All-Optical 2R Regeneration Using the Hysteresis in a Distributed Feedback Laser Diode

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***Abstract*—A broadband optical 2R regenerator based on a single distributed feedback laser is demonstrated for nonreturn to zero signals at a bitrate of 10 Gb/s. A semi-analytical approach for the influence of hysteresis on the transfer function of a 2R regenerator is shown.**

***Index Terms*—Distributed feedback (DFB) laser, hysteresis, 2R regeneration.**

I. Introduction

THE TELECOMMUNICATION industry has experienced a huge growth in the past years and the need for bandwidth is expected to increase further as new internet-based services are being implemented. Optical point-to-point wavelength-division-multiplexed (WDM) network links were able to fulfill the capacity requirements in the past and have been implemented worldwide. However, to meet the future demand, the logical next step in optical network evolution will be to implement the routing and switching in the optical domain. A major concern is however the accumulation of noise, which severely limits the cascadability of optical network nodes. Different techniques for 2R regeneration have been proposed in the past such as devices based on interferometers [1] and self-phase modulation [2], [3].

Recently, we demonstrated that a distributed feedback (DFB) laser diode shows a hysteresis in the lasing power under the injection of a holding beam [4], [5]. The underlying effect for the bistability is the spatial hole burning induced nonlinearity. The bistability at the lasing wavelength has been successfully applied to obtain flip-flop operation [4] and all-optical packet switching [6]. However, as illustrated in Fig. 1, the bistability is not only present at the lasing wavelength, but also in the transmission characteristics of the injected light. In this paper, we will demonstrate with numerical and experimental results that the transmission characteristic of the injected light can be used to improve the bit error rate (BER), and is therefore, applicable for 2R regeneration in optical systems. The injected light can have any wavelength outside the stopband of the DFB grating resulting in broadband operation of the 2R regenerator. This is a major advantage over 2R regenerators based on four wave mixing [7] and injection-locking [8], [9].

To the authors' knowledge, no research has been performed yet on the influence of hysteresis for 2R regeneration. In [10] and [11], a theoretical approach is given for hysteresis-based detectors in networks to give a suboptimal solution for the mismatch between the fixed bandwidth of electrical filters and the different bit-rates present in an optical network. The experimental results that will be presented in this paper suggest that the hysteresis in the transmission characteristic plays an important role and we will give the basis for a theoretical analysis on 2R regeneration with a hysteresis in the following section. Intuitively, one can consider that instead of a fixed decision level for the zero's and ones, the hysteresis causes the decision level to change dynamically and therefore reduces the bit error rate of a noisy signal. As outlined in [12] and [3], distinctive transfer functions for the ones and zeros are necessary for improvement of the BER of a signal. We follow a more intuitive approach but the presence of a hysteresis suggests that this condition is fulfilled and that our regenerator is what is called a class II optical regenerator in [3].

II. Theoretical Approach

In this section, we will investigate the influence of a hysteresis in the transmission characteristic of a 2R regenerator. The concept is illustrated in Fig. 2. We assume a step function [Fig. 2(a)] with a hysteresis of width h. When a noisy signal is sent through the regenerator, a normal regenerator will distinguish between the ones and zeros using a static decision level. We will assume that the probability distribution function of noise on the one (pdf_1) and zero (pdf_0) levels is equal and the optimal position of the decision characteristic is at $1/2$. We also assume that the electrical SNR after the receiver is predominantly determined by the optical signal to noise ratio before the receiver.

When we use a hysteresis in the transfer characteristic on the other hand, the decision level will change dynamically with the bit pattern. This will improve the BER because the transfer function will be different for the ones and zeros [12]. As can be seen in Fig. 2(c), the decision level will be lower for a one and higher for a zero allowing a wider distribution of noise. There is a small adverse effect caused by the increased threshold to change from one state to the other, but we will demonstrate that for small values of the hysteresis and fast regenerators this has little or no influence.

Manuscript received September 14, 2009; revised October 30, 2009; accepted November 10, 2009. Date of publication December 31, 2009; date of current version October 6, 2010. This work was supported by the Fund for Scientific Research (FWO), the IAP-project "Photonics@be" and the Erasmus Mundus program. The work of K. Huybrechts was supported by the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT) under a specialization grant.

