DLR Experimental Systems for Free Space Optical Communications

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Abstract

Two coherent optical transmission systems, both transmitting 565 Mbit/s at 1064 nm are presented. These systems have been designed for experimental studies in the laboratory and in a stationary free space optical link. The aim is to demonstrate the suitability of such high–bitrate coherent optical data transmission schemes for future space applications. The prototype breadboard system uses PSK modulation with homodyne reception. A new synchronization technique made it feasible to build up a low–complexity receiver allowing a power efficient transmission 3.5 dB above the shot noise limit. The second system is a compact and robust DPSK system with heterodyne detection. This system is embedded in a new stationary test facility, which shall allow free space communication experiments between two buildings (760 m).

1 Introduction

Free space optical communication for satellite and deep space applications is a challenging aim for the next decades. Advances in the development of fast electronic circuits and high quality optical components, such as lasers and optical modulators, allowed the realization of very high sensitive and high speed coherent optical communication systems in the past. For future space applications, such systems will offer many advantages over the traditional microwave transmission schemes, such as reduced receiving and transmitting antenna size, higher transmission capacity, avoidance of interference problems in the overcrowded microwave fequency spectrum and many others.

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Much work has been already done in this field [1,2,3,4,5,6]. Since 1989, also the DLR institute for communications technologie has spread its activities in digital communication systems up to the optical frequencies. In the following, the DLR experimental systems for free space optical communications will be presented.

In section 2 a breadboard PSK homodyne system with a special technique for carrier synchronization will be presented. This system allows a power efficient operation 3.5 dB above the shot noise limit with 565 Mbit/s. For testing and demonstration of the components and the systems under more realistic conditions a stationary 760 m free space link between two buildings has been established. This testbed, which is presently equipped with a 2-DPSK optical heterodyne system, will be presented in section 3.

2 The Optical Homodyne System

Free space optical communication between satellites and especially for deep space applications require the most sensitive transmission scheme as possible. As is shown in theory, the best performance in this sense offers an optical PSK system with homodyne detection [7,8]. In such a system some kind of an optical PLL is required, that allows the local oscillator laser (LO) to be tuned to exactly the same frequency and phase as the transmitted carrier. Normally, the phase locking of the LO in an optical homodyne system is one of the most critical problems in the realization. The DLR breadboard PSK homodyne experimental system, which uses a new variant of a carrier synchronization technique is presented in the following.

2.1 PSK Homodyne Receiver Synchronization Using Synchronization Bits

Phase control of the local oscillator in an optical PSK homodyne system is usually performed by means of the Costas loop technique [9]-[15] or the pilot carrier technique [16]-[23] In spite of higher complexity and the need of an optical hybrid the Costas loop is often preferred to the simple pilot carrier technique because AC coupling is possible and the PLL is independent of the data signal [9,10,24,25]. In the following new approach, the advantages of the Costas Loop are combined with the simplicity of the pilot carrier receiver.

Proceeding from the Costas Loop design, the principle of the synchronization method is shown in figure 1 and 2. Instead of feeding a fraction α of the received light into the quadrature arm continuously as done in a Costas Loop receiver (fig. 1), the inphase arm and quadrature arm are used alternately (fig. 2). It can easily shown, that if the quadrature arm is used for a portion α of time, the properties of this receiver are the same as compared to a Costas Loop receiver with splitting ratio α. The phase error

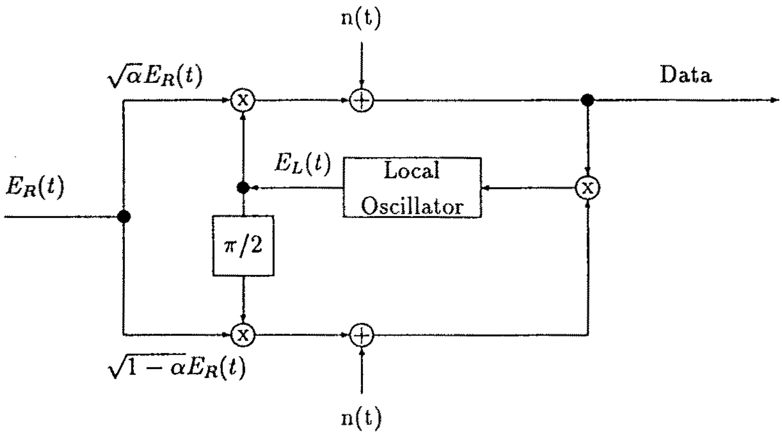


Figure 1: Principle of the PSK homodyne receiver with a conventional Costas loop.

