Optical satellite communications with Erbium doped fiber amplifiers

Martin Pfennigbauer* and Walter R. Leeb

Institut für Nachrichtentechnik und Hochfrequenztechnik,
Technische Universität Wien, Gußhausstraße 25/389, A-1040 Wien,
Tel.: +43/1/58801/38901, Fax.: +43/1/58801/38999,
email: martin.pfennigbauer@ieee.org

Abstract: For implementing an optical free-space transmission system at data rates up to 10 Gbit/s, commercially available devices developed for terrestrial fiber optic applications may be employed to advantage. We designed, set up and tested a breadboard consisting of an NRZ/RZ transmitter with a booster amplifier of 1 Watt optical output power and an optically preamplified direct detection receiver. The main objective was to determine the receiver sensitivity and assess critical components. With the breadboard parameters optimized, the required average number of photons per bit at the receiver input was 55 for a bit error probability of BEP = 10^{-6} in case of NRZ coding. We further demonstrated a sensitivity improvement of about 1 dB by applying RZ coding. The measurements yielded excellent agreement with simulations performed with a tool especially designed for this purpose.

1. Introduction

Since the early seventies efforts towards optical space communications have been undertaken worldwide, not at least in Europe. Links from ground to space (and vice versa), deep space communications and intersatellite links were considered [1,4]. Recently, the first non-classified optical intersatellite link has been established between SPOT4 and ARTEMIS, two satellites built by European consortia [10]. Our aim was to investigate the possibility of implementing an optical intersatellite link using devices developed for terrestrial applications at data rates up to 10 Gbit/s. This should result in simple and robust terminals.

There are two major contenders today for highly sensitive space borne optical receivers in the multi-Gigabit/s range: optically preamplified direct detection receivers and coherent receivers. Although the theoretical limit of the receiver sensitivity is lower for coherent detectors than for direct detection reception, the experimentally achieved values are better for the latter technology [9,5,8]. Both technologies perform equally well with respect to sensitivity towards background radiation [3,12]. However, in our opinion, considering system complexity and availability of critical system components, optically preamplified direct detection reception is the clear winner, especially at data rates beyond 1 Gbit/s.

Excellent optical amplifiers are available in the form of Erbium doped fiber amplifiers (EDFA). They can serve both as booster amplifier in the transmitter and as preamplifier in the receiver. When employing EDFAs, the system wavelength is set to 1,550 nm. Compared to links operating at $\lambda = 850$ nm or $\lambda = 1{,}064$ nm, the larger antenna beam widths can be cited as a disadvantage. Still, because of the excellent state-of-the-art of the available components and their robustness, we chose an optically preamplified direct detection system at 1,550 nm for our investigations. With a transmit power of 1 W and the high receiver sensitivity we achieved within this study, one may close a link with some 70 dB transmission loss if the data rate does not exceed 10 Gbit/s. For a low-earth orbit scenario

*Corresponding Author

with a link distance of some 5,000 km this would imply telescope diameters of some 6 cm, while for a geostationary intersatellite link with a distance of 80,000 km the required telescope diameter amounts to 25 cm.

The problem of pointing, acquisition and tracking will not be addressed here. We assume that an appropriate system providing sufficient alignment of the transmit and receive telescopes is available on board the satellite [1,10].

2. Breadboard Setup

The breadboard we set up consisted of an optical transmitter with a transmit power of 1 Watt, of devices simulating free-space loss, and of an optically preamplified receiver. The nominal wavelength was $\lambda = 1{,}550$ nm, the data rate was R = 10 Gbit/s and the modulation format was either non-return-to-zero coding (NRZ) or return-to-zero coding (RZ). As far as possible, commercially available devices were used. Figure 1 shows the block diagram.