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Digital Object Identifier 10.1109/JSTQE.2009.2037022

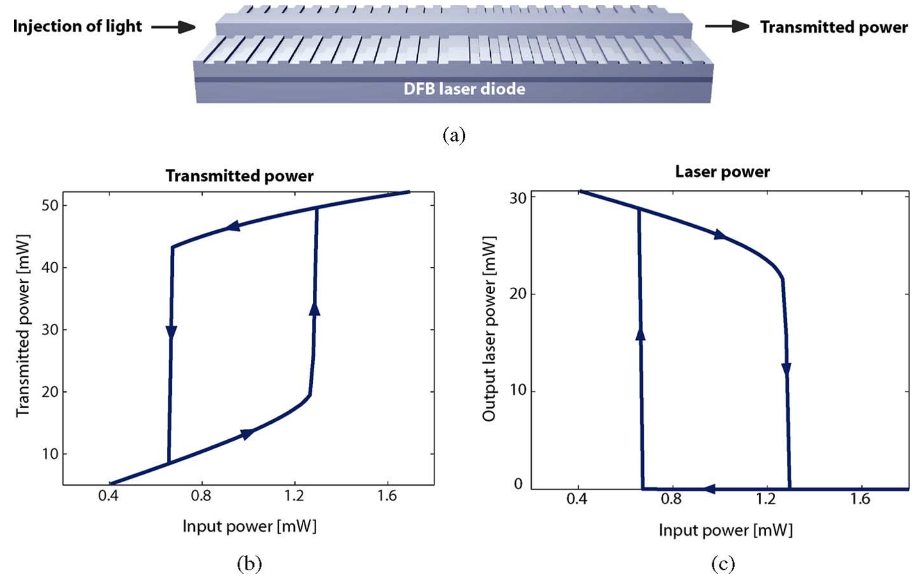

Fig. 1. Bistability in a DFB laser diode under injection of light at a different wavelength. (a) Schematic representation of a $\lambda/4$-shifted DFB laser. (b) Simulation of transmission of light at a different wavelength through a DFB laser. (b) Corresponding laser output power.

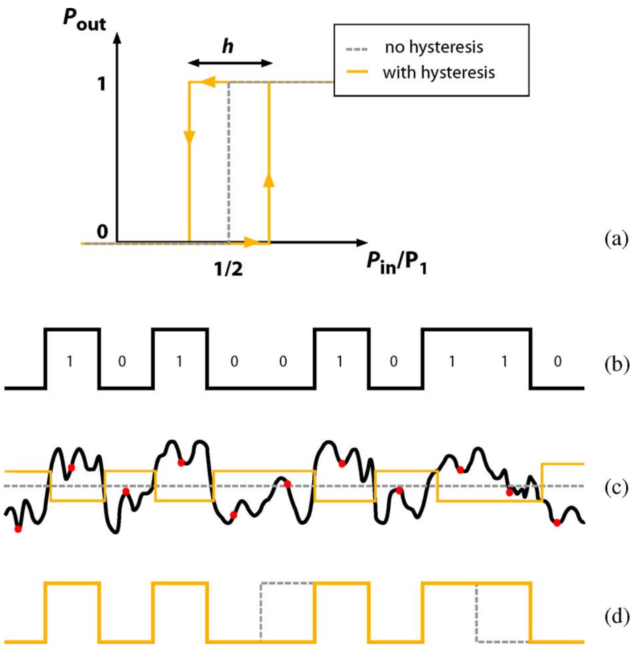

Fig. 2. Concept of using a hysteresis for 2R regeneration (a) Transmission characteristic of the regenerator, (b) original bit-pattern, (c) bit-pattern with noise with a dynamically fluctuating decision level (orange) and static decision level (dashed), (d) reconstructed bit pattern at the detector after regeneration with hysteresis (orange) and without (dashed).

