Infotech@Aerospace
26 - 29 September 2005, Arlington, Virginia

AIAA 2005-7118

Quantum Optical Communication for Micro Robotic Explorers

John D. Lekki[*], Quang-Viet Nguyen[†], and Binh V. Nguyen[‡]
NASA Glenn Research Center, Cleveland, OH, 44135

Murad Hizlan[§]
Cleveland State University, Cleveland, OH, 44115

One way to improve the acquisition of planetary information from robotic landers is to use many smaller robotic explorers that can cover more ground than a single conventional rover, given that the existing launch capabilities constrain the mass of planetary robotic landers to a relatively fixed value. In addressing this vision, NASA has been challenged in the National Nanotechnology Initiative to research the development of miniature robots built from nano-sized components. These robots have very significant challenges, such as mobility and communication, given the small size and limited power generation capability. The research presented here has been focused on developing a communications system that has the potential for providing ultra-low power communications for robots such as these. In this paper an optical communications technique that is based on quantum entangled photons is presented. This technique both minimizes radiated power and is appropriate for the size scale of the robot. Simulations of this system show that the radiated power may be reduced to extremely low levels for line-of-sight communication over distances of several kilometers, even in the presence of ambient light. The immunity to background noise makes this technique very promising in comparison to classical optical communications for ultra-low power applications. The results of this research will generate requirements definitions for transceiver components built from nanotechnology. Results from experiments demonstrating aspects of this communications technique are presented.

I. Introduction

In this research, we investigate the experimental behavior, error performance and sources of degradation of a quantum communications system being developed at NASA Glenn Research Center (GRC). This system exploits the temporal coincidence property of quantum-entangled photons to communicate at power levels several orders of magnitude less than what is currently achievable through classical means. The ultimate goal is the realization of ultra-low power micro size optical communications and sensing devices for use in micro robots and micro spacecraft in support of future NASA exploration missions.

This research is motivated by the National Nanotechnology Initiative Grand Challenge issued to NASA to develop Microcraft for Space Exploration. The vision for this Grand Challenge is summarized as: "*Continuous presence in space … with nanotechnology enabled low powered microspacecraft. Reduce the size and energy consumption ten fold.*"[1] The benefit of reducing the size and energy consumption is significant because of the considerable potential to increase mission capabilities without increasing launch costs.

The size of these devices and the small amounts of power on which they must operate make designing a communications system for them a major challenge. The power that these very small spacecraft would be able to

---

[*] Electronics Engineer, Optical Instrumentation and Non Destructive Evaluation Branch, MS 77-1, 21000 Brookpark Rd., Brook Park, OH 44135.
[†] Research Aerospace Engineer, Combustion Branch, MS 5-10, 21000 Brookpark Rd., Brook Park, OH 44135
[‡] Electronics Engineer, Digital Communications Branch, MS 54-8, 21000 Brookpark Rd., Brook Park, OH 44135.
[§] Associate Professor, Department of Electrical and Computer Engineering, SH 338, 2121 Euclid Avenue, Cleveland, OH 44115.

generate can be estimated from a simple calculation of the power generation capacity of an appropriately sized solar cell. A high efficiency (~20% energy conversion) solar cell on Earth can generate about 50 W/m^2 once weather conditions and night hours are accounted for.[2] Thus a microcraft solar cell with an area in the range of 1 mm^2 to 1 cm^2 would generate between 50 μW and 5mW of power. The power consumption goal of a micro robot communications system should therefore be on the order of micro watts. This research effort has the ultimate goal of developing a transmitter capable of a range of at least 1 kilometer using only micro watts of power. This experiment, which demonstrates communication with very low radiated power, is an important first step toward this goal.