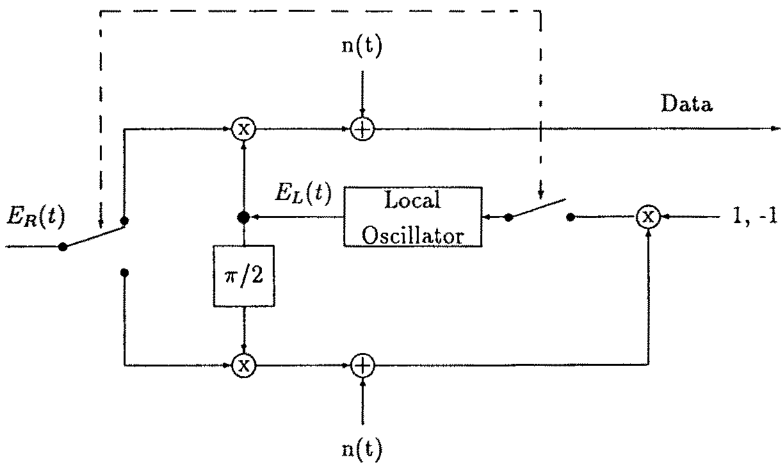


Figure 2: Principle of the sync–bit synchronization technique derived from the Costas loop design, where inphase and quadrature arms are used alternately.

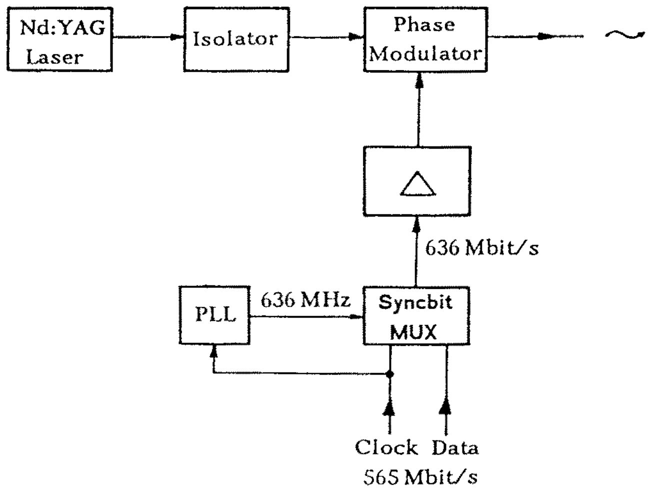


Figure 3: Block diagram of the PSK transmitter.

signal is obtained by sampling the quadrature signal and multiplying it with the polarity of the bit sent at this time.

The switching of the received light power to the quadrature arm and the generation of the phase error signal could be done at every bit for the portion of time αT_B (T_B = duration of one bit) or every $1/\alpha$ bit for the time T_B. Which technique is applied depends on the laser linewidth–to–bitrate ratio. If entire bits are used for synchronization as shown in figure 1, these bits are called synchronization bits.

As can be seen in figure 2, inphase and quadrature arms are never used at the same time. Therefore, with regard to the practical realization, only one optical frontend and one signal path is sufficient. Switching between the inphase and quadrature functions of this signal path could be simply obtained by shifting the phase of the local oscillator by 90 degrees at the right moments, but there will be still the need for a phase modulator in the receiver. The most elegant method with lowest complexity provides the 90 degree switching in advance in the transmitter, where a phase modulator is present at all. This technique has been realized in a experimental setup in the laboratory.

2.2 Homodyne Experimental Setup

The principle block diagram of the homodyne transmitter is shown in figure 3. The

