Dependence of Optically Preamplified Receiver Sensitivity on Optical and Electrical Filter Bandwidths—Measurement and Simulation

Martin Pfennigbauer, *Student Member, IEEE*, Martin M. Strasser, *Student Member, IEEE*, Martin Pauer, and Peter J. Winzer, *Associate Member, IEEE*

***Abstract*—In this letter, we investigate both experimentally and by means of simulations, the dependence of receiver sensitivity on the optical filter bandwidth as well as on the bandwidth of the detection electronics for the optical noise limited direct detection case. The experiment is in good agreement with simulations employing advanced Gaussian noise statistics. Bandwidth optimization is performed both for nonreturn-to-zero and return-to-zero coded signals, yielding a measured sensitivity only 1.4 dB off the quantum limit at a data rate of 10 Gb/s.**

***Index Terms*—ASE, direct detection receiver, filter bandwidth, ISI, ON–OFF-keying, optical preamplification, NRZ, RZ.**

I. Introduction

HIGHLY SENSITIVE direct-detection (DD) receivers are key components for the design of high-speed communication systems. Sensitive receivers reduce transmitter or midspan amplifier requirements, extend link distances, and provide additional system margins. Especially for the emerging class of free-space optical communications systems, high receiver sensitivities are of major interest, since large channel loss, due to atmospheric attenuation in terrestrial applications and due to huge transmission distances in space-borne systems, has to be overcome without inline amplification.

Optically preamplified DD receivers show the best performance when employing matched optical filters [1]–[3]. However, owing to technological constraints as well as to wavelength stability problems, nonmatched filters are commonly used [e.g., Fabry–Pérot filters, fiber Bragg gratings (FBGs), or arrayed waveguide grating routers (AWG)]. In order to maximize receiver sensitivity, optimum optical filter bandwidths ranging from 0.9 to 8 times the data rate have been proposed for nonreturn-to-zero (NRZ), ON–OFF keying (OOK) transmission [4]–[7]. In this work, we experimentally determine the dependence of receiver sensitivity on optical and electrical filter bandwidths, verifying the simulation results obtained in [8]. We also experimentally demonstrate the superiority of advanced expressions for the beat noise variances [4], [9], [10] over the commonly used noise formulas given in [6]. For the case of RZ coding, using nonmatched FBGs as optical filters, we reach a sensitivity of 52 photons per bit (ppb) at a bit-error ratio $\mathrm{BER} = 10^{-9}$, which is 1.4 dB above the quantum limit. To the best of our knowledge, this result is the best reported sensitivity for optically preamplified OOK at 10 Gb/s [11]. Although this result was achieved for pseudorandom binary sequence (PRBS) of length $2^7 - 1$, we found only 0.4-dB penalty when using $2^{31} - 1$.

II. System Setup

A. Transmitter

A schematic of the experimental setup is shown in Fig. 1. A PRBS of length $2^7 - 1$ at data rates up to 10 Gb/s was used to modulate the light from a distributed-feedback (DFB) laser operating at a wavelength of 1550 nm. In order to achieve high extinction ratio, the NRZ modulation was performed in two steps, using an electroabsorption modulator (EAM) integrated with the DFB, in combination with a dual-drive $\mathrm{LiNbO_3}$ Mach–Zehnder modulator (MZM). For RZ coding, a third MZM was employed for pulse carving. It was sinusoidally driven to produce RZ pulses with 33% duty cycle.

B. Receiver

To set the receiver input power for bit error rate (BER) measurements, a variable attenuator linked transmitter and receiver part of the system. The received input signal was amplified by an erbium-doped fiber amplifier (EDFA), providing high gain (38 dB) at a low noise figure (3.3 dB). To spectrally curtail the EDFA's amplified spontaneous emission (ASE), a subsequent optical bandpass was implemented.We employed Bragg filters of different bandwidths to optimize system performance. A broadband (50 GHz) p–i–n photodiode performed optoelectronic conversion, followed by an electrical low-noise amplifier with a bandwidth of 18 GHz. A fifth-order Bessel lowpass together with the finite bandwidth of the bit-error-ratio test (BERT) set the electrical bandwidth of the receiver.The bandwidth of the Bessel filter was varied in order to achieve best receiver sensitivity. The overall conversion gain amounted to 1350 V/W.

As it is well known [6], DD causes beating of signal with ASE (variance $\sigma^2_{s,\mathrm{ASE}}$ after electrical filtering) and ASE with itself ($\sigma^2_{\mathrm{ASE,ASE}}$). Due to the large gain of the optical amplifier, the beat noise terms were the dominating noise sources in the

---

Manuscript received November 15, 2001; revised February 20, 2002. This work was supported by the Austrian Science Fund (FWF) under Grant P13998-TEC.