II. Concept

The idea of using quantum optics for communication in very low signal-to-noise ratio (SNR) environments has been around for some time. Mandel[3] first proposed one such system in 1984 and a demonstration experiment was performed by Hong, *et. al.,*[4] in 1985. In this experiment, illustrated in Fig. 1, pairs of polarization entangled photons are generated and transmitted to the receiver over two beams of light that are on-off keyed with the data. The receiver detectors can detect individual photon arrivals. The coincidence detector circuit produces a pulse when a pair of photons triggers detectors 1 and 2 in temporal coincidence. If there is no signal present, ambient light incident on the detectors will produce what are called *accidental coincidences* at a rate

$$R_a = R_1 R_2 \tau \tag{1}$$

where R_1 and R_2 are the detector 1 and detector 2 count rates, in photons/s, and τ is the two-sided coincidence window size in seconds. By making the coincidence window time smaller, the rate of accidental coincidences from ambient light can be made to be much smaller than the rate of coincidences due to the arrival of entangled photon pairs, which are inherently coincident. In general, more than one set of entangled photons will be transmitted during a bit period. Bit value decisions can be made by comparing the number of coincidences per data bit duration to a threshold value. This process results in a relatively high detector output SNR from a very small detector input SNR, making reliable communications possible where classical detectors would be swamped by the presence of ambient light.

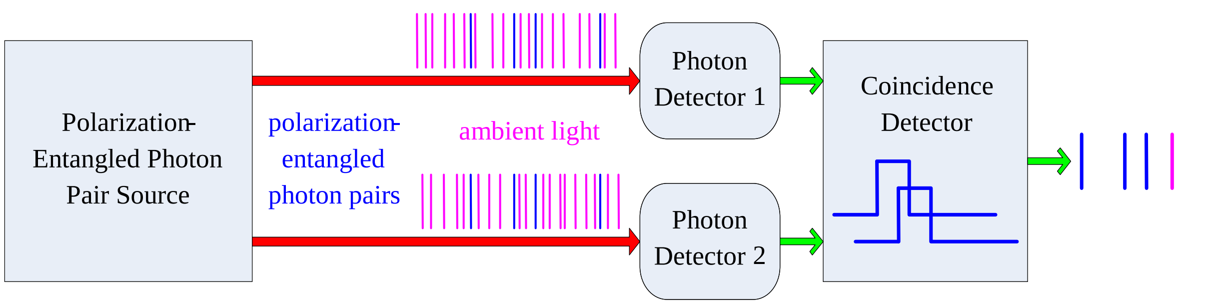

Figure 1. Conceptual quantum communicator

III. Experiment

The Quantum Communications and Sensing Team at NASA Glenn Research Center has implemented an advanced version of the quantum communicator as shown in Fig. 2. In contrast to the system demonstrated by Hong, which encoded information through on/off keying, this system encodes information with two symmetric entanglement states. Figure 2 shows the block diagram of the architecture of the GRC implementation. The optical source consists of a UV laser-pumped spontaneous parametric down conversion (SPDC) entangled photon source which generates two beams of light with identical, but random polarizations, similar to the source described by Kwiat *et al.*[5]. For the receiver, photon detectors A and B are set to detect only H photons whereas detector C is set to detect only V photons through the use of a polarizing filter and polarizing beam splitter, as shown in Fig. 2. Binary data modulates a variable phase retarder, keeping H and V photons intact under state "1," and changing H photons into V, and V photons into H under state "0." As a result, photon detectors A and B trigger H photon