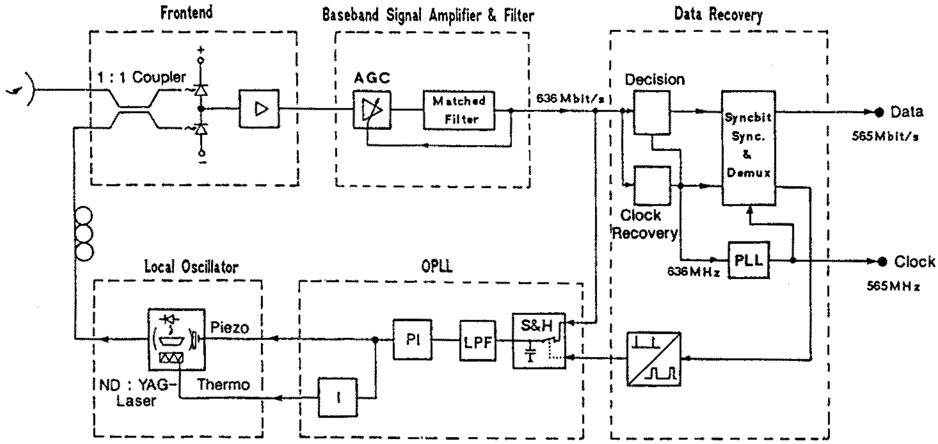


Figure 4: Block diagram of the PSK homodyne receiver.

optical path contains a diode pumped Nd:YAG laser with wavelength $\lambda = 1064$ nm and $P_s = 45$ mW output power. The laser is screened against backreflections by the optical isolator. The external modulator is a travelling wave $LiNbO_3$ phase modulator. Prior to phase modulation ("1" $= +90^0$, "0" $= -90^0$), the incoming data stream is supplied with the synchronization information by insertion of one synchronization bit (0^0) after every eighth bit. An example for the resulting modulating signal with the sync–bits and the expanded symbol rate of 635.625 Mbit/s is shown in the upper trace in figure 5.

The PSK homodyne receiver is shown in figure 4. It consists of a simple balanced frontend with transimpedance amplifier. The level of the shot noise is about 8 dB higher than the thermal noise (LO power $P_l = 4$ mW). The signal then passes to an amplifier with automatic gain control (AGC) and a matched filter. Since the pulse shape of the transmitted signal is rectangular, the detected signal after the matched filter has a triangular form, as shown in the middle trace of figure 5. The following clock recovery regains the 635.625 MHz clock even when an optical phase lock is not yet achieved. This is required for the following digital logic, which finds the synchronization bits, to sample the analog signal at the right moment to obtain the phase error signal. The frequency and phase of the local oscillator are controlled by temperature and a piezo crystal. The synchronization bits still contained in the detected signal after the matched filter (see fig. 5) are removed by means of a demultiplexer, and the original data with 565 Mbit/s is regained (fig. 5,lower trace).

Figure 5: Exemplary waveforms in the realized transmission system (5 ns/division): Modulating signal (phase of the transmitted light), baseband signal after matched filter and recovered data stream.

2.3 Performance Results

The measurement setup for the performance evaluation of the homodyne system is shown in a short form in figure 6. The transmitted digital signal is a pseudo-random sequence of length $L_p = 2^{10} - 1$. The signal is transmitted over a short free space distance on the optical bench and attenuated by defocussing the telescopes. A 3 dB coupler splits the incoming light so that the optical power meter indicates the power of the light directly at the input of the receiver. This method is easier and more accurate than deriving the input

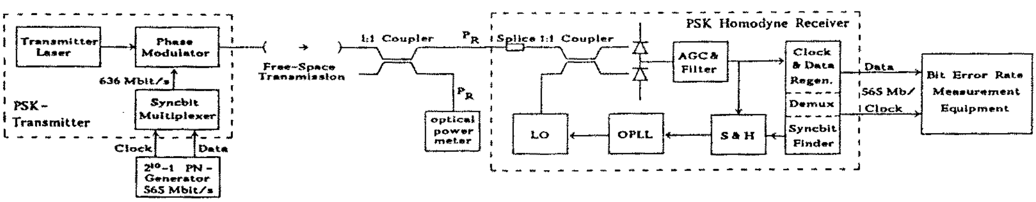


Figure 6: Measurement setup for the PSK system.

