Optical in-line regeneration for 40Gbit/s WDM transoceanic systems

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Abstract:- Error-free 40Gbit/s regenerated transmission over more than 20,000km is demonstrated using new InP Mach-Zehnder modulator with WDM compatibility, in good agreement with numerical simulations. This is a first step towards Nx40Gbit/s transoceanic system demonstration.
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The first response to the demand for capacity in transoceanic transmission systems is the technique of wavelength-division-multiplexing (WDM), which allows a substantial increase in system capacity without constraints in the terminal's electronics bandwidth. Considering next the transmission format in transoceanic applications (6-12Mm distances), one of the main advantage of RZ-soliton over linear-NRZ is the possibility to use substantially higher line rates such as 10, 20 or 40 Gbit/s with possibly longer amplifier spacing (60-200 km). However, two main impairments of long-haul soliton transmission, i.e. the Gordon-Haus and the WDM-collision timing jitter, ultimately require in-line control in the frequency and/or time domain. Among these is "3R" optical regeneration based on synchronous modulation (SM). The principle makes possible unlimited-distance propagation [1]. More specifically, intensity modulation (IM) combined with narrowband filtering suppresses timing jitter and blocks noise accumulation [1], while pure phase modulation (PM) reduces jitter without suppressing noise [2]. Actually, efficient jitter/noise control was shown to require both IM and PM [3].

Because "3R" regeneration potentially addresses the terabit/s submarine system market, the current challenge is to further increase the capacity. A key requirement is that it could operate at 40Gbit/s, both for WDM granularity and SONET/SDH layer considerations; 40Gbit/s granularity minimizes the number of WDM channels to transmit (hence, of parallel in-line modulators), which reduces both system complexity and cost. In order to further reduce the number of regenerators in WDM systems, simultaneous regeneration of WDM channels in a single modulator is also possible [4]. This last solution points towards a potential superiority of ‘optical’ over ‘electronic’ regeneration. It has been studied through various numerical simulations [4], and experimentally implemented at 20Gbit/s [5-6].

Up to now, only single-channel 40Gbit/s experiments have been demonstrated [7-9] but Nx40Gbit/s WDM upgrade of such systems could be rapidly requested. For that, it is required to operate optical regenerators with adequate specifications. It should first operate at 40GHz and provide both IM and PM with independent control of their depths. Practical device implementation in WDM systems will require long-term stability as well as polarization insensitivity, hence excluding the use of $LiNbO_3$ materials [7]. Simultaneous WDM implementation (multiple channels passing through a single regenerator), should require immunity to crosstalk and wavelength insensitivity, excluding electro-absorption modulators [8].

Recently, we have reported a newly developed 40GHz InP Mach-Zehnder (MZ) modulator meeting these requirements. It combines both polarization and wavelength-independence and provides adjustable IM/PM response through a dual-electrode, push-pull configuration [9]. Figure 1 shows an ESM picture of the modulator (top left) and the schematic of a dual-electrode Mach-Zehnder modulator (bottom left) along with two graphs showing polarization and wavelength-insensitive response of the modulator.

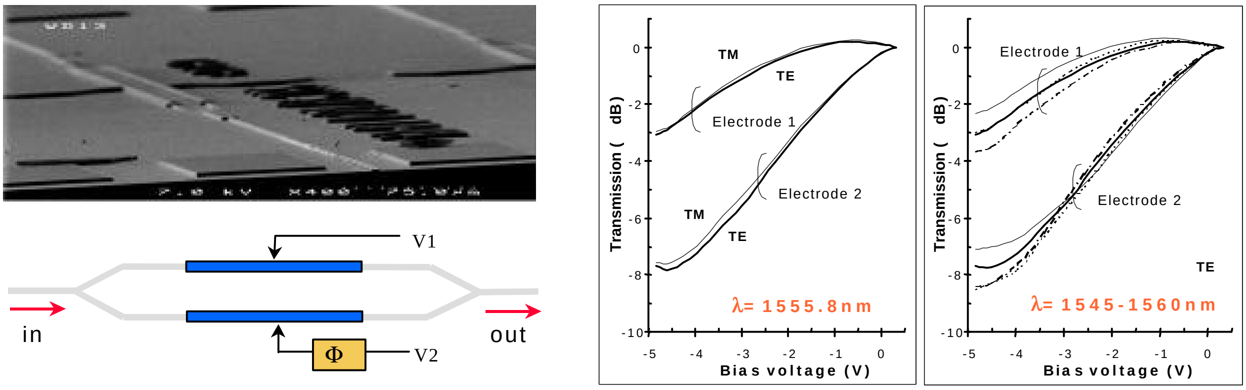

Figure 1 : ESM picture (top left) and schematic of dual-electrode Mach-Zehnder modulator (bottom left) along with transmission vs. bias voltage graphs for TE/TM polarization modes of input light at 1555.8nm (middle) and for 1545-1560nm wavelengths with TE polarization mode (right).

