Contribution to the study of optical functions for signal regeneration in high-bit-rate transmission systems

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July 8, 2010



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Signal degradation in long-haul transmission

Generic optical transmission system



Communication channel: Optical fibers

Fiber impairments

- Fiber losses
- Fiber dispersion (chromatic dispersion, PMD)
- Nonlinear optical effects
- \Rightarrow Need for signal regeneration

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Optical signal regeneration



► 1R: reamplification



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Optical signal regeneration



- IR: reamplification
- ► 2R: reamplification + reshaping



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Optical signal regeneration



- IR: reamplification
- ► 2R: reamplification + reshaping
- ► 3R: reamplification + reshaping + retiming



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1R regeneration: erbium-doped fiber amplifier (EDFA)

© One device for all WDM channels, transparent to bit rate and modulation format

Optoelectronic repeater: up to 40 Gbit/s

☺ High electrical consumption



1R regeneration: erbium-doped fiber amplifier (EDFA)

© One device for all WDM channels, transparent to bit rate and modulation format

Optoelectronic repeater: up to 40 Gbit/s

😕 High electrical consumption

All-optical solutions for 2R and 3R regeneration

High-bit-rate applications (40 Gbit/s and higher)

© Good performance/complexity ratio; installation and operation: cost effective

© WDM compatible: one device for processing several channels, or high integration capability

 ${}^{\scriptsize (c)}$ Not technologically mature enough \Rightarrow need for research



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Objective: theoretical and experimental study of all-optical functions for signal regeneration in high-bit-rate transmission systems (42.7 Gbit/s and higher)

Key component: microcavity saturable absorber

- Short response time (<5 ps) \Rightarrow High-bit-rate operation
- Wide operating bandwidth (>20 nm)
- Simple (needs neither a bias voltage nor a temperature controller)
- WDM compatible (one chip for several WDM channels with spatial demultiplexing)



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Outline

Saturable absorber for WDM-compatible 2R regeneration

Principle of microcavity saturable absorber Simulation Experimental results

All-optical 3R regeneration based on synchronous modulation Principle of signal regeneration by synchronous modulation Architecture of the regenerator under study Cascadability evaluation experiment

Phase-shift-keying (PSK) signal regeneration

PSK signal regeneration Power limiter saturable absorber Experimental results

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Nonlinear transmission function of a 2R regenerator



2R regeneration

- Intensity noise reduction
- Extinction ratio improvement



Multiple quantum wells embedded in a microcavity



 R_f : Front mirror reflectivity η : MQW absorption coefficient R_b : Back mirror reflectivity

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Multiple quantum wells embedded in a microcavity



 R_f : Front mirror reflectivity η : MQW absorption coefficient R_b : Back mirror reflectivity

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Multiple quantum wells embedded in a microcavity



 R_f : Front mirror reflectivity η : MQW absorption coefficient R_b : Back mirror reflectivity

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Multiple quantum wells embedded in a microcavity

► Low input power: behaves like an anti-reflecting coating



- *R_f*: Front mirror reflectivity
- η : MQW absorption coefficient
- R_b: Back mirror reflectivity

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Multiple quantum wells embedded in a microcavity

- Low input power: behaves like an anti-reflecting coating
- ► High input power: behaves like a partially reflective mirror



- *R_f*: Front mirror reflectivity
- η : MQW absorption coefficient
- R_b: Back mirror reflectivity

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Multiple quantum wells embedded in a microcavity

- Low input power: behaves like an anti-reflecting coating
- High input power: behaves like a partially reflective mirror



- *R*_f: Front mirror reflectivity
- η : MQW absorption coefficient
- *R_b*: Back mirror reflectivity

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 R_{f} : front mirror reflectivity R_{b} : back mirror reflectivity η : QW absorption coefficient

Characteristics

- Resonance wavelength in C band
- Nonlinear absorption: saturation of excitonic absorption ⇒ η(P_{in}) decreases with input power
- ► Heavy ion (Ni⁶⁺) irradiation ⇒ recovery time of <5 ps, suitable for high-bit-rate operation

¹By **UPN:** D. Massoubre *et al., Appl. Phys. Lett.*, 2006, vol. 88, p.153513 July 8, 2010 Thesis defense



Experimental transmission function





 \bigcirc Reflectivity increases with input power \Rightarrow extinction ratio enhancement

^(C) Needs a complementary function for a full 2R regeneration

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Experimental transmission function

