POWER EFFICIENT OPTICAL COMMUNICATIONS FOR SPACE APPLICATIONS

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ABSTRACT

Optical communications technology promises substantial size, weight and power consumption savings for space to space high data rate communications over presently used microwave technology. These benefits are further increased by making the most efficient use of the available optical signal energy. This presentation will describe the progress to date on a project to design, build and demonstrate in the laboratory an optical communication system capable of conveying 2.5 bits of information per effective received photon. Such high power efficiencies will reduce the need for photon collection at the receiver and will greatly reduce the requirements for optical pointing accuracy, both at the transmitter as well as the receiver. A longer range program to demonstrate even higher photon efficiencies will also be described.

INTRODUCTION

A substantial interest in space to space optical communications was generated in the late 1960's as a result of the invention of lasers and the realization that communications components could be reduced in size and weight by going to optical wavelengths. This enthusiasm quickly subsided as the inefficiencies and reliabilities of lasers, as well as the magnitude of the optical pointing problems were fully appreciated. Recent advances in gallium arsenide semiconductor laser technology have almost completely eliminated the problems associated with optical signal generation. The severity of pointing requirements can likewise be diminished by designing systems which do not require large optical received power concentrations at the receiver.

It was originally believed that optical communications would be limited by the "quantum limit" to one nat of information per received photon (1 nat = 1.44 bits). However, it has more recently been recognized that this limit does not apply to direct optical detection and that substantially higher power efficiencies should indeed be possible [1-5]. Yet, such studies dealt with quantities such as channel capacity and computational cutoff rate, and simply prove the existence of such systems, not the actual design of systems to achieve such performance. For this reason a project was initiated at the Jet Propulsion Laboratory to design a system capable of conveying 2.5 bits/detected photon and to demonstrate the performance of the system in the laboratory environment. The 2.5 bit number was selected because it was comfortably, but not excessively above the "quantum limit". Later systems designs will utilize the knowledge gained from this project to achieve even greater power efficiencies.

DESCRIPTION OF THE 2.5 BIT/DETECTED PHOTON PROJECT

A block diagram of the laboratory demonstration system is shown in Figure 1. The heart of the optical portion of the system consists of a gallium arsenide semiconductor injection laser and a direct detection photomultiplier tube. The GaAs laser diode is a high quality, single spatial mode device operating at 0.85 µm and has the reliability and durability characteristics of solid state devices. The light emitted from the laser is passed through some elementary optics followed by 70-100 dB of neutral density filters (attenuators) which simulate space loss. The attenuated optical signal is then applied to a photomultiplier tube (PMT) detector which has a high internal gain ($>10^6$), a quantum efficiency around 20% and, with moderate cooling, an extremely low dark current. Of course, to eliminate stray laboratory light, all of the optical components must be placed in an extremely dark enclosure.

Surrounding the optical components are the modulation and coding hardware. The laser diode is driven by a 256 slot/word PPM modulator which decides, based on an 8-bit input word, which slot the pulse should be placed in and then provides a current pulse during that slot to turn on the laser. Obviously, the inverse of this process is applied to the PMT output to recreate the 8-bit word. To improve the performance of the system, an 8-bit Reed-Solomon code is then used to surround the PPM portion of the system. An 8-bit Reed-Solomon encoder considers 8-bit segments of the incoming (binary) data stream as individual (generalized) symbols and then performs error correction coding over strings of these generalized symbols. Since the code symbol size and PPM word size are matched, PPM word erasures or errors correspond to single Reed-Solomon code symbol erasures or errors respectively. Such codes are well known for their burst erasure fill-in capabilities and furthermore, can compensate for combinations of errors and erasures. The data streams supplied to the encoder and delivered from the decoder are then compared for an overall bit error rate measurement.

The demonstration program was divided into four phases. The first phase involved only the PMT and its associated preamplifier and was intended to characterize the dark current noise distribution of the detection system. In the second phase the laser was added and the optical pulse erasure and error statistics were evaluated. The PPM modulator and demodulator, which were specially designed and fabricated for the project, were added in phase III so that the PPM word error and word erasure probabilities could be measured. The final phase will encompass the coding hardware and will demonstrate the 2.5 bit performance goal.