M. Pfennigbauer, M. M. Strasser, and M. Pauer are with the Institut für Nachrichtentechnik und Hochfrequenztechnik, Technische Universität Wien, Wien A-1040, Vienna, Austria (e-mail: martin.pfennigbauer@ieee.org).

P. J. Winzer is with Bell Laboratories, Lucent Technologies, Holmdel, NJ 07733 USA.

Publisher Item Identifier S 1041-1135(02)03794-1.

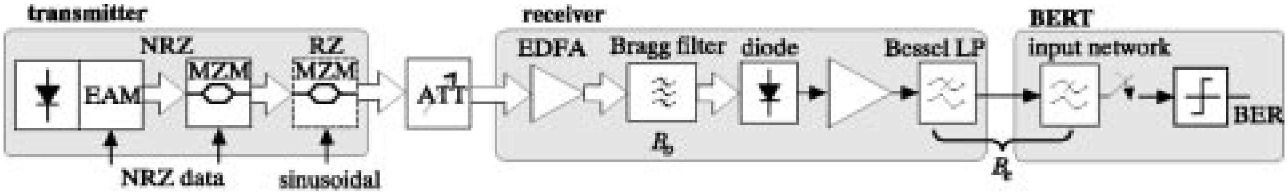

Fig. 1. Experimental setup: (N)RZ transmitter and optically preamplified direct detection receiver.

receiver. Shot noise as a consequence of the quantum nature of the optoelectronic conversion process (σ^2_{shot}) and thermal noise originating from the detection electronics (σ^2_{th}, noise power density 40 nV/$\sqrt{\text{Hz}}$) contributed only to a negligible extent to the total noise. Measuring the noise variances at the input of the BERT, the ratio of the beat noise terms $(\sigma^2_{s,\text{ASE}} + \sigma^2_{\text{ASE,ASE}})$ to the noise terms $\sigma^2_{\text{shot}} + \sigma^2_{\text{th}}$ was found to be more than 50 for a "0" bit and about 500 for a "1" bit.

The pattern generator and the BERT were driven by the same clock signal; sampling instant and decision threshold were optimized for each measured data point.

III. RECEIVER BANDWIDTH DEPENDENCE

A. Bandwidth Optimization

Receiver sensitivity was optimized by varying optical and electrical filter bandwidths. Experimental results were obtained by setting the receiver input power and measuring the BER. These results were compared to simulations employing the standard Gaussian noise formulas [6] which assume rectangular filters and time-independent optical field, and their exact versions, taking into account the actual filter transfer functions (both amplitude and phase) as well as the optical field waveform [4], [9], [12]. Here, results for both experiment and simulations are expressed in terms of a sensitivity penalty with respect to the quantum limit

$$\gamma_q = 10 \log(n_s/n_q) \quad [\text{dB}] \tag{1}$$

where the receiver sensitivity n_s denotes the average number of photons per bit leading to BER $= 10^{-9}$. The quantum limit n_q is 38 ppb [1].

Experimental results and corresponding simulations are shown in Fig. 2. As pointed out in [8], optimizing optical and electrical filter bandwidths involves a careful tradeoff between noise on the one hand, and on the other hand, intersymbol interference (ISI) for NRZ, and peak power reduction due to spectral signal energy truncation for RZ.

Fig. 2(a) gives the results for the optical bandwidth. Measurements (bullets), performed for NRZ coding at an electrical bandwidth of $B_e = 0.75R$, lead to an optimum optical filter bandwidth of $B_o = 1.35R$. The corresponding simulations using the advanced Gaussian approximations are represented by solid lines. For RZ coding (measurements: triangles, simulations: dashed lines), an optimum around $B_o = 2.7R$ is revealed. Here, an electrical bandwidth of $B_e = 0.9R$ was used. The performance gain of RZ compared to NRZ amounts to 1.5 dB, a fact that can mainly be put down to the absence of ISI for the temporally more confined RZ pulses. For both NRZ and RZ, experiment and simulations show excellent agreement. In the case of RZ coding, a sensitivity of 52 ppb was reached using an optimized optical bandwidth of $3R$, which represents—to the best of our knowledge—the best reported sensitivity for optically preamplified OOK at 10 Gb/s.