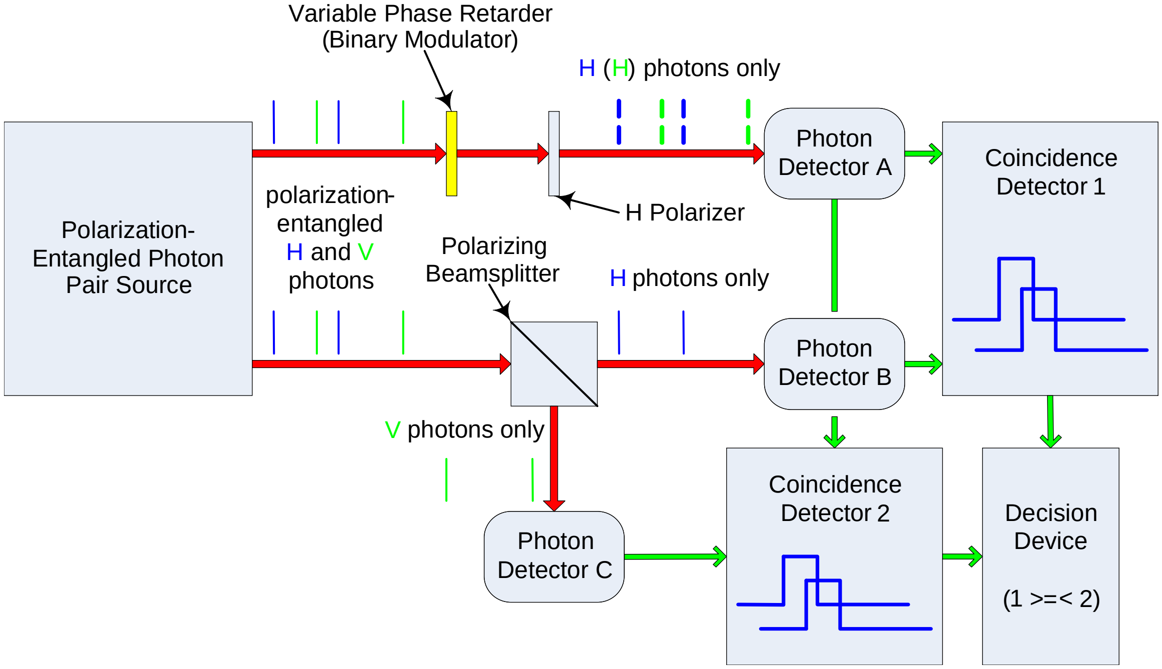

Figure 2. NASA GRC Quantum Communicator Block Diagram

coincidences in coincidence detector 1 when state "1" is transmitted, and detectors A and C trigger V photon coincidences in coincidence detector 2 when state "0" is transmitted. Decisions are made by comparing the number of coincidences per data bit from the two coincidence detectors. If coincidence detector 1 count is greater than coincidence detector 2 count then the receiver records a "1;" if not the receiver records a "0". As in the conceptual system, accidental coincidences due to ambient light and un-entangled photons from the laser source are expected to be much smaller than signal coincidences, affording reliable communications under very low SNR.

The experimental implementation of the above architecture is schematically shown in Fig.3. Here, the beam from a 351 nm (< 150 mW) single-frequency argon-ion laser is first spectrally filtered using a UV dispersing prism (not shown), and then passes through a UV dielectric polarizing beam-splitter cube to produce a pump beam with better than 1000:1 polarization purity. A zero-order quartz half-wave plate sets the polarization state of the beam to 45 degrees prior to passing through two thin (0.69 mm), optically contacted, orthogonally-aligned, Type-I beta Barium Borate (BBO) crystals to generate the SPDC light. Due to the 45 degree orientation of the polarization state of the pump beam, it then has an equal probability of producing either a HH or VV SPDC photon pair from either crystal. Thus, the photon pairs emitted from this source have identical but random (in time) polarizations, constituting an efficient hyper-entangled photon source as first described by Kwiat et al.[5] Similar setups have also been previously described to use blue diode pumped twin BBO crystals with good success[6]. The SPDC photons are emitted in a cone, with entangled photons arranged diametrically along the cone. By selecting a fraction of the cone emission using apertures, two beams of hyper-entangled photons are created. Although the photons are hyper-entangled, we only utilize the polarization properties of the photons in this report. One of the beams then passes through a digital logic controllable liquid crystal phase modulator set to act as a bi-state half-wave plate (0 or $\lambda/2$) which encodes information onto the beam via polarization rotation (either H or V). The beam then passes through a polarizing beam splitter analyzer, and is filtered using a bandpass filter centered at 702 nm (2 nm FWHM) before being focused with a 75 mm focal length lens onto the active area of a single-photon counting module (SPCM) consisting of a thermo-electrically-cooled (TEC), actively quenched, avalanche photodiode (APD) operated in a Geiger mode (Perkin Elmer SPCM-AQR-13). These detectors have an approximate 60% quantum efficiency at 700 nm and a 50 ns dead-time between pulses, with < 250 dark counts/s. In the Det. B & C beam path, similar optical components are used with the exception of the polarizing beam-splitter analyzer which acts as polarization state sorter. Detectors B & C use band pass filters centered at 702 nm but with a 5 nm FWHM.