To date all four phases of the demonstration project have been analyzed and the first three phases have been experimentally confirmed. The analysis of the demonstration clearly indicates that the 2.5 bit/detected photon goal can be achieved. The results of this analysis are shown in Figure 2 where the probability of decoded bit error is shown as a function of the energy efficiency parameter, ρ, measured in bits/detected photon. The performance curves are shown for two Reed-Solomon codes, the NASA standard (255, 223) code and the slightly more complex (255, 191) code, and the performance of each code is shown for several values of post PMT detector threshold, γ. This figure shows that although the (255, 223) code falls slightly short of achieving the 2.5 bit/detected photon goal, the (255,191) code easily accomplishes the objective.

The first three phases of the demonstration have been experimentally shown to conform to our theoretical predictions using the experimental setup shown in Figure 3. These phases were deemed to be the most crucial since they involve the validity of the modeling of the physical processes associated with photon detection. The final phase involves only demonstrating the performance improvement of a well known error and erasure correcting code and is expected to yield no surprises.

THE NEXT STEP

As stated earlier the 2.5 bit/detected photon goal was only intended to be the first step in the development of power efficient optical communications. A much more ambitious program is now being formulated to exploit the intuition and understanding afforded by the first step. The specific program objectives are to develop and demonstrate <u>in space</u> an optical communication system which emits one watt of optical output power and has a communications data transfer efficiency of 50 Mbps at 10 bits per received photon. The demonstration would be conducted from the Space Shuttle and the link would be established by a corner reflector on some host satellite. Thus, both the transmitter and receiver equipment would be recoverable after the demonstration for use in subsequent testing activities or even operational deployment.

The communications range was not specified in the objective as it is a free parameter which depends on the desired aperture sizes. However, the following example serves as a convenient and practical illustration. We assume that 50 Mbps is to be transmitted across an 80,000 Km intersatellite link. We assume also that one watt of optical power is available and that both the transmitting and receiving optics are 50% efficient (1 μm wavelength assumed). Then, with a 10 bit/received photon performance capability, the above link could provide a bit error rate of 10^{-6} with a 7 dB margin using only 2 cm telescopes at both ends. It should be pointed out that the diffraction limited beam divergence for such a telescope (and hence the pointing accuracy requirement) is no more stringent than that of a deep space tracking antenna used at 100 GHz.

It should be further pointed out that the extension from 2.5 bits per detected photon to 10 bits per received photon represent more than a factor of four increase. That is because quantum detection efficiencies are taken as unity when referring to detected photons whereas they are not when referring to received photons. Since present photomultiplier tube detectors are approximately 20% efficient, a factor of 20 improvement is required for the follow-on program. Such improvements will require developments not only in communications system design but physical components as well. Several promising technology developments which make such performance projections plausible will also be described.

CONCLUSION

Optical communications offers substantial benefits for space to space communications provided its major technological obstacles can be overcome. The primary remaining impedement, that of pointing accuracy, can be greatly diminished by achieving higher data transfer-power-efficiencies. We have described a demonstration project already in progress which is confirming 2.5 bit/detected photon efficiency and a follow-on program reaching for even higher power efficiency.