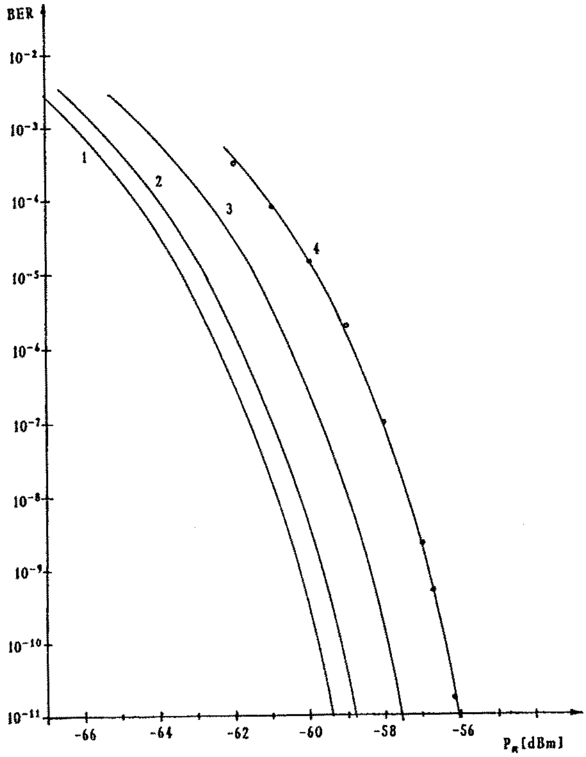


Figure 7: Bit error rate against optical input power: (1) ideal system, shot noise limited, (2) system performance including loss due to synchronization, (3) with additional loss due to quantum efficiency and (4) experimental result.

power from the IF current level. Measurement accuracy depends only on the asymmetry of the coupler, loss of the splice and accuracy of the power meter. The asymmetry of the coupler can easily measured and has been taken into account; the splice has been considered to be a part of the receiver and the accuracy of the power meter is better than 10% in the nanowatt range. Therefore the maximum error is approximately 0.4 dB. The bit error rate (BER) has been measured as a function of the received optical power P_R in the receiver and the results are shown in figure 7.

Curve 1 represents the ideal 565 Mbit/s PSK homodyne receiver assuming photodetectors with 100% quantum efficiency and with no loss due to synchronization. As compared to this ideal curve, the realized receiver (curve 4) requires 3.5 dB more light power.

The degradations in figure 7 can be explained as follows:

Wavelength	$\lambda = 1064$ nm (Nd:YAG)
Information bit rate	$f_B = 565$ Mbit/s
Channel bit rate	$f_C = 635.625$ Mbit/s
Bit error rate	$BER = 10^{-9}$
Data (pseudo random)	$L_p = 2^{10} - 1$

Received light power required for an ideal system [8] (shot noise limit)		-60.3 dBm
Losses:		
Increase of channel bit rate by 9/8		0.5 dB
Quantum efficiency of photodiode ($\eta = 0.75$)		1.3 dB
Other Implementation losses		1.7 dB
Received light power required in the realized system	Σ	-56.8 dBm

Table 1: Characteristics of the realized PSK homodyne system.

- The sync–bit carrier recovery technique described above causes a 0.5 dB sensitivity penalty (curve 2), because after every eighth data bit, a non information carrying sync–bit is inserted. This causes an increase of the channel bitrate by the factor 9/8 which results in a degradation of ($10\log(9/8) = 0.5$) dB, due to the increased receiver filter noise bandwidth.
- The non–ideal quantum efficiency of the photodiodes $\eta \approx 75\%$ causes further ($-10\log 0.75 \approx 1.3$) dB degradation (curve 3).
- The residual loss of 1.7 dB (curve 4) represents the effects of the thermal noise of the first amplifier and non–ideal baseband filtering and data clock recovery.

The performance and the technical characteristics of the PSK homodyne system are also summarized in table 1. The measured performance of this realized PSK homodyne system can be characterized alternatively by the need of 20 photons per bit. This is, to the best of our knowledge, the best sensitivity obtained to date with a coherent optical communication system at 565 Mbit/s.

3 The Free Space Testbed

3.1 Objective

In order to have a testbed for free space experiments the DLR institute of communications has built up a stationary test facility allowing free space optical communication between two buildings. The aim is to have a flexible facility for experiments under nearly real conditions for testing systems and components for future coherent optical space transmission schemes. The possible experiments are manifold like e.g.

- gathering experiences with different telescopes under nearly farfield reception conditions,
- testing of high power lasers or laser amplifiers used in future optical space transmission systems,
- on-earth experiments concerning the pointing, acquisition and tracking (PAT) problems,
- investigation of athmospheric effects on coherent optical transmission schemes and
- channel measurements of the athmospheric link.

Due to the open concept, also experiments with components and systems of external partners could be foreseen.