The photon arrivals at the detectors produce TTL logic signals that are resolved to within 350 ps and are coincidence-gated using discrete CAMAC logic modules to produce a 6.5 ns coincidence window. The coincidence

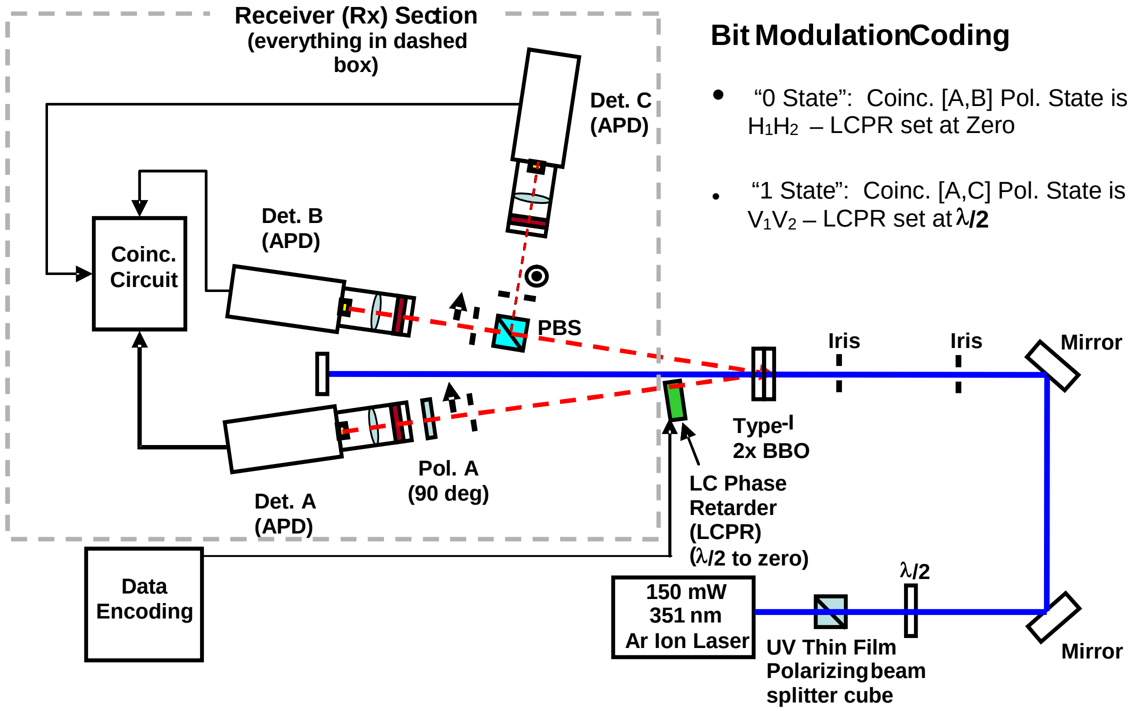

Figure 3. Schematic of Quantum Communication System

pulses are then counted using two photon counters controlled by a PC running a custom developed LabView software interface. The whole apparatus is contained within a light-tight enclosure with black walls. In order to simulate an ambient light source, an array of individually selectable incandescent light bulbs (typical 60 W, 120 VAC) was placed above the system *inside* the enclosure. By changing various combinations of three red and one white light bulb, and a variable intensity fiber optic light source aimed at a white cardboard diffuser placed around the BBO crystal housing, we are able to control the amount of background light. After careful alignment of the optical system, typical single photon rates from the BBO crystal were in the 250,000 counts/sec range for 60 mW of laser pump power.

In order to determine the bit-error rate (BER) performance of the GRC Quantum Communicator, we have developed custom software on National Instruments LabView 7.0 platform for generating, transmitting and receiving pseudorandom data sequences (Fig. 4). The software interfaces with two Dual Channel Gated Photon Counters connected to coincidence detectors and photon detectors, and controls the variable phase retarder (modulator). With this set-up, we are able to determine the BER for any data rate with varying laser power and background light intensity. The software collects statistics and full histogram data from individual photon detectors and coincidence counters, and determines BER within any desired confidence level and interval.

The data transmission is real-time and the data rate is determined as the reciprocal of the counting time allocated for each data bit. This is due to the 5 to 20-ms switching time required by the liquid crystal variable phase retarder used for modulation. In fact, the major contributor to the detection error in the laboratory setup is this particular modulator, as will be discussed later.