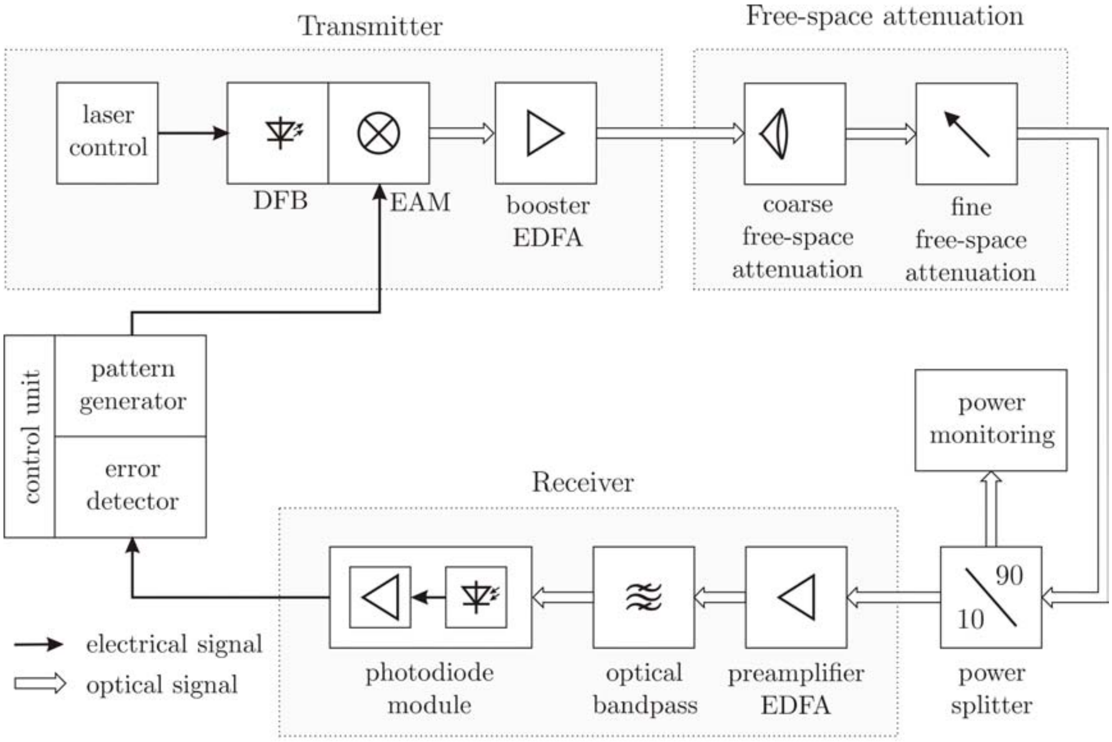

Figure 1: Block diagram of breadboard setup. (DFB…distributed feedback laser, EAM…electro-absorption modulator, EDFA…Erbium doped fiber amplifier).

2.1. Transmitter

A distributed feed back laser (DFB) with an integrated electro-absorption modulator (EAM) served as transmitter source. This device (ALCATEL model 1915LMM) offers easy on-off-keying capability. The electrical signal source was a pattern generator, providing an NRZ-coded signal. For RZ coding the breadboard was modified (see Subsect. 3.3). The modulated optical signal with an average power of about –3 dBm is amplified by a booster EDFA (noise figure F = 5 dB) to achieve an optical output power of 1 W at the transmitter output. The booster EDFA (IRE POLUS model EAD-1-C-PM) is polarisation maintaining.

This property was not exploited in the course of this project but would be required in a two-way link where beams with right-handed and left-handed circularly polarized light would be used in either direction, respectively.

2.2. Free-space loss simulation

Link attenuation due to space loss was simulated in the laboratory. Coarse attenuation of about 40 dB was obtained by picking up only a small fraction of the beam diverging from the EDFA´s fiber pigtail with a single-mode fiber input face placed at a distance of a few mm. For fine adjustment we employed a commercial variable attenuator equipped with single-mode fiber interfaces. The overall attenuation, including the power splitter at the receiver input, amounts to some 70 dB.

2.3. Receiver

In the receiver part, an EDFA with a small-signal gain of 38 dB and a noise figure of 3.3 dB served as optical preamplifier (OPREL model OFP14W-1132S). An optical band-pass filter followed to reduce the broadband amplified spontaneous emission (ASE) generated by the EDFA. Theoretical analysis [14] showed that there is an optimum bandwidth for the filter, depending not only on data rate but also on the shape of the received pulses and on the electrical bandwidth of the photo-diode module. Today, only fiber Bragg gratings have bandwidths narrow enough to achieve optimum receiver sensitivity. To invert the bandstop characteristic of a fiber grating to the desired bandpass characteristic, an optical circulator was added. Four Bragg filters with different bandwidths were used to experimentally verify computational results.