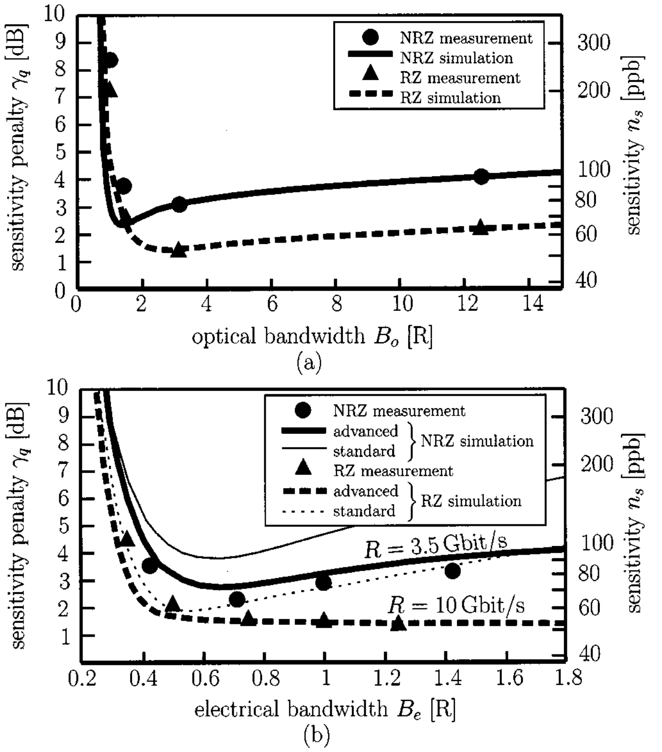

Fig. 2. Sensitivity penalty relative to the quantum limit as a function of (a) optical filter bandwidth and (b) electrical filter bandwidth. The vertical axis on the right gives the sensitivity in photons per bit (ppb). Measurements (symbols) and simulation (lines) are compared for NRZ coding (solid/bullets) and RZ coding (dashed/triangles).

In Fig. 2(b), the sensitivity is shown as a function of the electrical filter bandwidth for constant optical bandwidth. Again, the bullets and triangles represent experiments, while the solid and dashed lines stand for calculation results for NRZ $(B_o = 2.86R)$ and RZ coding $(B_o = 3.12R)$, respectively. The thick lines show the calculation results for the advanced Gaussian method, while the thin lines represent the results when applying the standard noise formulas [6]. For NRZ coding, the optimum electrical bandwidth is $B_e = 0.65R$, while for RZ coding the sensitivity is almost independent of the electrical bandwidth when chosen above $0.6R$. This can be attributed to the fact that both electrical signal power and $\sigma^2_{s,\text{ASE}}$ are proportional to B_e^2 for $B_e \lesssim 3R$ which lets their quotient (driving the BER) become independent of B_e [12]. At 10 Gb/s, the results for NRZ (not shown) were significantly distorted due to the bandwidth limitation of the BERT (13.5 GHz); since NRZ is typically limited by ISI, knowledge of the optical signal field, as well as of the

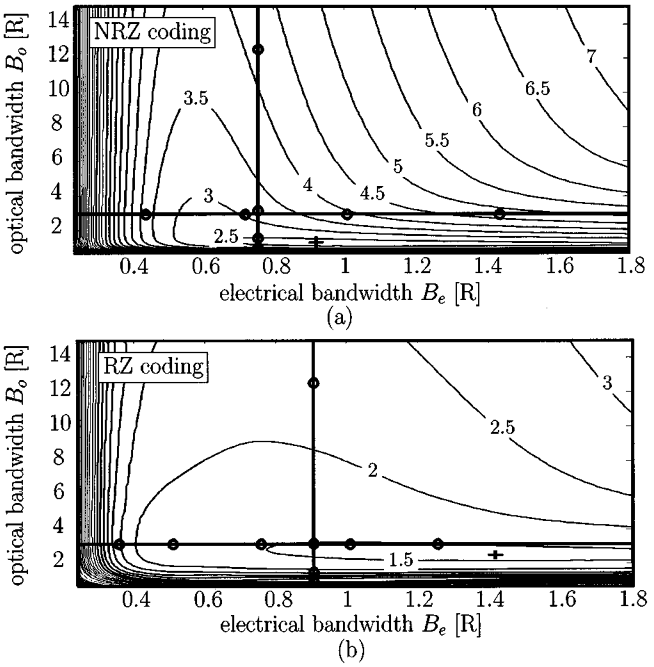

Fig. 3. Simulated receiver sensitivity penalty as a function of optical and electrical filter bandwidth for (a) NRZ coding and (b) RZ coding. The horizontal and vertical lines indicate the bandwidths at which experimental results were obtained.

optical and electrical filter characteristics is crucial to accurately predict receiver performance. Owing mainly to the inability to accurately measure the transfer function of the BERT's input network, we used a reduced data rate of 3.5 Gb/s to measure the receiver performance as a function of the electrical bandwidth for NRZ coding. By comparing the results of the two different simulation methods with the experimentally achieved sensitivities, the superiority of the advanced Gaussian method—especially for high electrical cutoff frequencies—is obvious [10].