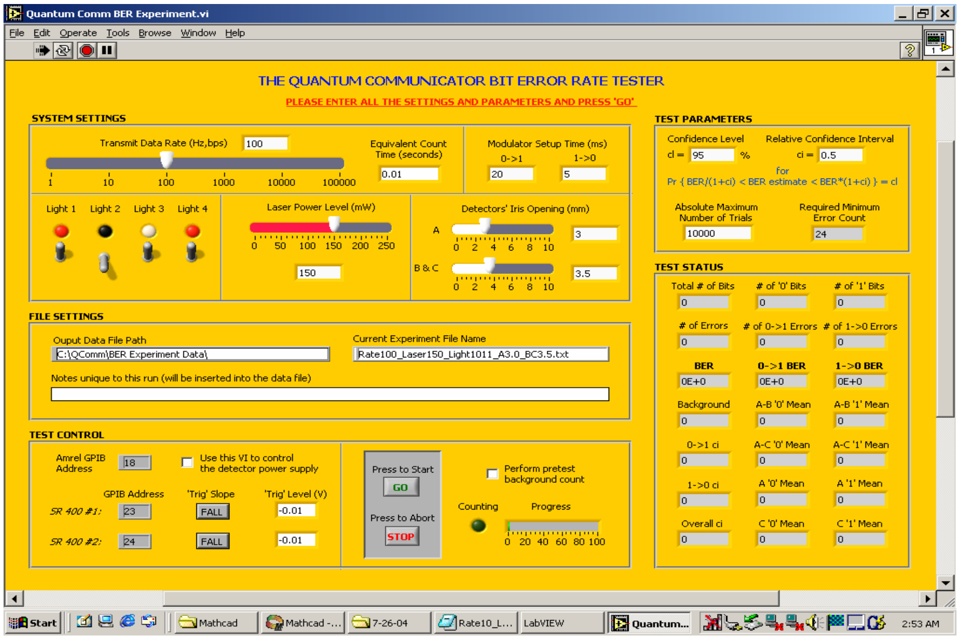

Figure 4. GRC Quantum Communicator BER Tester interface.

IV. Results

We conducted numerous tests with varying data rates, laser intensities, background light levels, coincidence window sizes, modulator setup times, optical aperture settings and various other parameters. In Figs. 5 and 6, we plot representative BER results for data rates of 10, 30, 100, 300 and 1000 bps at laser source power levels of 3, 5, 10, 30, 50 and 100 mW and two-sided coincidence window size of 3.5 ns in the presence of two extreme background light intensities. Figure 5 shows the BER plots in the presence of minimal background light, corresponding to approximately 900 photons/s total detected on the three photon detectors, whereas Fig. 6 shows the same plots in the presence of maximum background light, corresponding to approximately 250,000 photons/s total.

We immediately observe from Figs. 5 and 6 that there is very little difference in BER performance, especially for higher data rates, between the case with minimal background light intensity and that with maximum background light intensity. This is due to the relatively small size of the coincidence window that results in approximately 20 accidental coincidences per second under maximum light and almost none under minimal light. If we consider per-bit coincidences, the comparative detrimental effect of the two different background light intensities becomes relatively insignificant, especially at higher data rates. The effect of background light can be diminished even further by the use of smaller coincidence window sizes.

Another interesting observation is the relatively poor performance of the system at higher data rates. We should expect worse performance at higher data rates since, for any given laser power level, average coincidences per second will stay fixed but average coincidences per data bit will decrease with increasing data rate. This closes the gap between the '1' state and the '0' state in terms of the Poisson mean coincidence rate per bit, resulting in higher error probabilities. We have found, however, that the degradation in BER performance was much worse than what the theory predicted. This can be attributed to the less-than-perfect modulator we used in the laboratory setup.