The most relevant parameters of the subsequent photo-diode module are bandwidth, conversion gain, and circuit noise. Commercially available products with integrated amplifier typically provide bandwidths in the range of the data rate for which they have been designed. Receivers with larger bandwidths usually provide low conversion gain. Earlier simulations showed that electrical bandwidths close to the data rate are optimum, anyway [14]. Thus, when using a commercial device, a subsequent electrical low pass filter is not required. The device we employed (LUCENT model 2860-C) has a bandwidth of 8 GHz, the electrical spectral noise density amounts to $1.8 \cdot 10^{-8}$ V/√Hz and the optical-to-electrical conversion gain is 3,800 V/W at $\lambda = 1{,}550$ nm. An error detector was used to determine the bit error probability of the received data.

3. Receiver sensitivity measurements and calculations

To achieve the highest possible receiver sensitivity with the setup described, we optimized the following parameters:

- laser drive current,
- laser emission wavelength,
- peak-to-peak modulation voltage,
- modulator bias voltage,
- bandwidth of the optical bandpass filter.

Laser drive current, modulation voltage amplitude and bias influence the transmit signal´s pulse shape. The laser emission wavelength must match the center wavelength of the Bragg filter in the receiver. Sampling instant and decision threshold of the error detector have to be optimized for each measurement separately. A pseudo random bit sequence with a bit length of 2^7-1 was transmitted.

3.1. Simulation of receiver sensitivity

To calculate the bit error probability for a receiver with optical preamplification and on/off-keyed input signals, we developed a simulation tool. The input parameters of this program are the input pulse form, the EDFA´s properties (noise figure and gain), the optical filter characteristics as well as bandwidth, conversion gain and noise of the photo-diode module.

3.2. Measurements with NRZ-coded input signal

The receiver sensitivity S (defined here as the receiver input power required to achieve a bit error probability of BEP = 10^{-6}) was determined as a function of the optical filter bandwidth by employing four different optical bandpass filters. For each filter the laser emission wavelength was optimized separately to obtain maximum transmission and thus highest sensitivity (cf. Fig. 2). Figure 3 presents the four optimum sensitivity values together with the interval of measurement uncertainty (±0.18 dB, as guaranteed by the manufacturer of the optical power meter used). The receiver sensitivity is also expressed by the required number of photons per bit, n_S, at the receiver input. The filter with a bandwidth of B_o = 16 GHz appears to be the best choice, the filter with B_o = 31 GHz leads to similar performance. The broadest filter is suboptimum because of the high amount of noise caused by amplified spontaneous emission (ASE), detected by the photo-diode module. On the other hand, the consequence of a too small filter bandwidth is pulse shape distortion and signal energy rejection, resulting in a clear sensitivity penalty. Figure 3 shows that increasing the filter bandwidth from its optimum value results in less sensitivity degradation than decreasing it by the same amount; if in doubt, broader filters have to be preferred.

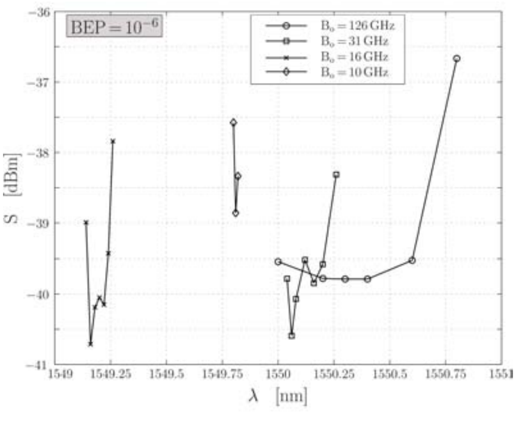

Figure 2: Receiver sensitivity S vs. wavelength λ for four optical bandpass filters differing in bandwidth and center wavelength in case of NRZ coding with an extinction ratio of ζ = 10.8 dB. (B_o…optical bandwidth).

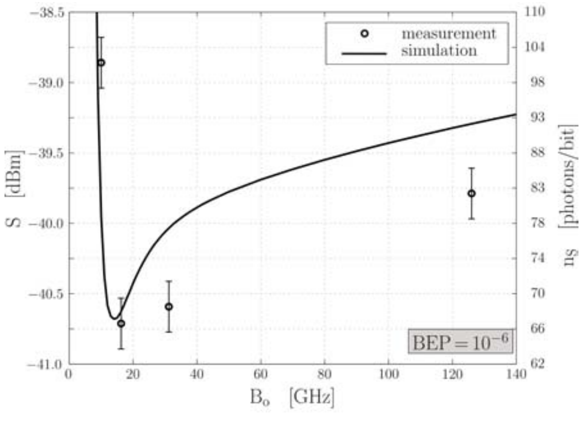

Figure 3: NRZ coding: Measurement and simulation results for the receiver sensitivity expressed either in dBm (S) or in photons/bit (n_S) vs. optical filter bandwidth B_o. The intervals indicated by the vertical lines represent the measurement uncertainty of ±0.18 dB.