B. Joint Optical/Electrical Bandwidth Tolerances—RZ Gain

Comparing the presented results for NRZ and RZ coding shows that not only the optimum performance is better for RZ, but also that this format has a higher tolerance to suboptimum choices of both the optical and electrical filter bandwidths. This additional advantage is revealed when the sensitivity penalty (γ_q) is shown as a function of optical and electrical filter bandwidths [Fig. 3(a) for NRZ; (b) for RZ]. The bandwidth at which measurements were performed are highlighted by horizontal and vertical lines and dots. Both plots reveal joint optimum bandwidth constellations: $B_o = 1R$ and $B_e = 0.9R$ for NRZ, and $B_o = 2.5R$ and $B_e = 1.4R$ for RZ. It becomes clear through the spacing of the contour lines that RZ is more robust to suboptimum bandwidth choices.

Fig. 4 shows the gain of RZ coding over NRZ as a function of optical and electrical filter bandwidths. Note that the RZ gain is almost independent of the optical filter bandwidth over a wide range of B_o. For optical bandwidths in excess of $2R$, the RZ gain increases both for higher andlower electrical bandwidths than $0.6R$ (which is optimum for NRZ). This fact illustrates the advantage of RZ especially at low electrical bandwidths, which are often a limiting design parameter in high data rate systems.

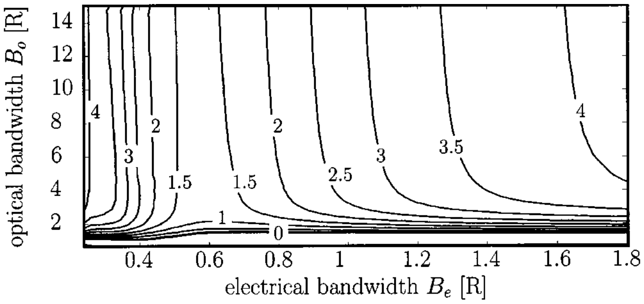

Fig. 4. RZ coding gain as a function of optical and electrical filter bandwidth.

IV. CONCLUSION

Near-quantum-limited performance of optically preamplified direct detection receivers was achieved by optimizing the bandwidth of the optical bandpass and the electrical cutoff frequency of the detection electronics. For RZ coding, our receiver featured a sensitivity of 1.4 dB off the quantum limit at a data rate of 10 Gb/s, while NRZ exhibited a penalty of 2.5 dB. We experimentally verified the results presented in [8], and demonstrated the superiority of the advanced Gaussian approximation for the noise statistic of DD receivers over the commonly used noise approximations.

ACKNOWLEDGMENT

The authors would like to acknowledge valuable discussions with W. R. Leeb.

REFERENCES

[1] P. S. Henry, "Error-rate performance of optical amplifiers," in *Proc. Optical Fiber Commun. Conf. (OFC'89)*, 1989, Paper THK3.
[2] L. Kazovsky, S. Benedetto, and A. Willner, *Optical Fiber Communication Systems*. Norwood, MA: Artech House, 1996.
[3] D. O. Caplan and W. A. Atia, "A quantum-limited optically-matched communication link," in *Proc. Optical Fiber Commun. Conf. (OFC'01)*, 2001, Paper MM2.
[4] L. Boivin and G. J. Pendock, "Receiver sensitivity for optically amplified RZ signals with arbitrary duty cycle," in *Proc. Optical Amplifiers and Their Applications (OAA'99)*, 1999, Paper ThB4.
[5] I. Jacobs, "Effect of optical amplifier bandwidth on receiver sensitivity," *IEEE Trans. Commun.*, vol. 38, pp. 1863–1864, 1990.
[6] N. A. Olsson, "Lightwave systems with optical amplifiers," *J. Lightwave Technol.*, vol. 7, pp. 1071–1082, July 1989.
[7] S. R. Chinn, "Error-rate performance of optical amplifiers with fabry-perot filters," *Electron. Lett.*, vol. 31, pp. 756–757, 1995.
[8] P. J. Winzer, M. Pfennigbauer, M. M. Strasser, and W. R. Leeb, "Optimum filter bandwidths for optically preamplified NRZ and RZ receivers," *J. Lightwave Technol.*, vol. 19, pp. 1263–1273, Sept. 2001.
[9] S. Saito, T. Matsuda, and A. Naka, "An analytical signal and noise expression for optical preamplifier receivers and its application," in *Proc. Optical Amplifiers and Their Applications (OAA'97)*, 1997, Paper TuD11.
[10] P. J. Winzer, "Receiver noise modeling in the presence of optical amplification," in *Proc. Optical Amplifiers and Their Applications (OAA'01)*, 2001, Paper OTuE16.
[11] W. Atia and R. S. Bondurant, "Demonstration of return-to-zero signaling in both OOK and DPSK formats to improve receiver sensitivity in an optically preamplified receiver," in *Proc. 12th Annual Meeting of LEOS*, 1999, pp. 226–227.
[12] P. J. Winzer and A. Kalmar, "Sensitivity enhancement of optical receivers by impulsive coding," *J. Lightwave Technol.*, vol. 17, pp. 171–177, Feb. 1999.