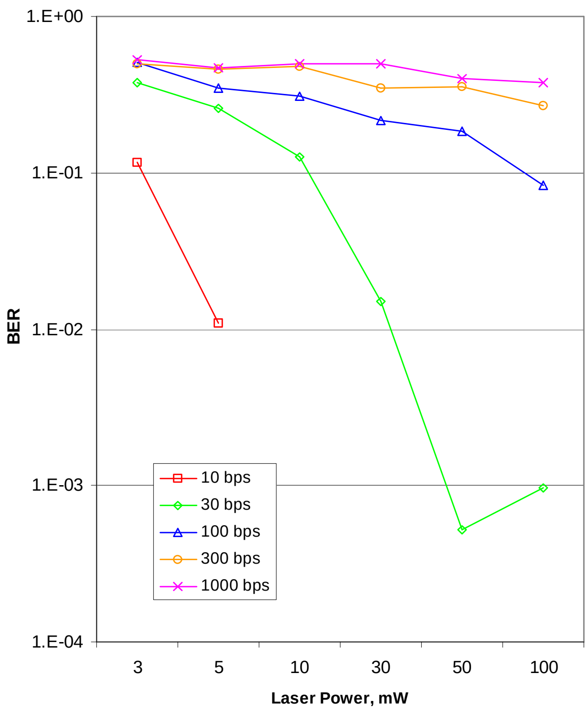

Figure 5. BER with minimal background light

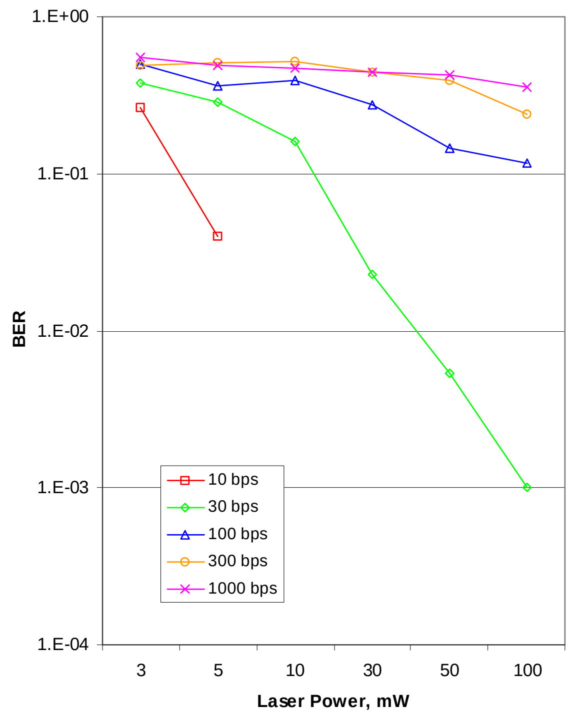

Figure 6. BER with maximum background light

The liquid crystal variable phase retarder we used for the modulator requires a finite setup time, on the order of 5 to 20 ms, in order to completely switch states. As explained in Sec. III, we accounted for this within the BER test procedure. However, even after significantly increasing the setup time, we found that the phase retarder frequently failed to completely switch states; more so at higher data rates. Table 1 displays the average coincidence detector counts per second accumulated during the BER tests for various data rates at a 30-mW laser source power in the presence of minimal background light. We observe from this table that the ratio of transmitted state to opposite state (contrast ratio) coincidence counts drops from about six at 10 bps to about one or two at 1000 bps, while the total counts stay reasonably fixed for each detector. These ratios would stay virtually fixed for a perfect modulator. Obviously, the dropping ratios significantly affect the BER performance by severely degrading the separation between the two states. We also observe from Table 1 that at higher data rates, the modulator somewhat prefers the "0" state, as evidenced by the slight increase in ratio for the AC coincidence detector counts at 300 bps to 1000 bps. Table 2 displays the detector counts per second under steady state for various laser power levels in the presence of minimal background light. This data shows that in the steady state condition, the contrast ratios (AC:AB for the '0' state and AB:AC for the '1' state), are very good, generally ranging from 24 to 68. This demonstrates that by using an improved polarization modulator, we would expect a significantly improved BER performance.