Signal: ASK, RZ 33%, 42.7 Gbit/s, 1547 nm



Seflectivity increases with input power \Rightarrow extinction in enhancement

Needs a complementary function for a full 2R regeneration

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Saturable absorber



Extinction ratio enhancement
 Increase of intensity
 fluctuation on mark level



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Saturable absorber



Extinction ratio enhancement
 Increase of intensity
 fluctuation on mark level

Power limiter



Intensity noise reduction on mark level



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Saturable absorber



Extinction ratio enhancement
 Increase of intensity
 fluctuation on mark level

Power limiter



Intensity noise reduction on mark level

⇒ Saturable absorber+Power limiter=full 2R regeneration

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Complementary function (2)

SOA²



 High integration capacity, wide amplification spectrum
 Operation limited to 10 Gbit/s by SOA recovery time

²M. Gay et al., Photon. Tech. Lett., vol. 18, p. 1273, 2006 ³D. Rouvillain et al., OFC, 2002, Anaheim, California, FD11 July 8, 2010 Thesis defense



Complementary function (2)

SOA²



 High integration capacity, wide amplification spectrum
 Operation limited to 10 Gbit/s by SOA recovery time

SPM + centered filtering³



⊗ Low integration capacity
 ☺ High-bit-rate operation (Kerr effect)
 ⇒ used in this thesis

²M. Gay et al., Photon. Tech. Lett., vol. 18, p. 1273, 2006 ³D. Rouvillain et al., OFC, 2002, Anaheim, California, FD11 July 8, 2010 Thesis defense



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Principle of operation: SPM-based power limiter



Operating conditions

- Power limiting: $\Delta f_{max@P_{sat}}$ =Filter BW (ΔF)
- Minimum chirp (C): Soliton regime

⇒ Original analytical method for optimization of regenerator parameters: Fiber (γ , D, Length), P_{sat} , Contrast_{SA}, Filter BW **Fotom**

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Simulation: 2R regenerated transmission link



- Signal: RZ 33%, 42.7 Gbit/s
- OSNR 23 dB (over 1 nm)
- N: No. of laps
- Regenerator parameters γ=2.1 rad/W/km, D=4.2 ps/nm/km, L=2.4 km, P_{sat}=18.3 dBm, Contrast=5 dB, Filter BW=1.2 nm

Simulation results



Distance improvement ratio (at a given Q factor)

$$DIR = \frac{N_{with \ 2R}}{N_{w/o \ 2R}}$$



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WDM regeneration:

Regenerator performance vs. signal wavelength

Regenerator bandwidth:

- SA bandwidth (>20 nm)
- SPM-based power limiter bandwidth
 - + Need for soliton: 2R
 performance depends on D
 + Wavelength dependence:
 fiber dispersion (D) changes
 with wavelength

Simulation results

- ▶ L=2.4 km, P_{sat}=18.3 dBm
- D=4.2 ps/nm/km@1550 nm
- D slope 0.1 ps/nm²/km



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Fiber-coupling technique



French national project ASTERIX:

SA chip: LPN, 3-5 Lab, IEF Fiber array: Yenista Optics Packaging: Foton/Persyst

Description

- ► A special micro-lensed fiber array: 8 independent fibers
- Fiber array is fixed to the SA mirror with an UV adhesive
- Mode field diameter 4.5 μ m

Packaged device: very stable

 \bigcirc Simultaneous processing of eight channels on <1 mm² July 8, 2010 Thesis defense







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▶ Signal: RZ 33%, 42.7 Gbit/s, PRBS 2³¹ − 1



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▶ Signal: RZ 33%, 42.7 Gbit/s, PRBS 2³¹ − 1

 100 km NZ DSF, 4.5 ps/nm/km @ 1550 nm, erbium amplification



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- ▶ Signal: RZ 33%, 42.7 Gbit/s, PRBS 2³¹ − 1
- 100 km NZ DSF, 4.5 ps/nm/km @ 1550 nm, erbium amplification
- ▶ 2R regenerator: SA + SPM and centered filtering



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Recirculating loop experiment



- ▶ Signal: RZ 33%, 42.7 Gbit/s, PRBS 2³¹ − 1
- 100 km NZ DSF, 4.5 ps/nm/km @ 1550 nm, erbium amplification
- 2R regenerator: SA + SPM and centered filtering
- ASE filtering and power balance control