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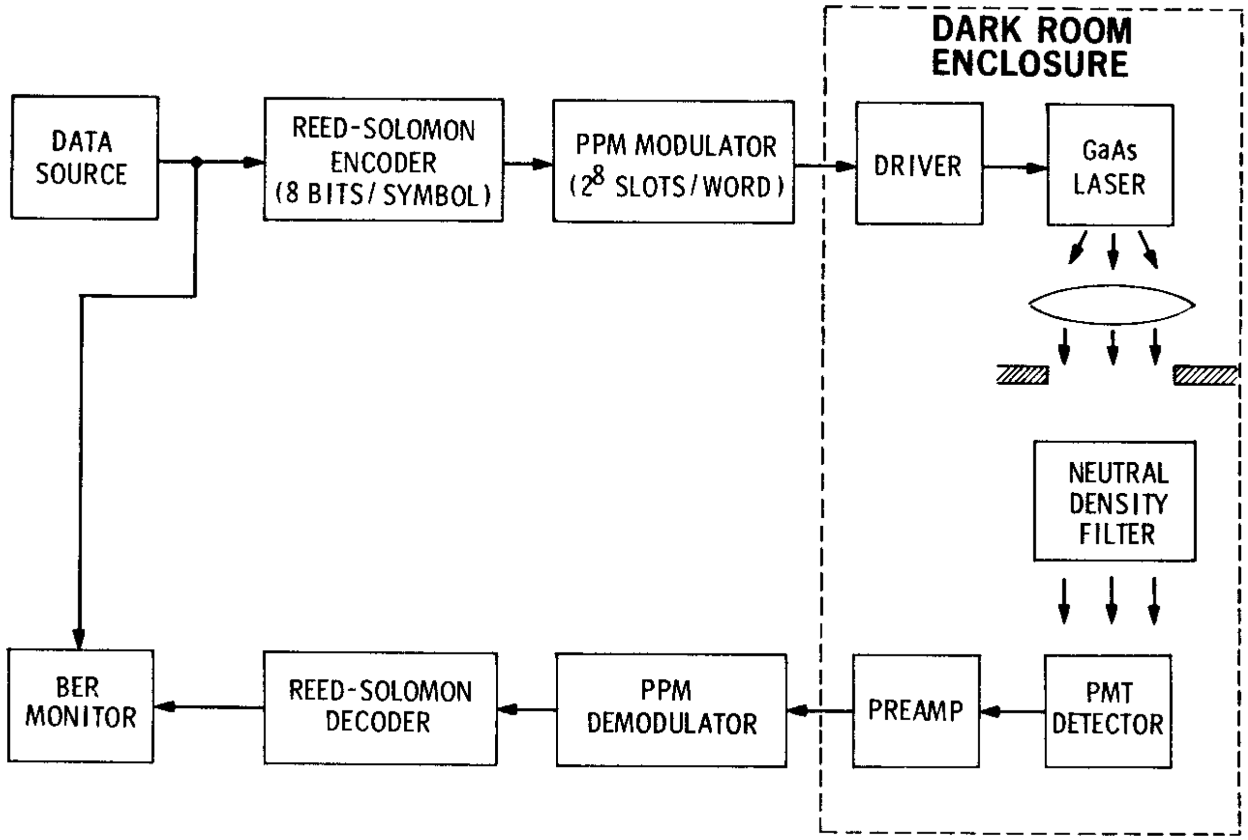

Fig. 1. Block diagram of 2.5 bit/detected photon demonstration system.

