First Experimental Demonstration Of Full-Duplex Optical Communications On A Single Laser Beam

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Abstract

We present the results of the first experimental demonstration a novel communications architecture that will be deployed on a Space Shuttle mission in 2003. This architecture can provide a very lightweight, low power consumption, low data rate communications link between the earth and LEO satellites. A unique characteristic of this system is that it provides full-duplex communications on a single beam is presented. The results of first experiments demonstrating this full duplex communications architecture are presented.

Introduction

The planned flight experiment is called Lightweight Optical Wavelength Communications without a Laser in Space (LOWCAL.) The LOWCAL system is designed to offer a very lightweight, low power consumption, low data rate communications link from LEO satellites. LOWCAL will use this novel architecture for a free-space optical communications link. The "Lightwire" concept provides for the first time full-duplex communications on a single beam. In addition, we propose utilizing for the first time a novel data format for free-space optical communications. The current proposed application is a ground-to-LEO link. These concepts however, are generally applicable to other free-space optical communications systems as well. The results of the first laboratory demonstration of this system will be presented.

In this system, the laser and the return link receiver are both located on the ground. The optical elements located on the spacecraft are the retro-modulator and a simple forward link receiver. Data rates on the order of 10-kbps are currently possible without taxing the current laser or modulator technology. In fact, the transmitter laser for such a system is a semiconductor device. The envisioned system would include a Faraday Anomalous Dispersion Optical Filter[1,2,3,4] (FADOF) in the receivers and tracking system to allow 24-hour operation of the system. We previously reported the first solar blind laser communications system utilizing a FADOF in the receiver.[5] The FADOF is an ultra-high background rejection optical filter developed by one of the authors (T. M. Shay) that essentially prevents skylight from reaching the photodetector while transmitting 80% of the signal photons. Without a FADOF in the receiver the transmitted laser power would need to be increased by at least a factor of 4 for the acquisition to be feasible for daylight operation at a Zenith angle of $\pi/3$.

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Communications System

Nearly all of the optical communications experiments to date have utilized either On-Off Keying (OOK) or various coherent optical communications keying (PSK or FSK). We choose to employ for the first time Circular Polarization Keying[6] (CPK). A block diagram of the system is shown in Fig. 1. The diode laser transmits a constant average power beam to the remote modulator. The transmitted beam is directed through a quarter-wave plate (λ/4 in Fig. 1) that converts the linearly polarized laser beam into a circularly polarized beam. The laser beam is then directed through the aperture-sharing element (ASE) that is literally a mirror with a hole in it.

data is encoded in the polarization of the return beam. The liquid crystal (LCS) retro-modulator flips the right-handed polarized transmitter light into left-handed for a "1", while for a "0" the incident left-handed polarization is left unchanged. The liquid crystal retro- modulator acts exactly like a corner cube reflector, that is, the retro-modulator directs the beam incident on the spacecraft directly back to the transmitting telescope. Then the aperture-sharing element (ASE) collects the return signal and directs the return signal to the receiver quarter-wave plate (λ/4) that converts the left and right-hand circular polarized light into two orthogonal linear polarizations. The linear polarizations are then separated in the polarizing beam splitter shown in Fig. 1. The end result is the photons that constitute the "1's" are sent to the receiver
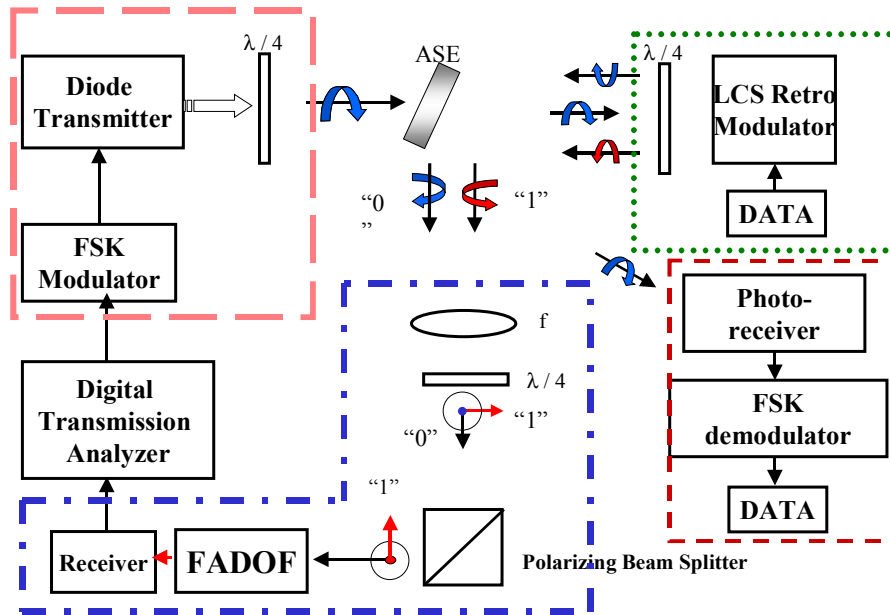