Another source of inefficiency in the laboratory setup is the generation of coincident photons through the use of parametric down conversion. Because of this inherent disadvantage, we have to use a relatively large laser source power in order to obtain a very small number of coincident photons per second. The actual received energy may be calculated by using the formula

$$E_r = \frac{h \cdot c}{\lambda} N \tag{2}$$

where h is Planck's constant, c is the speed of light, λ is the wavelength of the light source (7.02×10^{-11} m), and N is the photon count. In order to gain a better understanding of the actual energy levels involved, we recalculate the plots in Fig.5 as a function of *received energy per bit* using the data from Table 2, where the received energy per bit is determined by the average total number of photons received per bit on detectors A, B and C. Figure 7 shows

Table 1. Test average coincidence detector counts per second at 30 mW laser power in the presence of minimal background light

Data Rate, bps	AB counts per second				AC counts per second			
	AB | "0"	AB | "1"	AB Total	1:0 Contrast Ratio	AC | "0"	AC | "1"	AC Total	0:1 Contrast Ratio
10	99	612	711	6.2	607	113	720	5.4
30	180	464	624	2.6	464	188	652	2.5
100	257	456	712	1.8	433	268	701	1.6
300	282	423	705	1.5	372	234	606	1.6
1000	350	390	740	1.1	500	270	770	1.9

Table 2. Steady-state detector counts per second in the presence of minimal background light

Laser Power, mW	State "0" counts per second					State "1" counts per second				
	A	B	C	AB	AC	A	B	C	AB	AC
3	1530	880	1230	1	24	2140	910	2150	24	0
5	4300	2620	2950	2	100	5250	2530	3000	110	1
10	9500	6000	6200	5	220	11000	5900	6200	260	1
30	31000	18100	15000	23	740	32500	17900	17200	760	9
50	44000	28000	24400	40	1250	40000	28000	27800	1375	20
100	94000	57200	55100	85	2540	97400	56000	59500	2750	46

the BER plots as a function of received energy (Joules) per bit in the presence of minimal background light. We observe from Fig. 7 that reliable communication is possible, with the addition of error correction coding when necessary, at remarkably low received energy levels on the order of a picoJoule per bit. We also see from this figure that, when normalized with respect to received energy per bit, performance differences among different data rates become insignificant, especially considering the possible use of an improved phase modulator.

In order to visualize the effect of background light, we recalculate the plot in Fig. 6 as a function of *optical signal-to-noise ratio* (SNR), where we use the data from Table 2 for the average total number of photons received per second on detectors A, B and C, and we use a background average total count of 250,000 photons/s, corresponding to the maximum light setting. The sum of the singles from Table 2 is proportional to the signal power and the background average total count is proportional to the noise power. Figure 8 shows the BER plots as a function of this SNR in the presence of maximum background light. We observe from Fig. 8 that reliable communication is possible at exceptionally low optical signal-to-noise ratio levels.

The singles in Table 2 are in effect mostly noise. In the calculation for Fig. 8 we have counted all of the singles registered from Table 2 as signal because they are generated by the signaling device. However, most of these single photons are not detected in pairs, and therefore appear as noise to the receiver, even though they are generated by the signaling device. These photons are not detected in pairs because, due to slight misalignment, the three detectors are seeing slightly different spatial portions of the quantum entangled light. To illustrate how low the signal level is, we have calculated the ratio of coincident photons to single photons, where the single photons are those that are from both the background light and the uncorrelated singles from the quantum entangled light. In the instance where the pump laser is at 30 mW this correlates to an SNR of -5.8 dB in Fig. 8. The coincident photon count to single photon count ratio for this same instance is -26.6 dB. If the system were designed so that photon pairs generated by the transmitter were reliably detected by the receiver then the SNR for Fig. 8 would be shifted lower by 20.8 dB. We believe that this type reliable transmission is possible, and so this result dramatically illustrates that reliable communication is possible even when the transmitted signal power is significantly less than the noise power.