The textbook definition [13] for the BER is given in terms of the probability $P(0|1)$ of deciding zero when a one is expected and the probability $P(1|0)$ of deciding one when a zero is expected. Since 1 and 0 bits are equally likely to occur, the BER can be defined as

$$\mathrm{BER} = \frac{1}{2}\left(P(0|1) + P(1|0)\right). \tag{1}$$

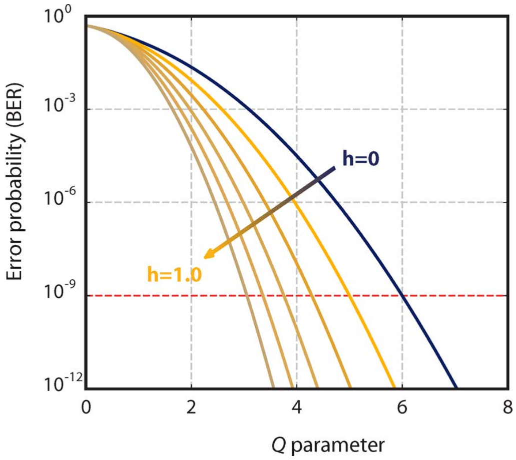

Fig. 3. Asymptotical behavior of BER as a function of the Q-parameter for different values of the hysteresis width h (and $n \to \infty$).

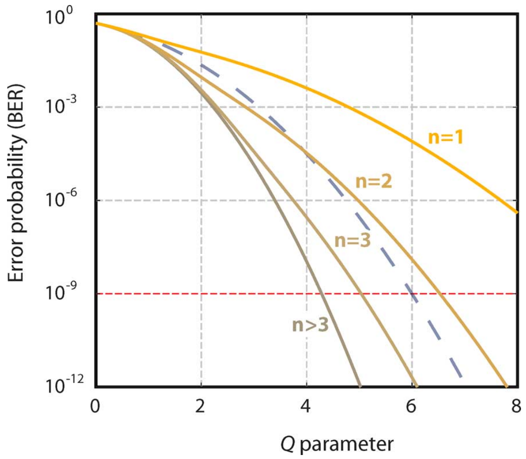

Fig. 4. BER as a function of the Q-parameter at different time steps n for a hysteresis with width $h = 0.4$. The dashed line represents the situation without hysteresis.

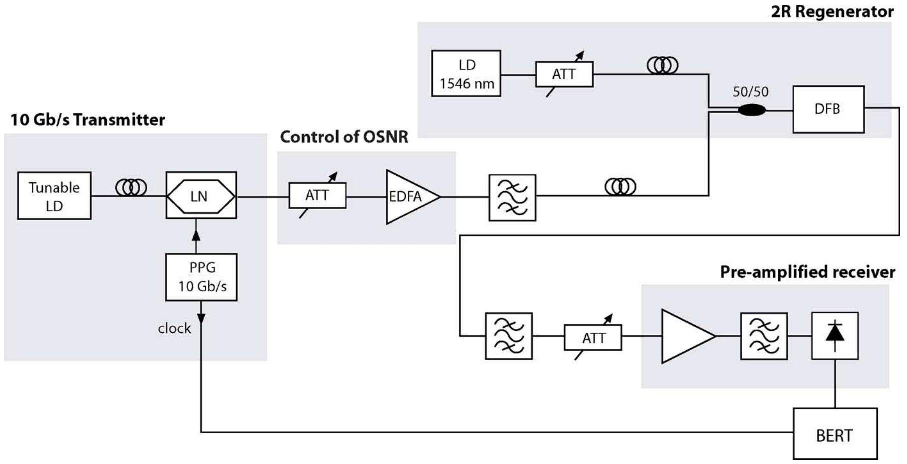

Fig. 5. Schematic of the setup. (LD: laser diode; LN: lithium–niobate modulator; PPG: pulse pattern generator; ATT: attenuator; EDFA: erbium-doped fiber-amplifier; BERT: bit-error rate tester.