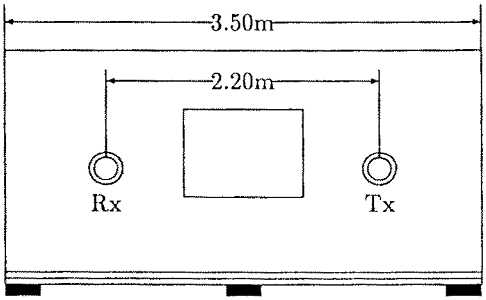
3.2 The Arrangement of the Testbed

A shelter with all optical and electronical equipment for the transmitter and the receiver is positioned on the flat roof of the institute building (5 floors). The shelter has two openings for the optical input and output beams. The optical link is established by choice with a mirror or a retroreflector, which is positioned on the roof of a second building with equal height. For a principal view of this facilities see figure 8. The shelter has been installed in the late 1991 and after the installation of the optical bench in the shelter, the first experiments using a coherent 565 Mbit/s DPSK heterodyne system [26] have been be started in April 92.

3.3 The Optical DPSK System for Free Space Experiments

The differential phase shift keying (DPSK) modulation scheme has been chosen because the obtainable receiver sensitivity is nearly as high (3dB difference) as with the theoretical best receiver (the PSK homodyne receiver), but no phase stabilization of the local

Front View of the Shelter



- trussed beton floor
- trussed front panel
- 2 separate telescopes (Tx and Rx)

Siteplan of the Optical Free Space Link(Top View)

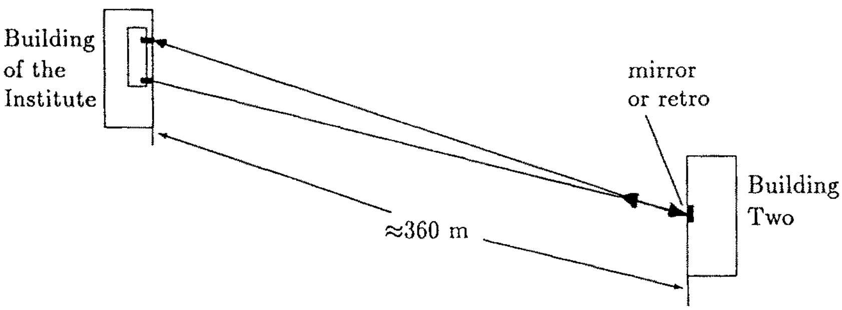


Figure 8: The principal arrangements of the shelter and the optical link.

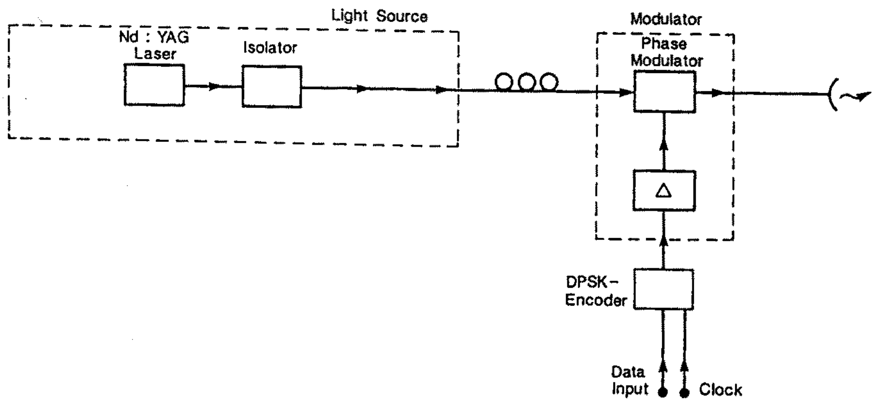


Figure 9: Block diagram of the DPSK transmitter.

oscillator is required. The realized system runs with a bitrate of 565Mbit/s. A compact transmitter and receiver design and the need of only one single 12 Volt power supply made this simple and robust coherent system suitable for the first outdoor experiments. Figure 9 shows the block diagram of the optical DPSK transmitter. As light source we used a commercial available diode-pumped single mode Nd:YAG laser with 50mW cw power emitting light at a wavelength of $\lambda = 1064$nm. The light is led via a polarization controller to a pigtailed $LiNbO_3$ travelling wave phase modulator. The DPSK differential encoder is realized in a device containing three standard logic GaAs IC's. The outgoing data stream is amplified to approximately 7 V_{pp} and amplitude controlled to achieve a constant modulation depth of ±90 degrees over a wide temperature range.