Taking into account the chosen scale of the ordinate, the simulation results included in Fig. 3 agree well with the measurement. The deviation is some 0.5 dB for broad filters, 0.1 dB for the optimum bandwidth and about 1 dB for the narrowest filter. The fact that the simulation results are worse than the measurement results may be explained by the noise model applied for the simulation: The assumed Gaussian distribution of the ASE results in a sensitivity error of some +0.5 dB compared to the correct theoretical model [13].

Sensitivity deviations for filters with small bandwidths may be caused by suboptimum laser wavelength setting and insufficient filter modeling. Our simulation did not take into account a possible asymmetry of the filter's transfer function. Such asymmetry leads to distortion with effects equal to that of intersymbol interference, resulting in higher optimum filter bandwidth. Other reasons for the discrepancy may be imperfect modeling of the electrical filter characteristics: The diode module has been modeled as Bessel filter of 5th order after measuring the magnitude of the transmission function. No information on the phase was available. Another reason for the difference between measurements and simulation could be attributed to imperfect modeling of the transmit signal's pulse shape.

To determine the influence of the extinction ratio of the transmit pulse, the modulation voltage and the bias of the modulation voltage were varied and the bit error probability vs. receiver input power was measured. Figure 4 shows the sensitivity as a function of the extinction ratio ζ. The maximum extinction ratio we could achieve was $\zeta = 11.8$ dB. This led to a receiver sensitivity of $S = -41.5$ dBm corresponding to $n_S = 55$ photons/bit.

In Fig. 4 we also included simulation results. Measurements and simulation were performed for an optical bandwidth of $B_o = 16$ GHz, they differ by less than 0.5 dB. The deviation of the measurement point for $\zeta = 11.8$ dB may be caused by the noise of the oscilloscope used for extinction ratio measurements, which introduces measurement inaccuracy especially for high extinction ratios, where the zero-bit power is low.

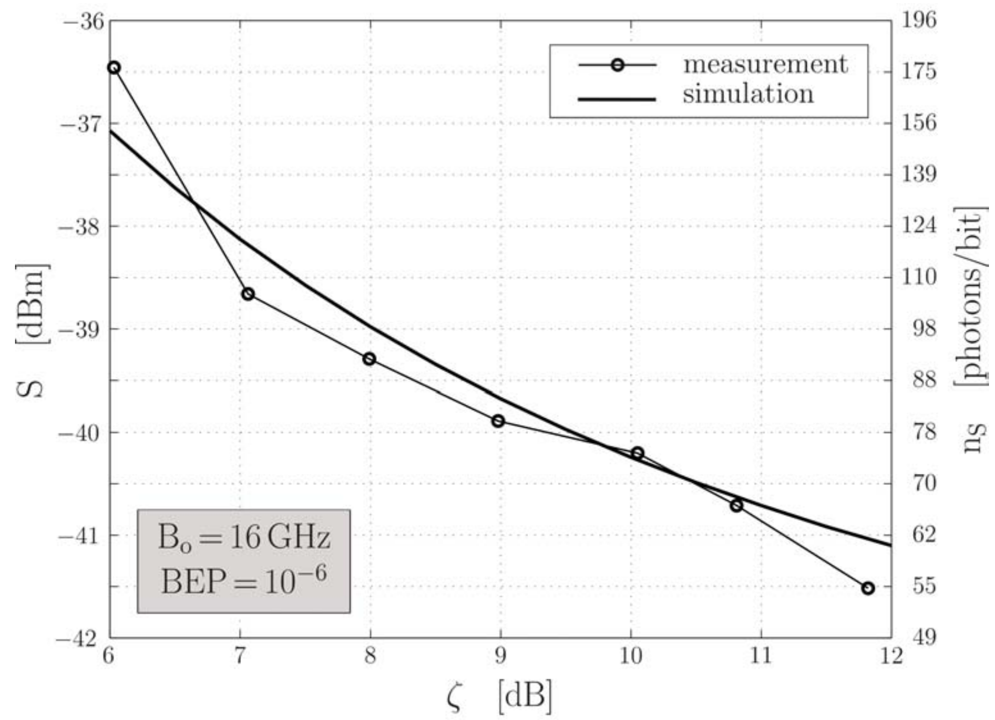

Figure 4: NRZ coding: Measurement and simulation results for the receiver sensitivity expressed either in dBm (S) or in photons/bit (n_S) vs. extinction ratio ζ. (B_o…optical bandwidth).