In case of standard Gaussian noise, the BER can be derived as a function of the Q parameter [13] by

$$\mathrm{BER} = \frac{1}{2}\int_{-\infty}^{1/2} \mathrm{pdf}_1(P)dP + \frac{1}{2}\int_{1/2}^{\infty} \mathrm{pdf}_0(P)dP \quad (2)$$

$$= \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \quad (3)$$

where we assumed that the noise distribution on the ones and zeros is the same. The Q-parameter in the above equation is defined as the ratio between signal power and the standard deviation of the Gaussian noise distribution [13].

When a decision characteristic with a hysteresis is used [as in Fig. 2(a)], we should consider a more complex analysis where the output depends on the state in a previous time step. This means that we will need to reconstruct the analysis to show how the device will switch states during a single bit period. The noise on these signals is mainly coming from ASE (amplified spontaneous emission) noise of the amplifiers and therefore fluctuating very fast. If we assume that the device has a reaction time that is significantly shorter than the duration of a single bit, we can look at it from the point of view of the threshold level which will change at the beginning of a bit period following a transition in the bit sequence while the noise is changing throughout the bit period. We will follow a similar procedure as in [11] and divide the time window of one bit in N different time steps. The error probability when there is no state difference will be lower than considered with a standard fixed decision characteristic. There is, however, also an adverse effect because of the higher threshold of changing from a zero bit to a one bit and *vice versa*. In the following analysis, we will show that this adverse effect can be overcome when the regenerator acts faster than the duration of individual bits and when the hysteresis is not very wide.

We can write the probability $p_{xy|z}$ to change from state x to y while z is given, as follows:

$$p_{00|1} = \int_{-\infty}^{(1+h)/2} \mathrm{pdf}_1\, dP = \frac{1}{2}\,\mathrm{erfc}\left((1-h)\frac{Q}{\sqrt{2}}\right)$$

$$p_{10|1} = \int_{-\infty}^{(1-h)/2} \mathrm{pdf}_1\, dP = \frac{1}{2}\,\mathrm{erfc}\left((1+h)\frac{Q}{\sqrt{2}}\right)$$

$$p_{01|0} = \int_{(1+h)/2}^{\infty} \mathrm{pdf}_0\, dP = \frac{1}{2}\,\mathrm{erfc}\left((1+h)\frac{Q}{\sqrt{2}}\right)$$

$$p_{11|0} = \int_{(1-h)/2}^{\infty} \mathrm{pdf}_0\, dP = \frac{1}{2}\,\mathrm{erfc}\left((1-h)\frac{Q}{\sqrt{2}}\right).$$

When using a hysteresis, the previous state is used to determine the next state and a recursive expression for $P_n(0|1)$ (being the probability on time step n to decide zero when a one is expected) can be written as

$$P_{n+1}(0|1) = P_n(0|1)\, p_{00|1} + P_n(1|1)\, p_{10|1}$$

$$P_1(0|1) = \frac{1}{2}\, p_{00|1} + \frac{1}{2}\, p_{10|1}$$

and a similar equation for $P(1|0)$. Because the noise distribution on the ones is assumed similar to the noise distribution on the zeros ($p_{00|1} = p_{11|0}$ and $p_{10|1} = p_{01|0}$) and $P(1|1) = 1 - P(0|1)$ we can write down the following recursive expression for the BER:

$$\mathrm{BER}(n+1) = \mathrm{BER}(n)\, p_{00|1} + [1 - \mathrm{BER}(n)]\;\, p_{10|1} \quad (4)$$

$$\mathrm{BER}(1) = \frac{1}{2}\, p_{00|1} + \frac{1}{2}\, p_{10|1}. \quad (5)$$

The second term of (4) appears to be dominant for realistic values of the hysteresis ($h < 1$) and the bit error rate asymptotically becomes equal to $p_{10|1}$ after a sufficient amount of time steps. This asymptotical bit error rate is depicted in Fig. 3 for different values of the hysteresis width. However, this figure does not take into account the adverse effect of the higher threshold for switching between two different states. As discussed above, the bit error rate will improve during the time window of a single bit. For high values of the hysteresis width, it will take more time steps to achieve an improvement. The evolution of the BER is depicted in Fig. 4 for different time steps n and a hysteresis width $h = 0.4$. We can observe an improvement in bit error rate after three time steps. This means that—according to this