Figure 1. Communications Link Block Diagram

The purpose of the aperture-sharing element is to separate the transmitted and returned beam paths. The transmitted beam is next directed through the hole in the mirror to the liquid crystal (LCS) retro-modulator. In circular polarization keying (CPK) the binary

FADOF and photo-receiver. CPK is the first novel technical features of this system.

The forward communications link uses a different format. The forward communications link uses sub-carrier FSK modulation. For the forward link the signal is collected by a 1-inch

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diameter lens and directed to a pin photo-receiver. The electrical signal from the photo-receiver is sent to an FSK decoder and then finally the output is compared to the transmitted bit stream.

The digital transmission analyzer transmits a pseudorandom bit stream and compares the transmitted bit stream with a received bit stream to measure the bit error rate of a communications link. Therefore, the digital transmission analyzer is a key instrument in the system.

Return Link

The return link uses a photo-multiplier receiver. The characteristics of this detector are listed in Table I. The quantum efficiency and responsivity were directly measured for the photodetector used in these experiments.

Table I. Return Receiver Characteristics

Responsivity	2,600 amps/watt
Quantum effficiency	0.011
Gain	750,000
Dark current	8 nA
Load resistance	100 kΩ
Bandwidth	20 kHz
Noise figure	~1

To simulate the conditions for our ground-to-space shuttle, we attenuated the return signal to 2.2-nW, the minimum expected signal level for our return link from space. This photo-receiver system is quantum noise limited at this received power, hence to a good approximation the signal-to-noise ratio in the communications mode is to a good approximation shot noise limited, thus

$$SNR_{comm} = \frac{P_s \cdot \eta_{PMT}}{B \cdot h\nu} \qquad (1),$$

where η_{PMT} represents the photomultiplier quantum efficiency, hν represents the signal photon energy, and B represents the signal electronic bandwidth. Solving for the minimum required signal power,

$$P_{min} = \frac{SNR_{min}}{\eta_{PMT}} \cdot B \cdot h\nu \qquad (2).$$

Eq. 2 shows that P_{min} is proportional to SNR_{min} and the electronic bandwidth, B. The minimum required signal power is calculated

$$P_{min} = 45 \text{ pW} \qquad (3).$$

The required signal to noise for a digital communications system is calculated using the complex error function. Assuming, that the probabilities of receiving a "1" and "0" are equal, and that the receiver threshold voltage is to set midway between, $V_1 + V_0 = 0$. A bit error rate of 10^{-6} requires the electrical SNR = 91. This is the minimum SNR that will provide a bit error rate of 10^{-6}. Therefore, a communications system in the field must exceed that SNR by at least one order of magnitude to overcome scintillation.

The last element is the liquid crystal shutter that is a phase-separated composite liquid crystal shutter[7] provided by Prof. Satyendra Kumar of Kent State University. The extinction ratio of liquid crystal shutters falls off rapidly with frequencies beyond 10 kHz. It is the trade off between liquid crystal extinction ratio and link power penalty due to the non-zero extinction ratio that limits the data rate of our proposed system to 10 kbps. The low power liquid crystal driver that we designed has a measured electrical power consumption of 50 milliwatts when unbiased data is transmitted at 10 kbps. The extinction ratio of liquid crystal shutter falls off rapidly with frequency, at 10

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kbps the extinction ratio was measured to be 0.035.

Forward Link

It is desirable to have bi-directional communications for the proposed applications. An obvious means of doing this is to simply time multiplex the forward link and return link modes. However, this reduces the data rate in both directions. Therefore, we invented a novel set of paired formats where the forward link data is invisible to the return link and hence the forward link beam can simultaneously serve as the carrier for the return link data. We have one optical beam that provides full-duplex operation without any penalty in data rate or signal-to-noise ratio.

