarization sensitivity of the SA-based regenerator, resulting in measured values lower than 0.3 dB.

A sine optical clock and the to-be-regenerated signal are simultaneously launched in the SA with a clock power level 15 dB greater. Under this condition, transmittance of the Saturable Absorber is mainly controlled by the external optical clock, which in turn induces an intensity modulation of the optical data signal. Synchronization is controlled by means of an optical delay line. At the operating frequency of 20 GHz, the SA-induced extinction ratio is measured to be greater than 3 dB at the signal wavelength after the output filter. Total insertion loss of this novel all-optical 3R regenerator is 10 dB (including circulator).

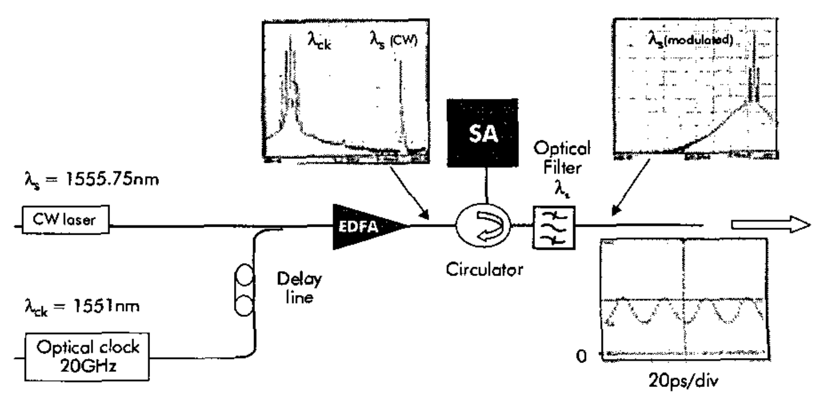
Such a Saturable Absorber-based regenerator exhibits several key advantages with respect to previously reported synchronous modulators. Indeed, since it is based on a fully passive SA component, no electric driving nor temperature control are required, resulting in significantly reduced power consumption.

20 Gbit/s regenerated loop transmission

As to evaluate the regenerative properties of this novel 3R regenerator, we implemented it into a loop experiment, whose configuration is shown in figure 2.

The recirculating loop consists of seven Dispersion Managed spans of TeraLight™ (D = +8 ps.nm^{-1}.km^{-1} chromatic dispersion at 1550 nm wavelength) and Reverse Dispersion Fiber© (RTL) (D = −16 ps.nm^{-1}.km^{-1}),[5] leading to a loop average dispersion of 0.01 ps.nm^{-1}.km^{-1}. Optimal Pre- and post-chirp fibers values are −64 and −213 ps.nm^{-1}, respectively. Span input power is set to be 0 dBm using in line 980 nm EDFA with 5 dB noise figure. Step Amplifier spacing (Z_A) is constant and set to 40 km. The 3R regenerator (Z_R) is located at a chirp free point and applied with 280 km periodicity (seven times Z_A).

The optical source is composed of a 10 GHz gain switched DFB emitting 20 ps optical pulses at 1555.75 nm wavelength. These pulses are then compressed down to 6 ps using −30 ps/nm Dispersion Compensating Fiber (DCF) and encoded with a 2^{31}−1 PRBS pattern at 10 Gbit/s prior to be optically time-multiplexed to provide 20 Gbit/s data stream. At the receiver end, Bit Error Rates (BER) are measured at 10 Gbit/s, after demultiplexing the 20 Gbit/s data stream using a polar-



TuN3 Fig. 1. Experimental setup of the novel polarization-insensitive regenerator for 20 Gbit/s all optical regeneration.