This component was also found immune from WDM crosstalk [9], which makes it amenable to simultaneous regeneration of WDM channels. In order to validate its properties, this new modulator was inserted into a recirculating loop and made it possible to demonstrate a single-channel regenerated transmission at 40Gbit/s over more than 20,000km. In addition, asymptotic stabilization of bit-error-rate (BER) at low levels ($<10^{-12}$) over transmission distance was experimentally shown for the first time through Q-factor measurements.

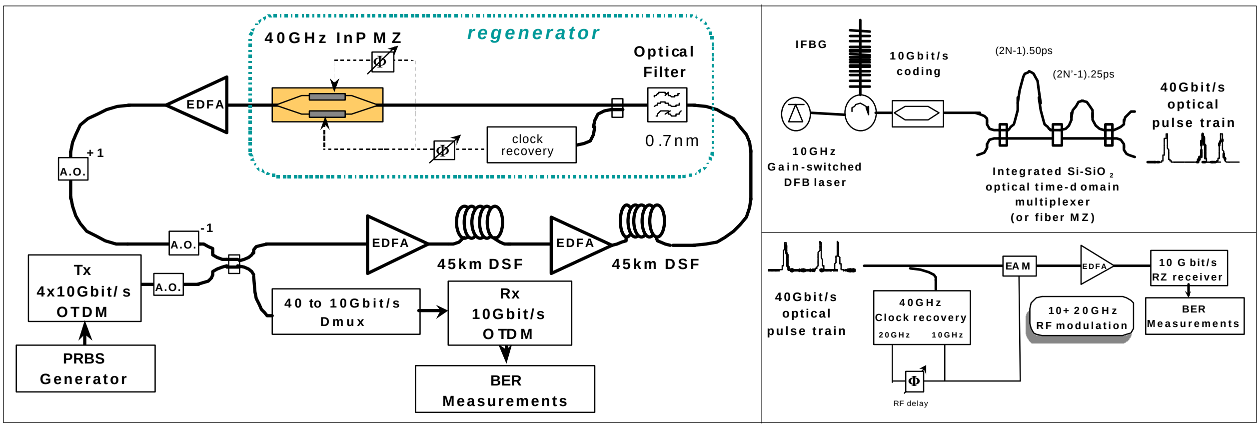

Figure 2: Experimental Q-factor vs. transmission distance with single-electrode (open circles) and push-pull (full squares) configurations. Insets shows 10Mm eye diagrams at 40Gbit/s and 10Gbit/s monitored on 45GHz photodiode before and after time-domain demultiplexing.

Figure 2 shows the 40Gbit/s experimental recirculating loop along with emitter/receiver experimental setup. Pulses at 10GHz repetition rate (20ps width) generated from a gain-switched DFB laser at 1555.75nm are first compressed to 6ps through a 30ps/nm, in-fiber Bragg grating. The output is then modulated by a 10Gbit/s, 2^7-1 PRBS sequence before time-interleaving through an integrated Si-SiO_2 double-MZ multiplexer, yielding a single-polarization 40Gbit/s signal. The loop consists of two 45km-long spans (0.24dB/km loss) and three 1480nm-pumped EDFAs ($NF=2n_{sp}/\eta_{in}$=7dB). The span dispersion is D=0.15ps/(nm·km), corresponding to a mean soliton power of 5±1dBm at the EDFA output. The RF clock, which is locally recovered at 40GHz through a Q=300 filter, is split with independent phase adjustments to drive the MZ in either single-electrode or push-pull operation. An optical bandpass filter of 0.7nm optimized width is inserted before the MZ for further jitter/noise control [1]. Bit-error-rate (BER) measurements are made at 10Gbit/s after demultiplexing through a PI electro-absorption modulator electrically driven by 20 and 10GHz RF sines, yielding a temporal switching window of 17ps. Error-counting is made by random sampling of the four 10Gbit/s tributaries. The evolution of amplitude Q-factor with distance was measured when operating the modulator in push-pull mode, which permits to adjust the effective PM. For the optimum operating point, corresponding insertion loss and IM depth are measured to be 16.3dB and 7.2dB, respectively.