3.3. Measurements with RZ-coded input signal

It was found analytically that there is an advantage in introducing return-to-zero coding (RZ coding) in systems with direct detection receivers [6,11] – even if the receiver bandwidth is kept equal to that optimal for NRZ signals. This was also confirmed by numerical simulations [7].

To generate an RZ-coded transmit signal some modifications in the transmitter were necessary (see Fig. 5). The EAM now serves as data modulator (cf. inserts (a) and (b)), while a Mach-Zehnder modulator (MZM) fed with a sinusoidal voltage of frequency equal to the data rate acts as NRZ-RZ converter (insert (c)). The bias of the MZM was chosen such that the resulting pulse form is a sine-square shaped RZ pulse with a duty cycle of about 0.5, as shown in insert (d) of Fig. 5. The duty cycle is defined as the ratio of pulse duration (full width half maximum) and bit duration T_{bit}. A polarization control was implemented to properly set the input polarization of the MZM.

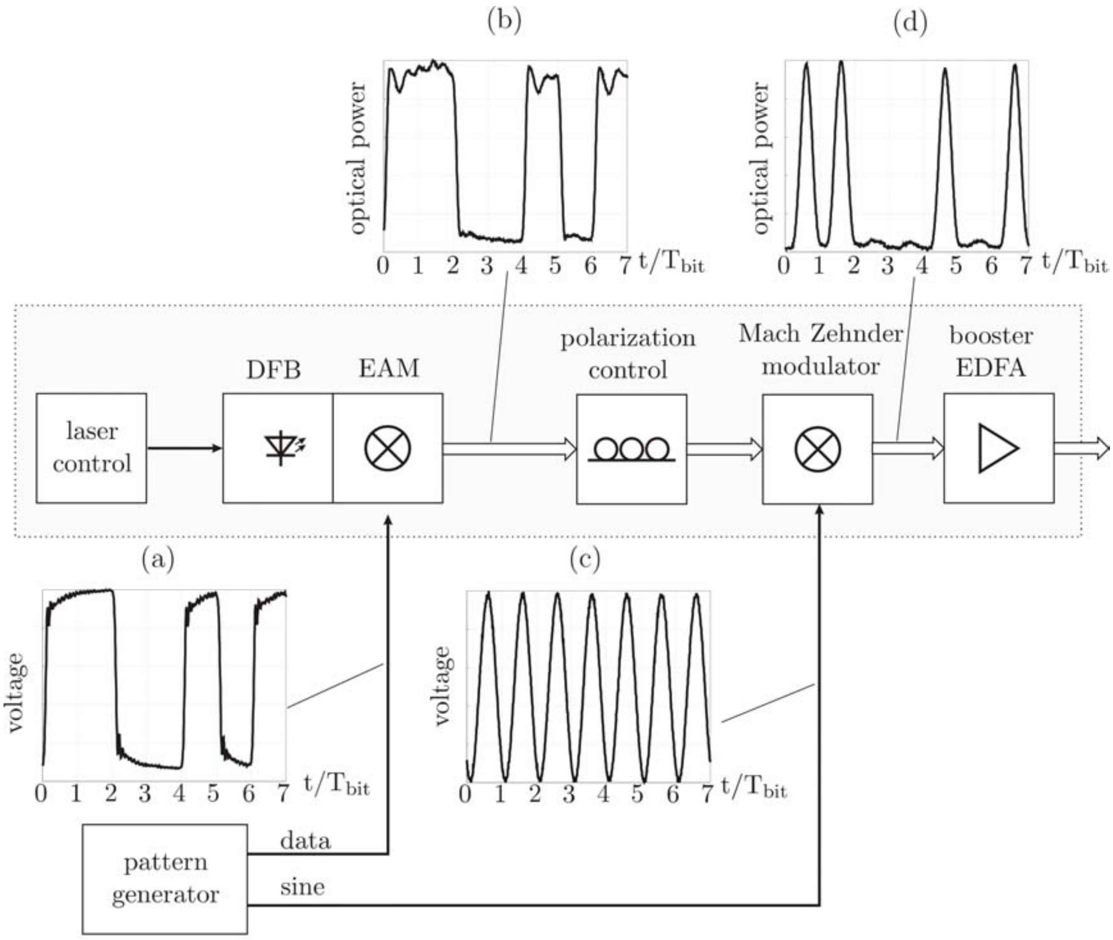

Figure 5: Block diagram of the breadboard transmitter for RZ modulation. The inserts (a) and (c) show the modulation voltages for the electro-absorption modulator (EAM) and the Mach-Zehnder modulator, respectively. (b) gives the optical power after the EAM, while (d) shows the RZ coded transmit signal. (T_{bit}…bit duration).