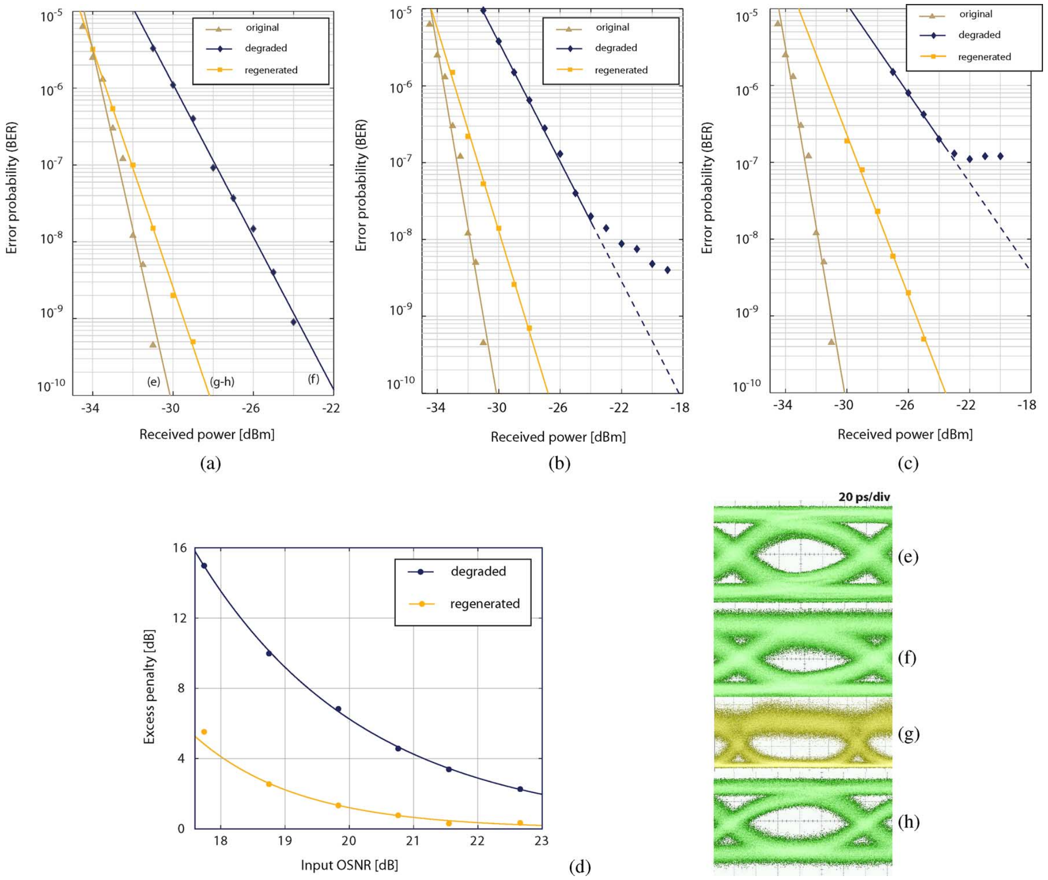

Fig. 6. BER as a function of the received optical power for different values of the OSNR, the power excess diagram and corresponding eye diagrams. (a) Input OSNR of 19.83 dB; (b) input OSNR of 18.75 dB; (c) input OSNR of 17.74 dB; (d) excess penalty for a BER of 10^{-9} of the degraded and regenerated signal compared to the original signal as a function of the input OSNR; (e) eye diagram of original signal from (a) at the receiver; (f) eye diagram of degraded signal; (g) eye diagram of the regenerated signal without electric filter (receiver bandwidth of 33 GHz); (h) eye diagram of regenerated signal.