Figure 10 shows the block diagram of the receiver. The incoming light is mixed with the polarization adapted light of a 4 mW MISER in a balanced frontend consisting of a symmetrical (k=0.47) 2x2 coupler and two InGaAs Photodiodes ($R_{eff} \approx 0.5$ A/W). The signal current is amplified by a transimpedance amplifier with an average noise power density of $14\text{pA}/\sqrt{\text{Hz}}$. The intermediate frequency (IF) is only twice the data rate, i.e. 1130 MHz. After bandpass-filtering and amplification, the conversion into the baseband is done by a delay-line demodulator. The data signal is low-pass filtered in a gaussian filter with normalized cutoff frequency $f_{3dB}T_B = 0.79$ and then led to the clock and data recovery unit. This device is a commercially available hybrid circuit using analog and digital GaAs chips, which has been modified for better threshold adjusting due to the

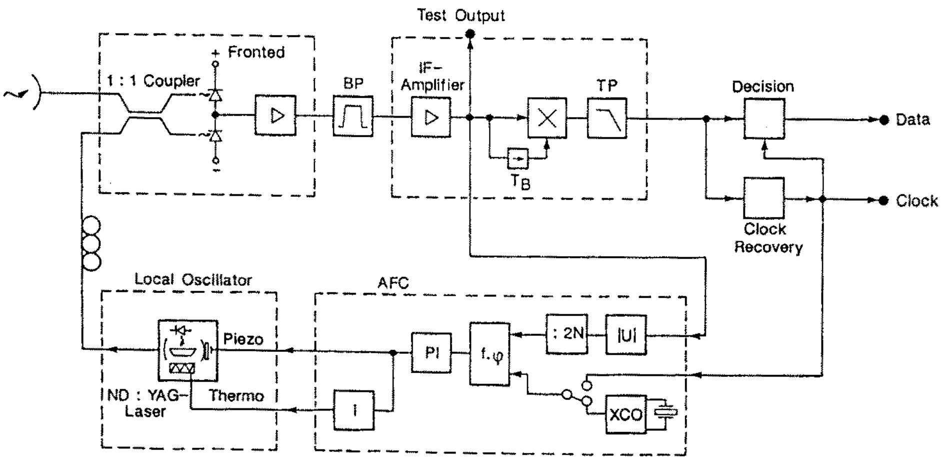


Figure 10: Block diagram of the DPSK heterodyne receiver.

demands of the DPSK scheme. Data and clock signals are available in ECL level.

Although there is no need to control the phase of the local oscillator in a DPSK heterodyne receiver, the intermediate frequency is to be stabilized by an AFC. In the AFC of this receiver the IF signal is squared and then bandpass-filtered and limited. Latter operations are required because of the amplitude distortions due to low IF and IF bandpass filtering. The so obtained 2.26 GHz signal is divided by 4 and compared with the recovered clock or a crystal oscillator signal. Frequency control of the local laser is achieved by using a piezo element and a temperature control unit. With the piezo element, fast but low-range frequency control is possible (±10MHz, speed up to 100 kHz), whereas the temperature control is used to compensate slow drifts by integrating the piezo signal. So the tuning range is only limited by the distance of mode hops of the local laser. Due to the filtering of the squared IF signal, the range in which the AFC is able to recognize a signal is only ±10 MHz. Therefore, the AFC has been supplied with a special device for frequency aquisition. If the IF deviation is larger than 10 MHz, no signal can be detected by the AFC and an oscillator at the frequency divider's input with approximately 2.5 GHz simulates an IF, which is too high. When the IF comes into the detection range, this oscillator signal is overdriven and frequency control begins. So care has to be taken, that when switching on the system, frequencies of transmitter laser and LO should be adjusted to a high intermediate frequency.

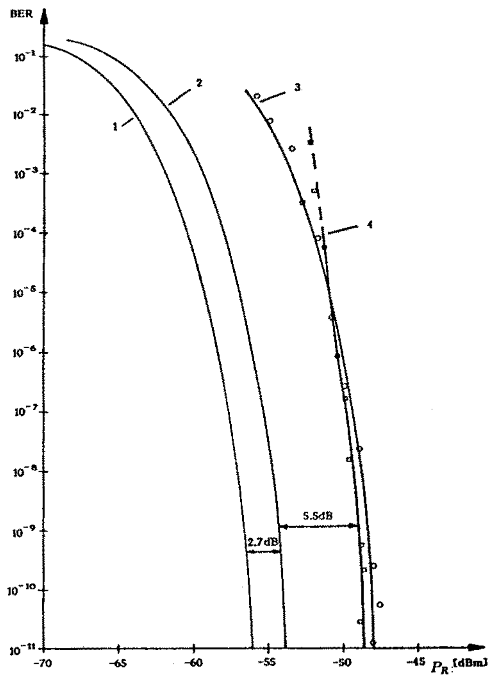


Figure 11: Bit error rate versus optical input power (1) ideal, (2) best realizable regarding the quantum efficiency of the diodes and the gaussian filter, (3) the realized system with hardwired clock and (4) with using the data clock recovery unit.