For RZ-coded signals, the same measurements and simulations as for NRZ were performed. Figure 6 presents the measurement and calculation results for the receiver sensitivity as a function of the optical filter bandwidth for RZ coding (the results for NRZ coding are also displayed for comparison). In contrast to NRZ coding, the experimentally determined optimum filter bandwidth is now $B_o = 31$ GHz. The corresponding sensitivity is some 1 dB better than that for NRZ coding in case of equal extinction ratio of $\zeta = 10.8$ dB but optimum filter bandwidth.

For RZ coding the difference between the measurements and calculation is less than 0.5 dB for large optical filter bandwidths. For narrow filters the differences are larger which may be explained by imperfect pulse and filter modeling. In both the simulation and measurement, RZ leads to better system performance.

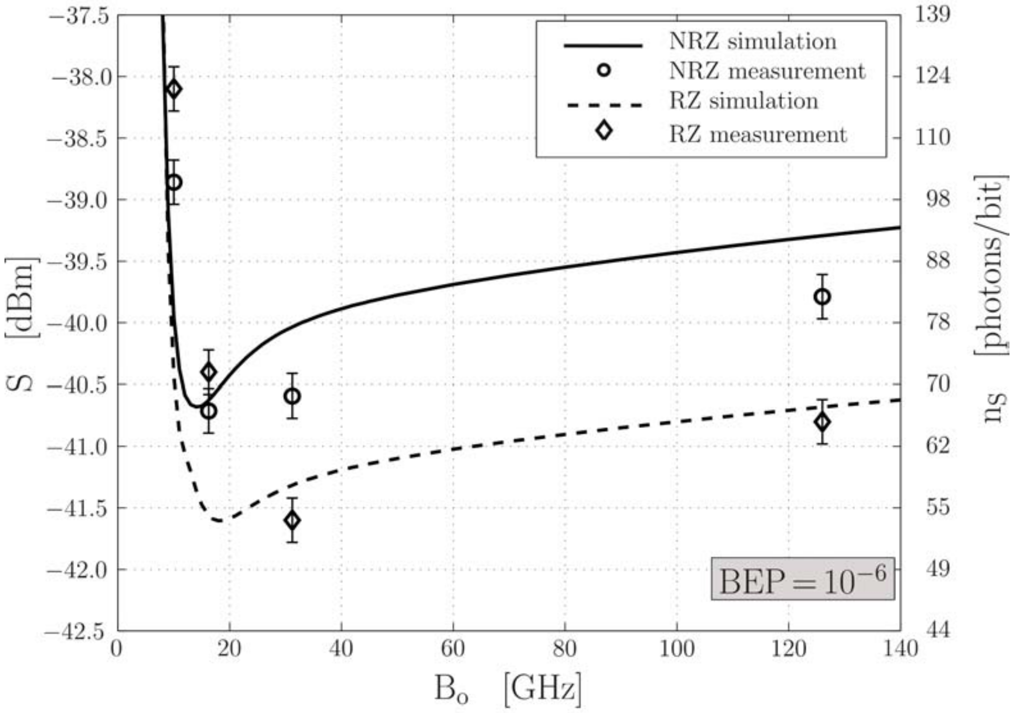

Figure 6: NRZ and RZ coding: Calculated receiver sensitivity expressed as required input power S and as photons per bit, n_S, vs. optical filter bandwidth B_o. The circles and diamonds represent the measurement results obtained with the available optical filters for NRZ and RZ coding, respectively.