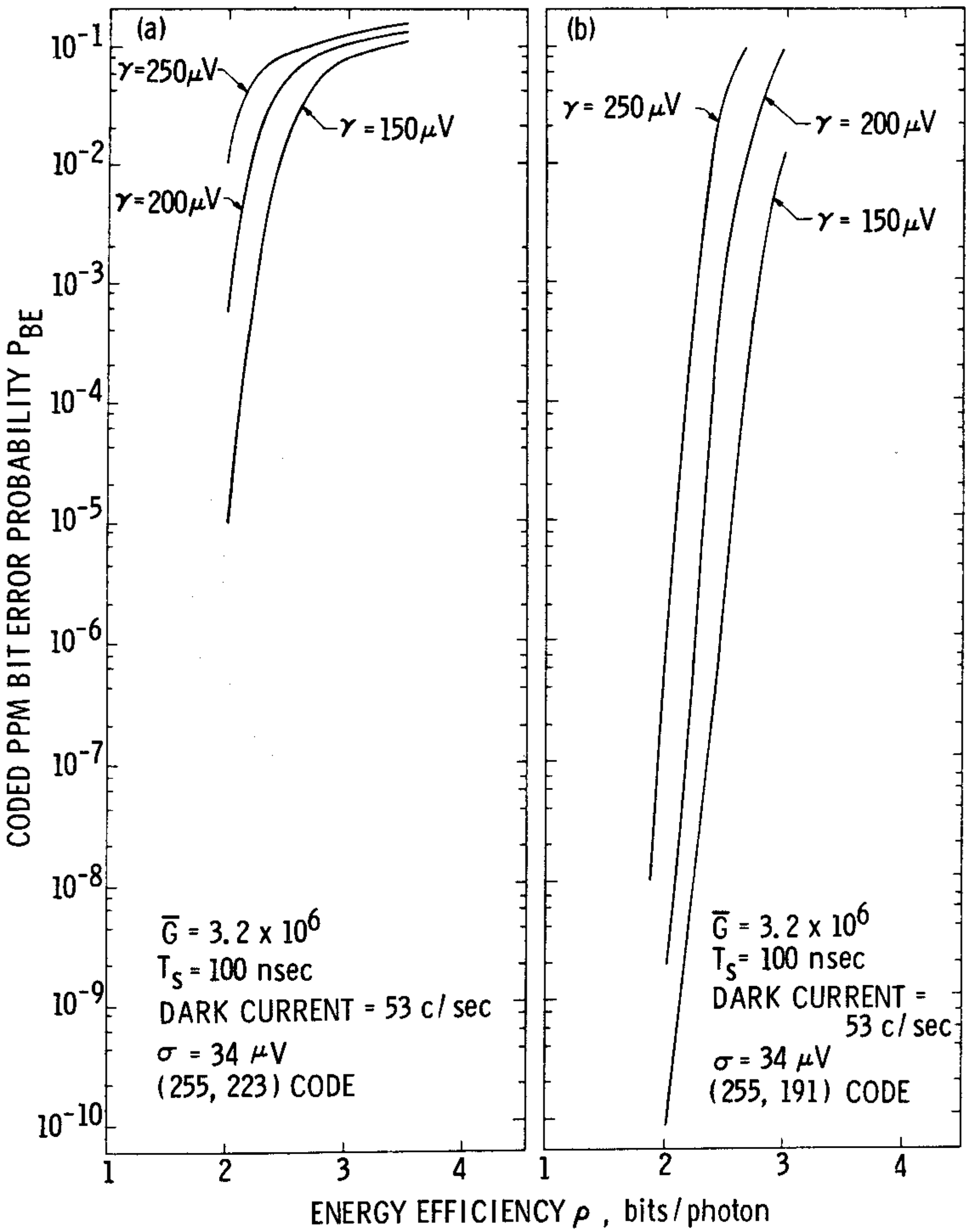

Fig. 2. Coded bit error performance for PMT gain of 3.2 x 10^6 and 53 dark counts/ sec.: (a) (255, 223) rate 7/8 R-S code, (b) (255, 191) rate 3/4 R-S code.

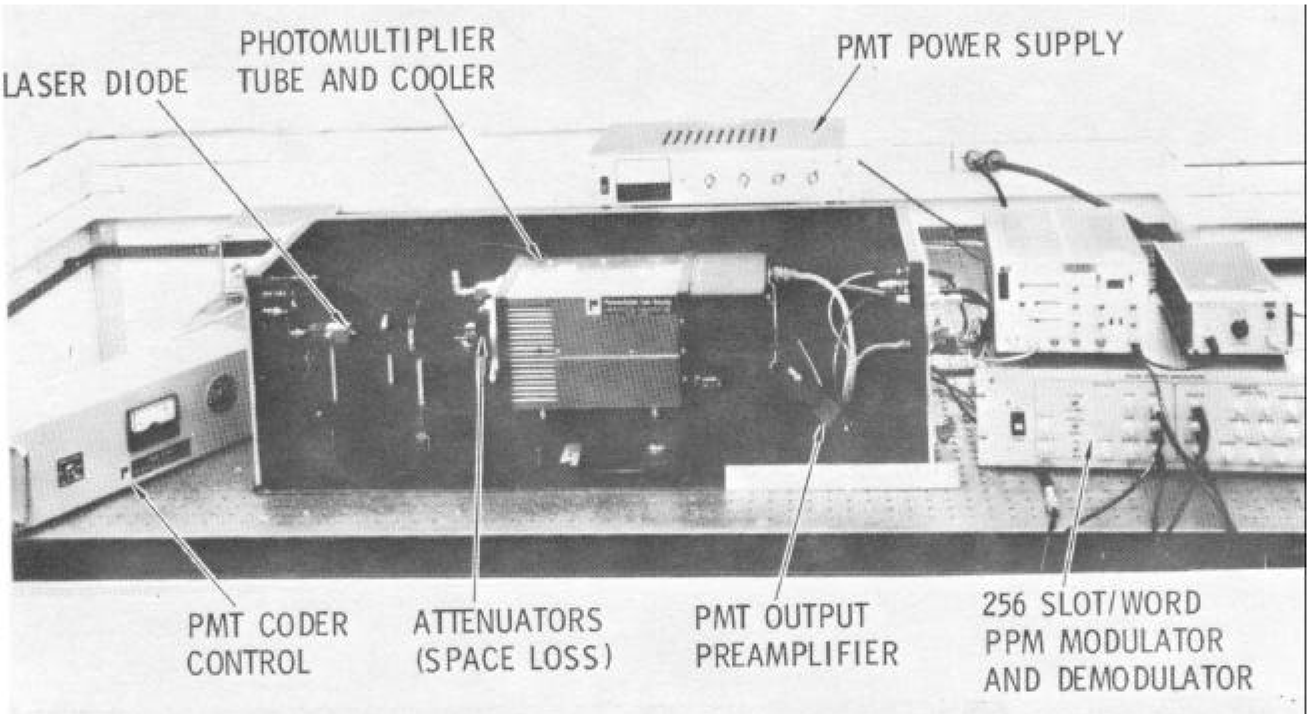

Fig. 3. Experimental setup for the demonstration system.