3.4 DPSK System Performance

The sensitivity of this receiver has been measured by using an IF power measurement technique [26]. Figure 11 shows the BER of the experimental DPSK system versus the optical input power. The ideal receiver at the shot noise limit is represented by curve 1, in curve 2 non-ideal quantum efficiencies of the photodiodes and the non-ideal baseband filter are taken into account. Curve 3 shows the sensitivity of the receiver described here without the data clock recovery unit, that means, that the data signal was sampled and decided in the receiver of the BER measurement equipment using the clock from the transmitter. The loss compared to curve 2 is mainly due to the high thermal noise of the transimpedance amplifier. Here some improvements will be made in the future. Other significant losses come from imperfect light coupling to the photodiodes, Finally, curve 4 shows the behavior of the BER of the complete system, i.e. with data clock recovery unit. One can see, that this device improves the sensitivity at low bit error rates,

Wavelength	$\lambda = 1064$ nm (Nd:YAG)
Bit rate	$f_B = 565$ Mbit/s
Bit error rate	$BER = 10^{-9}$
Data (pseudo random)	$L_p = 2^{23} - 1$

Received light power required for an ideal system [8](shot noise limit)		-56.3 dBm
Losses:		
Quantum efficiency of photodiode ($\eta \approx 0.75$)		1.3 dB
Non–ideal baseband filter (Gaussian)		1.4 dB
Noise and and frequency response of first amplifier		2.5 dB
Non–ideal modulation (driver for modulator)		1.5 dB
Other implementation losses (especially demodulator)		1.6 dB
Received light power required in the realized system	Σ	-48.0 dBm

Table 2: Characteristics of the realized DPSK heterodyne system.

but the transmission nearly breaks down at BER's higher than 10^{-4}, because increasing phase jitter of the clock sometimes causes a synchronization loss of the BER measuring equipment producing more than 10 errors at such a moment.

For all measurements we used a pseudo-noise pattern with a length of $2^{23} - 1$ and a bit rate of 565 Mbit/s. No error rate floor up to $BER = 10^{-14}$ has been observed. The measured sensitivity of $P_R = -48$ dBm of this system at $BER = 10^{-9}$ corresponds to a detection of 150 photons per bit. The characteristics of this DPSK system have been summarized in table 2. The AFC with automatic frequency aquisition allows the system to be switched on by only one switch. After a few seconds the system runs stable and transmits data with a bit error rate corresponding to the received light power. In a long term experiment over several weeks in the laboratory we could prove the stability of the system even under temperature variations caused by sunlight during daytime. This qualified the DPSK system now to be placed into the free space testbed described above. Besides data transmission for demonstration purposes, also a digitized video signal can now be transmitted.

3.5 Free Space Experiments

First experiments in April 92 have shown the arising of many problems, which have already been expected, e.g.

- the problem of the mechanical stability of the whole system, including the building on which it is installed,
- mechanical and thermal stability of the fitting and positioning elements of the telescopes and the coupling of the received light into the monomode fiber coupler,
- vibrations of the mirror,
- optical quality of the mirror respectively the retro,
- coherence losses and polarization disturbances due to athmospheric effects.

These effects are now going to be investigated, looking forward to report on the first experimental results in the future.

4 Conclusions

We have presented the realization of two experimental systems for coherent optical space communications. The very high sensitive PSK homodyne system has been built up as a breadboard system using a new method for carrier synchronization. This technique is similar to the Costas loop design, but requires less critical optical components and fewer analog RF components. By using synchronization bits, optical and analog components have been replaced by digital circuits, which simplifies monolithic integration and therefore makes it useful in critical environments, like in future space applications.

The less critical, but also less sensitive DPSK heterodyne system has been realized in a compact and robust form, so that it could be installed in the new test facility for free space communications, described above. This system will be a cheap and convenient playground for realistic free space experiments in the forefield of future satellite experiments.

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