4. Discussion

4.1. Transmitter

Measurement and simulation results showed that one of the most critical parameters for system performance is the transmit pulse extinction ratio ζ (cf. Fig. 4). A pronounced sensitivity degradation is to be expected when ζ becomes less than 10 dB. To avoid this, the modulation voltage, the modulator bias, and the laser drive current have to be adjusted and controlled precisely. With the DFB+EAM module investigated here, the maximum extinction ratio obtained was 11.8 dB. An additional modulator, driven with the data signal, may improve the extinction ratio and thus lead to higher system sensitivity.

Both measurement and simulation showed that laser emission wavelength deviations from the optimum value amounting to 20% of the bandwidth B_o of the optical filter will result in a sensitivity penalty of 1 dB. For the breadboard, a temperature stabilized laser diode mount was used to control the laser wavelength, thus providing sufficient wavelength stability. The optimum optical filter bandwidth for the breadboarded system was in the range of 15 to 20 GHz. On a wavelength scale, this corresponds to 120 to 160 pm.

For the link budget assumed for the breadboard, the influence of the booster EDFA´s ASE is negligible, while for other configurations, the booster noise might have to be considered [11].

4.2. Receiver

In a well-designed setup the preamplifier EDFA causes the dominating noise in the receiver. Therefore its noise figure should approach the theoretical limit of 3 dB as close as possible.

The optical bandpass was a critical component in the receiver setup. Its temperature dependent center wavelength and its bandwidth strongly influence the receiver sensitivity. Considering the results presented in Fig. 2 as well as temperature drift of the filter center wavelength and variations of the optical carrier frequency due to temperature changes and possibly Doppler shift, it is recommended to use filters with higher than optimum bandwidths. Another, technically-demanding, approach to overcoming these problems is to actively control the center wavelength of the filter.

The insertion loss of the circulator/grating combination plays a minor role because it attenuates the optical signal in the same way as the optical noise, and because the electrical noise is, in general, negligible.

For the breadboarded system, the data clock signal was taken from the pattern generator and fed to the error detector. In a real system, a clock recovery of its own will have to be implemented, as it is by now standard in terrestrial fiber systems.

The sampling instant and the decision threshold for the error detector were optimized manually for every measurement. The sampling instant, which is not that critical, could be fixed relative to the recovered clock signal. Using an automatic power control at the input of the photo-diode module could mitigate the problem of threshold optimization, since the decision threshold could then be set once and its optimum value would not change significantly for different receiver input power levels.

4.3. Devices requiring technological improvement for space application

For the laboratory setup described in this paper we intentionally chose and employed devices which are not only commercially available but also demonstrated high reliability and pronounced robustness when implemented in terrestrial fiber links. The toughest application of such fiber links is that in long-distance undersea communications. Still, the requirements in a space application are more demanding. We expect that the most critical stress will result from radiation. Temperature stress will not pose a problem in a typical satellite environment: The operating temperature range required in terrestrial applications is usually much larger than that inside an earth-orbiting satellite. For a free-space transmission system with high output power (>1 W) at $\lambda = 1.55\ \mu m$ based on direct modulation and optical preamplification, the EDFAs are the devices deserving most attention when space qualification is to be obtained.

5. Effects leading to the difference to the quantum limit

For NRZ coding the best sensitivity achieved in experiment and simulation is 3.1 dB worse than the quantum limit which amounts to $n_S = 27$ photons/bit for BEP = 10^{-6} [2]. We investigated the individual contributions of the effects leading to this difference by performing calculations with modified simulation parameters.

Setting the electrical noise and the noise from the booster EDFA zero, assuming ideal noise properties of the preamplifier EDFA (3 dB) and the transmit pulse (rectangular with infinite extinction ratio) leads to 0.5 dB sensitivity penalty relative to the quantum limit. This is attributed to the fact that the optical Bragg filter and the electrical Bessel filter are not matched to the signal pulse shape.

For a realistic noise figure of the preamplifier EDFA (e.g. 3.3 dB), a receiver setup without polarization filter, realistic electrical noise density ($N_0 = 1.8 \cdot 10^{-8}$ V/√Hz) and when including the influence of booster ASE, a 1 dB sensitivity penalty has to be expected.

Taking into account, finally, the measured extinction ratio and pulse shape in the simulation, leads to a sensitivity penalty of 3.1 dB. This indicates again that the transmit signal shape is the most important parameter influencing system performance.