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Experimental results 4 5

BER vs. transmission distance

DIR vs. signal wavelength

Channel 5



- ► Distance improvement ratio $DIR = \frac{Distance with regenerator}{Distance without regenerator}$
- DIR of 3 at BER of 10⁻⁴ over 13 nm
- Future prospectives: power limiter saturable absorber

⁴L. Bramerie *et al.*, *OFC*, Anaheim, California, 2007, PDP1 ⁵Q.T. Le *et al.*, *Electron. Lett.*, vol. 43, p. 1305, 2007 July 8, 2010 Thesis defense



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- Power limiter saturable absorber
- Experimental results

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Principle of signal regeneration by synchronous modulation

- Synchronous modulation for soliton transmission ⁶
- Linear transmission: 2R + synchronous modulation



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Principle of signal regeneration by synchronous modulation

- Synchronous modulation for soliton transmission ⁶
- Linear transmission: 2R + synchronous modulation



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Optoelectronic synchronous modulation + SPM-based 2R regeneration $^{\rm 7}$



Our experiment:

- Simple 2R regenerator with no wavelength shifting
- All-optical synchronous modulation performed by cross absorption modulation in a saturable absorber

⁷G. Raybon *et al.*, *OFC*, Anaheim, California, 2002, FD10 July 8, 2010 Thesis defense



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Architecture of the regenerator under study



All-optical 2R regenerator:

- Mark level equalization : SPM in fiber + centered filter
- Saturable absorber for extinction ratio enhancement

Synchronous modulation: cross absorption modulation while injecting an optical clock in saturable $absorber^8$



⁸D. Rouvillain *et al., OFC*, Anaheim, California, 2002, p. TuN3 July 8, 2010 Thesis defense

All-optical clock recovery



(French national project ROTOR)

Two self-pulsating semiconductor lasers

- Distributed Bragg reflector laser (DBR): polarization insensitive
- Quantum-Dot Fabry-Perot laser (QD): high quality of timing jitter filtering

 \Rightarrow A polarization insensitive and high performance optical clock recovery 9



⁹B. Lavigne *et al.*, *OFC*, Anaheim, California, 2006, PDP24 July 8, 2010 Thesis defense

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Recirculating loop experiment



▶ Signal: RZ 33% modulated at 42.7 Gbit/s, PRBS $2^{31} - 1$

- Two spans of 50 km NZ-DSF with dispersion of 4.5 ps/km/nm @ 1550 nm
- 10 dB Raman gain for each span



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BER vs. transmission distance¹⁰



Distance improvement ratio (DIR) at BER of 10^{-8}

- 2R regeneration: DIR=10
- 2R regeneration and synchronous modulation: DIR=22.5

¹⁰Q.T. Le *et al.*, *ECOC*, Berlin, Germany, 2007, Tu4.3.5 July 8, 2010 Thesis defense



BER vs. transmission distance¹⁰





 $BER = N.e^{-k.OSNR}$

Distance improvement ratio (DIR) at BER of 10^{-8}

- 2R regeneration: DIR=10
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¹⁰Q.T. Le *et al.*, *ECOC*, Berlin, Germany, 2007, Tu4.3.5 July 8, 2010 Thesis defense



Limitation of our technique: Gordon-Haus timing jitter (1)

Soliton in SPM-based 2R: Gordon-Haus timing jitter

ASE noise $\stackrel{SPM}{\rightarrow}$ Frequency fluctuation $\stackrel{CD}{\rightarrow}$ Arrival time fluctuations (timing jitter)

CD: Chromatic dispersion

Synchronous modulation (SM):





Limitation of our technique: Gordon-Haus timing jitter (1)

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CD: Chromatic dispersion

Synchronous modulation (SM):



• Attenuation of shifted pulses \Rightarrow detection errors

► Gordon-Haus timing jitter limit: low tolerance to ASE noise July 8, 2010 Thesis defense



Limitation of our technique: Gordon-Haus timing jitter (2)

Simulation: recirculating loop experiment

Pulse peak power vs. number of concatenated regenerators



- Signal: RZ 33%, 42.7 Gbit/s
- OSNR degradation
- N: No. of regenerators

OSNR=30 dB (over 1 nm)





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Limitation of our technique: Gordon-Haus timing jitter (2)

Simulation: recirculating loop experiment

Pulse peak power vs. number of concatenated regenerators



- Signal: RZ 33%, 42.7 Gbit/s
- OSNR degradation
- N: No. of regenerators

OSNR=25 dB (over 1 nm)



- ► Decaying pulses ⇒ detection errors
- Future prospectives: power limiter saturable absorber