We have named this the lightwire[8] concept. In this concept, we utilize different modulation schemes for the forward link and return link. For the return link, we utilize the CPK modulation described in the previous section of this paper, but for the forward link

number of photons received for a logical "1" during one bit period. Because the SC-FSK modulation transmits a constant average power regardless of the data, the two modulation formats are transparent to one another. Hence, the forward link and return link formats are invisible to each other. So we have full-duplex operation with one laser beam. At the return link receiver, the photodetector converts the optical photons into an RF electrical signal and then at that point conventional FSK signal processing is utilized. Fig. 2 below illustrates the "Lightwire concept" operating in conjunction with the CPK format. Finally, we have explicitly discussed the CPK and SC-FSK Lightwire format pair. However, the results are generally applicable to any other format pair that meets the invisibility requirement. For example, an on-off keying return link with a PSK or FSK forward link also constitute, a Lightwire format pair.

A Lightwire system with a CPK return link is compatible with many possible forward link formats. Two obvious choices are PSK and FSK. PSK has the well known 3-dB signal-to-
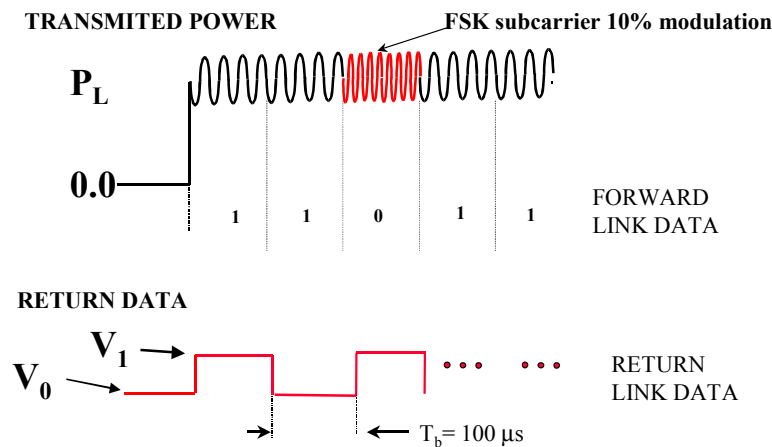

Figure 2. Lightwire Format Pair

sub-carrier FSK (SC-FSK) modulation is used. The CPK modulation format detects the total

noise ratio advantage over FSK. However, the disadvantage of PSK is the need for an absolute

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phase reference or, alternatively, the first bit in any transmission block can provide the phase reference and differential PSK can be employed. To simplify the forward link receiver and to optimize the data throughput, we have chosen to employ SC-FSK for the forward link. For a receiver we employ a simple phase lock loop tone decoder.

Experiments and Results

In our experiments we performed; a) a test of our sub-carrier FSK link, b) the first demonstration of a Circular Polarization Keying link, and c) finally the two links were operated simultaneously to perform the first "Lightwire" architecture demonstration. In these experiments, the signal levels, the noise levels, and the bit error rates were measured for each case.

Figure 1, is a schematic block diagram of the sub-carrier FSK test experiment. For the FSK link experiment the digital transmission analyzer transmits a psuedo-random bit stream to FSK modulator. The signal from the FSK remote receiver is sent returned to the digital transmission analyzer and compared to the bit stream transmitted by the digital transmission analyzer. The digital transmission analyzer then displays the bit error rate for the communications link. When the sub-carrier FSK link was tested at 10 kbps without any data being transmitted on the CPK link, there were no errors detected during the 10-minute duration of the tests. This corresponds to a bit error rate of less than $1.67 \ 10^{-7}$. For this case the measured signal-to-noise ratio was 1000.

Next the circular polarization keying communications link was tested. For the CPK link test the digital transmission analyzer's output signal was disconnected from the FSK modulator and the digital transmission analyzer's psuedo-random bit stream was transmitted to the retro-modulator's drive circuit. The signal from the return link's receiver was directed to the digital transmission analyzer and the bit streams were compared. In this case the measured signal to noise ratio was 138 and the bit error rate was again less than $1.67 \ 10^{-7}$. That is there were still no errors during the 10-minute test duration.

The final experiment was the "Lightwire" experiment where the psuedo-random data was transmitted on both links simultaneously. When these tests were performed again there were no errors detected during the experiments, illustrating that there was no detectable change in the signal to noise ratio for the return (CPK) link when data was encoded on the forward (FSK) link.

Conclusion

Circular polarization keying has been demonstration for the first time. In addition, we have also presented the first experimental demonstration of the 'Lightwire" concept that allows for the first time full-duplex communications on a single laser beam. We have demonstrated that the forward (FSK) link data is transparent to the return (CPK) link data and hence there is no measurable link degradation associated with the "Lightwire" communications architecture.

Acknowledgments

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