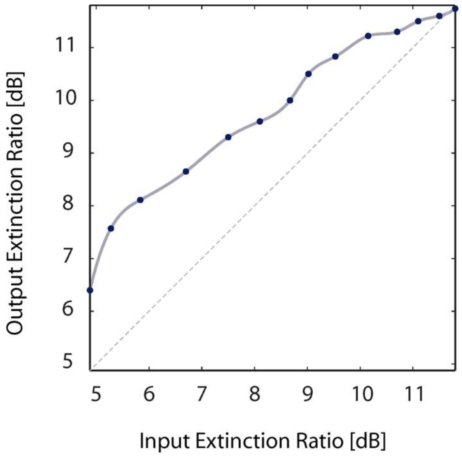

Fig. 7. Extinction ratio improvement.

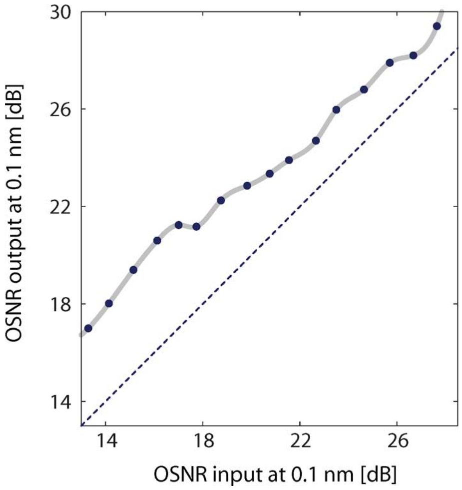

Fig. 8. OSNR in 0.1 nm at the output of the all-optical 2R regenerator as a function of the input OSNR.

model—the reaction time of the device should be four or five times faster than the bit duration when $h = 0.4$. The number of time steps needed for an improvement in bit error rate increases with the hysteresis width, e.g., for a hysteresis of $h = 0.1$ there is already an improvement in the second time step but it takes 15 time steps for a hysteresis width of $h = 0.9$.

We can conclude this section by stating that a hysteresis in the transmission characteristic makes the decision threshold to move dynamically with the signal. Therefore, the distinctive transfer function for the ones and zeros allows to improve the bit error rate. The theoretical model that is derived above, suggests however that the response time of the regenerator should be significantly faster with respect to the bitrate of the original signal.

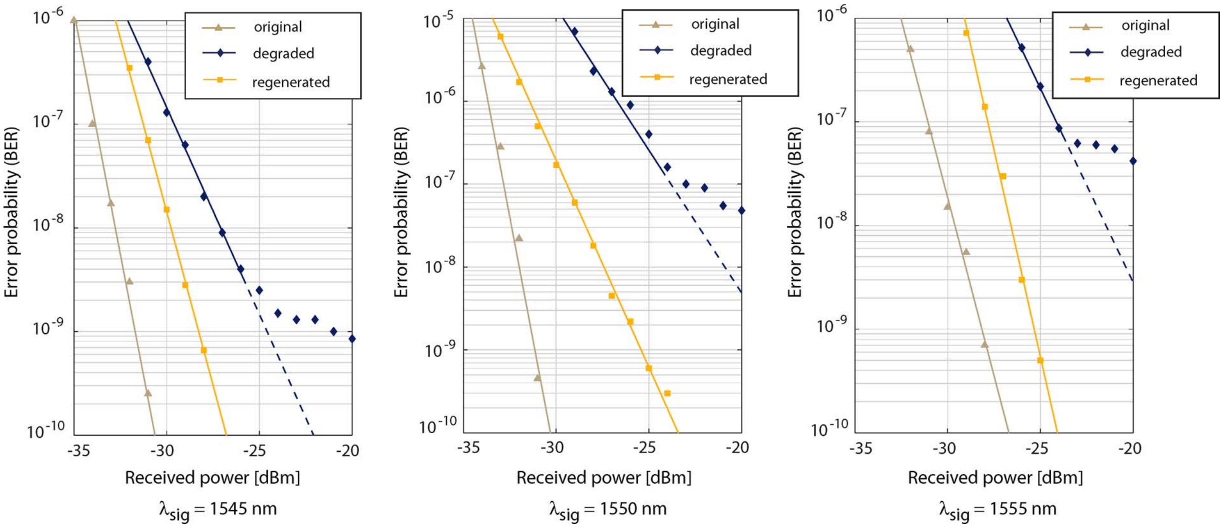

Fig. 9. Wavelength independence: BER as a function of the received optical power for different transmission wavelengths.