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PSK system degradation

- Linear phase noise: amplified spontaneous emission
- Nonlinear phase noise: conversion of intensity noise into phase noise (SPM) (Gordon-Mollenauer effect¹¹)

Regeneration issues

 For a complete regeneration: both phase and amplitude regeneration needed

¹¹J.P. Gordon and L.F. Mollenauer, *Optics Lett.*, vol. 15, p. 1351, 1990 July 8, 2010 Thesis defense Possibilities: phase-sensitive interferometric techniques

- ▶ FWM in Mach Zehnder interferometer ¹²
- ► SOA in Sagnac interferometer ¹³
- 🙁 Complex, instability issues

¹²K. Croussore *et al.*, *Optics Letters*, vol. 29, p. 2357, 2004
¹³P. Devgan *et al.*, *OFC*, Anaheim, California, 2005, PDP34
¹⁴M. Matsumoto, *Photon. Technol. Lett.*, vol. 17, p. 8094, 2005
¹⁵K. Cvecek *et al.*, *Photon. Technol. Lett.*, vol. 18, p. 1801, 2006
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Possibilities: phase-sensitive interferometric techniques

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Phase-preserving amplitude regeneration

- \Rightarrow prevents the accumulation of nonlinear phase noise
 - FWM in fiber ¹⁴
 - Modified NOLM ¹⁵

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Here: microcavity saturable absorber

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¹³P. Devgan *et al.*, *OFC*, Anaheim, California, 2005, PDP34
¹⁴M. Matsumoto, *Photon. Technol. Lett.*, vol. 17, p. 8094, 2005
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Power limiter saturable absorber ¹⁶ ¹⁷

- SA.0 for extinction ratio enhancement (classical SA)
- ► SA.1 for power limiter function: modification of R_f



¹⁶Proposed by ¹⁶PiEF: S. Sauvage, patent FR2904438A1, WO2008012437A1, Feb 2008

¹⁷Developed by ⁽²⁾/₂LPN: H.T. Nguyen *et al.*, *Appl. Phys. Lett.*, 2008, vol. 92, p. 111107
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Experimental transmission function

- Signal: ASK, RZ 33%, 42.7 Gbit/s, 1547 nm
- Reflectivity decreases with input power \Rightarrow power limiter
- Low thickness \Rightarrow low phase-amplitude coupling





Simulation of a regenerated DPSK system

(%)

Amplitude jitter

-W/o SA

- With SA

200

rail w/o SA1

th SA



RZ 33% DPSK, 42.7 Gbit/s

- Launched power: 4 dBm
- Amplification span: 100 km
- Distance between regenerators: 200 km

Dhase jitter (ع) 0.00 200 800 1000 400 600 Transmission distance (km) Amplitude noise reduction \Rightarrow less nonlinear phase noise Foton accumulation Thesis defense

400

Transmission distance (km)

600

800

1000

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Experimental setup



- Transmitter : signal RZ 33% DPSK @ 42.7 Gbit/s, 1550 nm ASE source: OSNR degradation
- Transmission: 100 km of NZ DSF (4.5 ps/nm/km @ 1550 nm) + DCF

High launched power to generate enough nonlinear phase noise

Receiver: delay interferometer + balanced detection (DPSK demodulator)



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BER vs. receiver input power ¹⁸ ¹⁹



¹⁸Q.T. Le *et al.*, *OFC*, San Diego, California, 2010, OMT4
¹⁹Q.T. Le *et al.*, *Photon. Technol. Lett.*, vol. 22, p. 887, 2010
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BER vs. receiver input power ¹⁸ ¹⁹



SA.1 based amplitude regeneration \Rightarrow prevents the detrimental effect of nonlinear phase noise accumulation

¹⁸Q.T. Le *et al.*, *OFC*, San Diego, California, 2010, OMT4
¹⁹Q.T. Le *et al.*, *Photon. Technol. Lett.*, vol. 22, p. 887, 2010
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Recirculating loop experiment at 42.7 Gbit/s



Signal spectrum is distorted by the SA.1 resonance \Rightarrow A gain equalizer (EG) is required.