6. Summary

A breadboard for an optical free-space communication system employing only off-the-shelf devices designed for terrestrial fiber applications was set up and tested. Core parts of the setup were a booster EDFA in the transmitter and an EDFA serving as optical preamplifier for the direct detection receiver. The booster amplifier provided an output power of 1 W, while the preamplifier, which appeared to be the dominating noise source of the system, had a noise figure of 3.3 dB, close to the theoretical minimum of 3 dB. Using a simulation tool we determined the optimum optical bandwidth of the receiver. With the parameters thus found, maximum receiver sensitivity was achieved.

Two modulation formats were implemented: NRZ and RZ. RZ coding lead to a performance gain of some 1 dB. It is less sensitive to suboptimum optical bandwidths at the receiver.

The best sensitivity we obtained was only some 3 dB above the quantum limit, proving the attractivity of preamplified receivers with direct detection for optical free-space communication.

Acknowledgments

This work was funded by the European Space Agency (ESA) under ESTEC/Contract No. 14459/00/NL/JSC and by the Austrian Science Fund (FWF), under Grant P13998-TEC. The authors would like to thank Martin Pauer, Martin Strasser, and Peter Winzer for valuable discussions.

References

[1] V.W.S. Chan, Optical space communications, IEEE J. on Selected Topics in Quantum Electronics, vol. 6, 2001, pp. 959-975.

[2] G. Einarsson, Principles of lightwave communications. John Wiley & Sons, Inc. 1996.

[3] W.R. Leeb, Degradation of signal to noise ratio in optical free space data links due to background illumination, Applied Optics, 28, 1989, pp. 3443-3449.

[4] H.P. Lutz, Optical communications in space – twenty years of ESA effort, esa bulletin, vol. 91, 1997, pp. 25–31.

[5] S. Norimatsu et al., 10 Gbit/s optical BPSK homodyne detection experiment with solitary DFB laser diodes, El. Lett., vol. 31, no. 2, 1995, pp. 125-127.

[6] S.D. Personick, Receiver design for digital fiber optic communication systems, Bell Sys. Tech. J., vol.52, 1973, pp. 873-874.

[7] M. Pfennigbauer, P.J. Winzer, M.M. Strasser, and W.R. Leeb, Optimum optical and electrical filter characteristics in optically preamplified direct detection (N)RZ receivers, in Proc. SPIE, Free-Space Laser Communication Technologies XIII, vol. 4272, 2001, pp. 160-169.

[8] M. Pfennigbauer, M.M. Strasser, M. Pauer, and P.J. Winzer, Dependence of optically preamplified receiver sensitivity on optical and electrical filter bandwidths - measurement and simulation, Phot. Technol. Lett., vol. 14, no. 6, 2002, pp. 831-833.

[9] M.M. Strasser, M. Pfennigbauer, M. Pauer, and P.J. Winzer, Experimental verification of optimum filter bandwidth in direct-detection (N)RZ receivers limited by optical noise, in LEOS ’99, IEEE Laser and Electro-Optics Society 14th Annual Meeting, vol. 2, 2001, pp. 485–486.

[10] T. Tolker-Nielsen, and G. Oppenhaeuser, In orbit test result of an operational optical intersatellite link between ARTEMIS and SPOT4, SILEX, in Proc. SPIE, Free-Space Laser Communication Technologies XIV, vol. 4635, 2002, pp.1-15.

[11] P.J. Winzer, and A. Kalmar, Sensitivity enhancement of optical receivers by impulsive coding, J. Lightwave Technology, vol. 17, no. 2, 1999, pp. 171-177.

[12] P.J. Winzer, A. Kalmar, and W.R. Leeb, Role of amplified spontaneous emission in optical free-space communication links with optical amplification – impact on isolation and data transmission; utilization for pointing, acquisition, and tracking, in Proc. SPIE, Free-Space Laser Communication Technologies XI, vol. 3615, 1999, pp. 134-141.

[13] P.J. Winzer, Receiver noise modeling in the presence of optical amplification, in Proc. OAA, Optical amplifiers and their applications, 2001, paper OTuE16.

[14] P.J. Winzer, M. Pfennigbauer, M.M. Strasser, and W.R. Leeb, Optimum filter bandwidths for optically preamplified NRZ receivers, J. Lightwave Technology, vol 19, no. 9, 2001, pp. 1263-1273.