III. EXPERIMENT

For the experiment, we use the setup as depicted in Fig. 5. A pulse pattern generator (PPG) generates a pseudorandom bit-sequence (PRBS) of $2^{31}-1$ bits. The original signal is being attenuated and amplified to decrease the OSNR. The regenerator is a standard, nonoptimized $\lambda/4$-shifted DFB laser diode from Alcatel-Thales with AR-coated facets. It has a κL value of 1.6, a bias current of 150 mA and its central wavelength is 1553 nm. Lensed fibers are aligned at both sides of the laser to couple the light. The degenerated signal has an input power of 5–7 dBm (depending on the power injected in the EDFA) and is combined with a holding beam of 5 dBm (both measured in fiber after the coupler). The holding beam is used to decrease the threshold for bistability and can be adjusted by an attenuator. The width of the bistability is approximately 1 dB wide (resulting in a value for h between 0.1 and 0.2 in the analysis of Section II). An optical bandpass filter with a width of 1 nm removes the lasing light so that only the signal at the original wavelength is sent to the preamplified receiver for a BER analysis. A variable attenuator is used to change the received optical power on the receiver in order to make BER-diagrams.

In Fig. 6(a)–(c), the BER diagrams as a function of the received optical power are shown for different values of the EDFA input power (and thus for different OSNRs). From these diagrams, it is clear that the 2R regenerator is able to improve the degraded signal significantly. Its noise suppression capabilities are demonstrated by Fig. 6(d) where the excess power penalty for the regenerated and degraded signal compared to the original signal are depicted as a function of the EDFA input power. The corresponding eye diagrams for the regeneration are depicted in Fig. 6(e)–(h). In Fig. 6(g), the regenerated signal is shown without an electrical filter that is matched with the 10 GHz bandwidth at the receiver side but on a regular optical scope with a 33 GHz bandwidth. This eye diagram illustrates that the regenerator might work also at higher bitrates. We want to point out that our 2R regenerator with hysteresis even reduces the BER when the degraded signal reaches the noise floor, determined by the OSNR; something which is beyond the capabilities of regenerators with a single decision level.

The extinction ratio improvement is depicted in Fig. 7. However, in this diagram, we did not take the influence of the 5 dBm holding beam into account and an amplified signal without holding beam might result in a better extinction ratio improvement. In Fig. 8, the OSNR at the output of the 2R regenerator is depicted as a function of the OSNR at the input. The OSNR is measured by setting the resolution of the spectrum analyzer to 0.1 nm and determining the difference between the signal and noise. The reduction of noise is important with regard to the cascadability of the regenerators.

The 2R regenerator can work at any wavelength outside the stopband of the DFB grating as illustrated for three arbitrary wavelengths in Fig. 9. The BER diagrams for different injected wavelengths are depicted and show broadband operation that is only limited by the spectral width of the gain medium. The gain medium in our device are quantum wells leading to a gain bandwidth of approximately 20 nm. The small differences between the graphs are mostly due to the spectral variation in gain of the EDFA.

When we separate the signal at the lasing wavelength (instead of the injected wavelength), we obtain the reversed, wavelength converted signal. The noise floor is much higher and error-free wavelength conversion was only obtained at a smaller bitrate of 3 Gb/s. This is because the carrier density changes much faster than the laser signal which also depends on the cavity decay time.

IV. CONCLUSION

A new concept for 2R regeneration is proposed using a hysteresis in the transmission characteristic. The concept is illustrated with experimental results showing bit error rate improvement of a 10 GB/s NRZ signal using a single DFB laser diode. The simplicity of the concept and the good performance make this regenerator suitable for application in optical access or metro networks. Since direct modulation of DFB lasers has been demonstrated at higher bitrates (up to 40 GHz), the presented technique might be also employed at higher speeds by using optimalized designs.

ACKNOWLEDGMENT

The authors would like to thank G.-H. Duan from Alcatel-Thales III/V-laboratories for providing the DFB laser diodes.

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