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BER vs. transmission distance ²⁰

- ▶ OSNR of 22.7 dB (over 1 nm), launched power of 13 dBm
- ▶ Distance improvement ratio of 1.6 obtained at BER of 10⁻⁴



²⁰Q.T. Le *et al.*, *ECOC*, 2010, accepted for oral presentation July 8, 2010 Thesis defense



WDM-compatible SA module

- First 8-channel SA module
- > 2R: SA + SPM in fiber and with centered filtering
- Demonstration of transmission distance improvement ratio of 3 obtained with all channels and over a 13-nm bandwidth
- However: operating bandwidth limited by SPM-based power limiter

Assessment of a novel power limiter saturable absorber

 Original technique for 2R regeneration based on saturable absorption devices



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3R regeneration by synchronous modulation

- Demonstration of the efficiency of all-optical synchronous modulation obtained by cross absorption modulation in a saturable absorber
- Distance improvement ratio of 22.5 achieved at 42.7 Gbit/s, and a significant margin obtained on receiver decision time
- However: performance limited by Gordon-Haus timing jitter in SPM-based power limiter
- Future prospectives: a better regeneration of mark levels (with power limiter saturable absorber) will allow this technique be improved



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Phase-preserving amplitude regeneration of a phase-encoded signal

- First demonstration of phase-preserving amplitude regeneration of an RZ DPSK signal based on a power limiter saturable absorber
- ▶ BER improvement obtained in nonlinear transmission regime
- Recirculating loop experiment shows a distance improvement ratio of 1.6
- Spectral distortion compensated by using a gain equalizer



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Theoretical and numerical

 Study of dynamic spectral resonance of the SA for better compensation

Experimental

- Demonstration of full WDM regeneration with SA.0 and SA.1
- Regeneration of signals with advanced modulation format (DQPSK)



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Les membres de jury: B. Dagens, A. Ramdane, J.C. Cartledge, S. Gosselin, Les directeurs: J.-C. Simon, L. Bramerie Les financeurs: a région Bretagne Les partenaires: LPN, 3-5 Lab, IEF, Prista Yenista Optics, RINCE, Orange Labs Mes collègues Mes amis Ma famille





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Publication list

Articles in refereed journals: author/co-author of 8 journal articles

- 1. "WDM compatible 2R regeneration device based on eight-channel saturable absorber module," *Electron. Lett.*, vol. 43, p. 1305, 2007
- "Noise Tolerance Assessment and System Design Discussion of a Saturable-Absorption-Based All-Optical 2R Regenerator," *IEEE Photon. Technol. Lett.*, vol. 21, p. 590, 2009
- "All-optical 2R regeneration using passive saturable absorption," Optics Comm., vol. 282, p. 2768, 2010
- "Saturable-Absorber-based Phase-Preserving Amplitude Regeneration of RZ DPSK Signals," *IEEE Photon. Technol. Lett.*, vol. 22, p. 887, 2010

Conference papers author/co-author of 13 international conference papers

- "Cascadability Assessment of an All Optical 3R Regenerator based on Synchronous Modulation in a Saturable Absorber and Optical Clock Recovery," *ECOC*, Berlin, Germany, 2007, Tu4.3.5
- "Phase-Preserving Amplitude Regeneration for RZ-DPSK Signals at 42.7 Gbit/s Using Saturable Absorber," OFC, San Diego, California, 2010, OMT4
- 3. "Cascadability Assessment of a Microcavity-Saturable-Absorber based Phase-Preserving Amplitude Regenerator in a DPSK transmission system," *ECOC*, 2010, accepted for oral presentation

Author/co-author of 9 French national conference papers

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Recirculating loop experiment: Tandem SA.0-SA.1



- ► Signal: RZ 33%, 42.7 Gbit/s, PRBS 2³¹ - 1
- OSNR of 18 dB (over 1 nm) equivalent to 200 km of transmission with in-line power of 5 dBm
- ► 2R regenerator: tandem SA.0-SA.1 ($P_{SA.1}^{in}$ =9 dBm, $P_{SA.0}^{in}$ =9 dBm)



After 10 laps



With regenerator



$BER = 10^{-8}$

- ▶ Without 2R: after 4 laps
- With 2R: after 10 laps
- \Rightarrow Improvement factor of 2.5

However, impossible to:

- Cascade the regenerator more than 10 times
- Plot a proper BER-evolution graph.



²¹M. Gay *et al., ECOC*, Brussels, Belgium, 2008, Tu4D2 July 8, 2010 Thesis defense

Explanation

Reflectivity spectrum (principle figure)



At high power:

- SA.0 spectrum approaches a flat response
- SA.1 spectrum becomes narrower
- Leads to spectral deformation of the signal
- ► The phenomenon accumulates in the loop July 8, 2010 Thesis defense