With these experimental system parameters, we have computed numerical simulations of this 40Gbit/s regenerated transmission experiment using the vector nonlinear Schrödinger equation with temporal and spectral resolution of 0.391ps/78MHz, resp. We took into account both 10 to 40Gbit/s OTDM and 40 to 10Gbit/s demultiplexing and incorporated polarization effects occurring in recirculating loops such as signal repolarization [10] and its effect when associated to fiber PMD. Theoretical Q-factors result from the concatenation of 3 runs with random noise/polarization seeds. Like in the experiment, the performance is set by the minima of amplitude and timing Qs between the four 10Gbit/s tributaries.

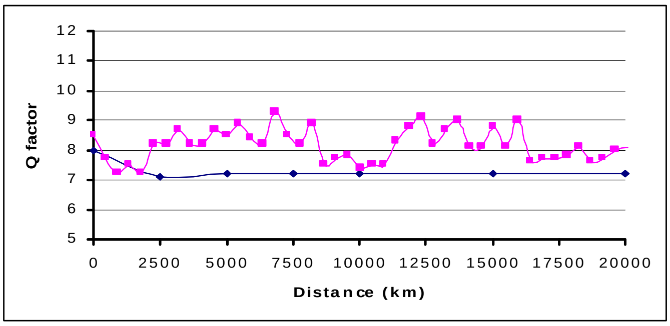

Figure 3: Theoretical and experimental Q-factor vs. transmission distance

Figure 3 shows both experimental measurements and numerical predictions of Q-factors with distance. Experimental Q-factors (smooth curve) are seen to rapidly reach an asymptotic value of 7.2 (BER<10^{-12}), thus demonstrating the efficiency of 3R regeneration; these measurements represent the first experimental confirmation of this type of evolution. Theoretical Q-factors (broken curve) also evolves towards an asymptotic value near 8 at 20Mm. Note the good agreement between experimental and numerically estimated values of Q-factors, confirming the possibility to model and predict SM systems performance. The slight difference among theses values can be explained by the incomplete estimation of full noise/polarization statistics in the simulations.

Optical 3R regeneration is a attractive candidate for achieving Terabit/s capacity over transoceanic distances with 40Gbit/s WDM granularity. In order to experimentally assess its potential, we have developed a new type of 40GHz, polarization-insensitive and wavelength-independent regenerator, and demonstrated an 40Gbit/s error-free transmission over more than 20,000km without measuring any signal degradation. Immunity to WDM crosstalk was also observed [9], showing the potential of this component for simultaneous WDM regeneration. Further improvement of the regenerator characteristics (modulator insertion loss, filtering) associated with numerical optimization of the system configuration (dispersion map, channel spacing) should, in the near future, lead to the first experimental investigation of Nx40Gbit/s regenerated transmission.

References

[1] M.Nakazawa, E.Yamada, H.Kubota and K.Suzuki, Electron. Lett., Vol.27, n°14, pp.1270-1272 (1991).
[2] N.J.Smith, K.J.Blow, W.J.Firth and K.Smith, Optics Commun., n°102, pp.324-328 (1993).
[3] O.Leclerc, P.Brindel, C.Duchet, M.Goix, E. Maunand and E.Desurvire, Electron. Lett., Vol.34, n°10, pp.1011-1013 (1998).
[4] O.Leclerc, E.Desurvire and O.Audouin, Optical Fiber Technol., Vol.3, n°2, pp.97-117 (1997).
[5] M. Nakazawa, K. Suzuki, H. Kubota, A. Sahara, and E. Yamada, Electron. Lett. 34, 104 (1998).

[6] O.Leclerc, P.Prindel, S.Bigo, E.Brun-Maunand and E.Desurvire, Electronics Letters, Vol.34, n°2, pp.199-201 (1998).
[7] K.Suzuki, H.Kubota, A.Sahara and M.Nakazawa, Electron. Lett., Vol.34, n°1, pp.98-100 (1998).
[8] G.Aubin, T.Montalant, J.Moulu, F.Pirio, J.-B.Thomine and F.Devaux, , Electron. Lett., Vol.32, n°24, pp.2188-2189 (1996).
[9] O.Leclerc, P.Brindel, D.Rouvillain, E.Pincemin, B.Dany, E.Desurvire, C.Duchet, E.Boucherez and S.Bouchoule, Postdeadline paper 35, Proc. of Optical Fiber Communications, OFC'99 (1999).
[10] C.R.Menyuck, D.Wand and A.N.Pilipetskii, Proc. of European Conference on Optical Communications, ECOC'97, Edinburgh, Vol.3, p.275 (1997).