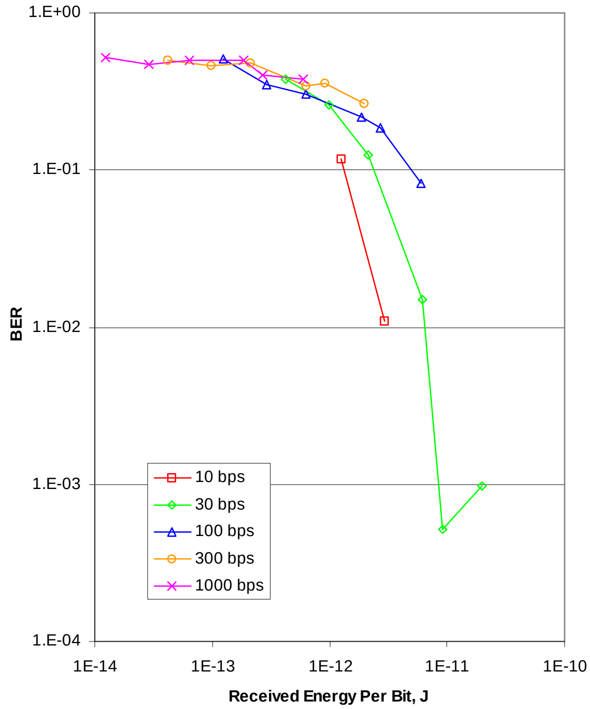

Figure 7. BER with minimal background light

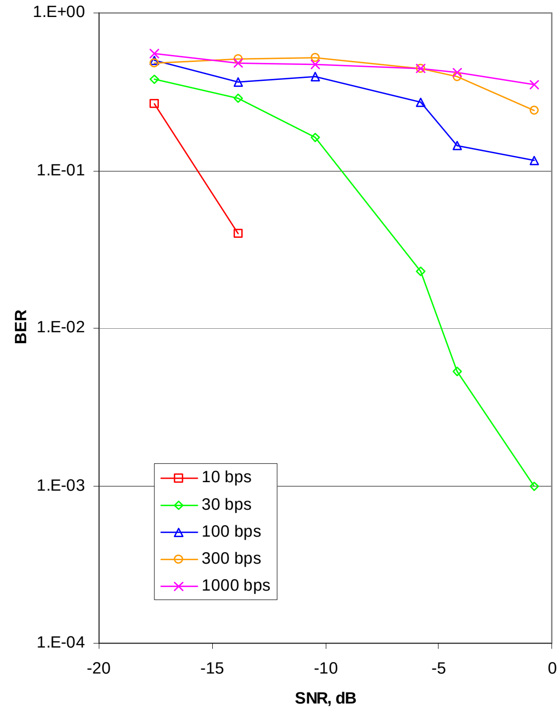

Figure 8. BER with maximum background light

V. Conclusions and Future Work

Through the use of quantum-entangled photons, we have shown that reliable communication is possible at remarkably low received energy levels on the order of one picoJoule per bit in the presence of an overwhelming background light, resulting in exceptionally low optical signal-to-noise ratios. While our experimental setup suffers from the inherent inefficiency of current quantum-entangled photon generation processes, and the use of an imperfect liquid crystal phase retarder as the modulator, it successfully demonstrates the feasibility of the concept.

Further studies will concentrate on improved generations of the Quantum Communicator, using significantly more energy efficient methods for coincident photon generation and beam forming, and enhanced modulation techniques that can be packaged into micro size devices. Our ultimate goal is to create ultra low power micro size optical communications and sensing devices.

Acknowledgments

This work was sponsored by the Alternate Energy Foundation Technologies Subproject of the Low Emissions Alternative Power Project at the NASA Glenn Research Center.

References

[1] National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology, "National Nanotechnology Initiative: The Initiative and Its Implementation Plan," July 2000, Washington D.C., pp. 61-62.

[2] "Solar Panel," *Wikipedia* [online encyclopedia], URL: http://en.wikipedia.org/wiki/Solar_panel [cited 8 September 2005].

[3] Mandel, L., "Proposal for almost noise-free optical communication under conditions of high background," *J. Opt. Soc. Am. B*, Vol. 1, No. 1, 1984, pp. 108-110.

[4] Hong, C., Friberg, S. and Mandel, L., "Optical communication channel based on coincident photon pairs," *Applied Optics*, Vol. 2482, 1985, pp. 3877-3882.

[5] Kwiat, P., Waks, E., White, A., Appelbaum, I. and Eberhard, P., "Ultrabright source of polarization-entangled photons," *Physical Review A*, Vol. 60, No. 2, 1999, pp. 773-776.

[6] Dehlinger, D. and Mitchell, M., "Entangled photon apparatus for the undergraduate laboratory," *Am. J. Phys.*, Vol. 70, No. 9, 2002, pp. 989-902.