Free-Space Coherent Optical Communication Receivers
Implemented with Photorefractive
Optical Beam Combiners

Final Report on NASA Grant NAG5-1462

January 1992

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1 Introduction

This grant provided \$50,000.00 of initial funding for a large project involving the demonstration of a coherent homodyne optical communication receiver that used a photorefractive material as an optical beam splitter instead of a partially transmitting, partially reflecting conventional optical beam splitter. The major source of funding for this project was the Office of Inovative Science and Technology of the Strategic Defense Initiative Organization via the U.S. Army Strategic Defense Command. The following paper, which will appear in the conference proceedings of the S.P.I.E. sponsored OE/LASE '92 conference, 1635 "Free-Space Laser Communication Technologies IV" describes in detail the research preformed as a result of the funding provided by this award.

Coherent optical homodyne receiver performance with an iron doped indium phosphide photorefractive beam combiner

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Abstract

Performance measurements are reported of a coherent homodyne optical communication receiver that contained an iron doped indium phosphide photorefractive beam combiner, rather than a conventional optical beam splitter. The system attained a bit error probability of 10^{-6} at received signal powers corresponding to less than 100 detected photons per bit. The system used phase modulated Nd:YAG laser light at a wavelength of 1.06 microns.

1   Introduction

Two-wave mixing in photorefractive materials results in the formation of a volume index of refraction grating that can coherently combine light from an unmodulated optical "pump" beam with a rapidly phase or amplitude modulated optical signal beam provided the time scale of the modulation is much faster than the time scale of the refractive index grating formation or erasure [1]-[3]. Consequently, photorefractive materials can be used as beam splitters in coherent optical receivers. Unlike conventional optical beam splitters, however, the refractive index grating formed in these materials can automatically adjust to changes in spatial mode profiles or angle of arrival of either optical beam on time scales comparable to the grating formation time without the need of complicated auxiliary electro-mechanical optical alignment prerserving subsystems required in conventional coherent receivers. The simplicity of this type of coherent optical receiver may make it an attractive candidate for high data rate free-space optical intersatellite communication links.

The experimental performance of such a receiver containing an iron doped indium phosphide (InP:Fe) photorefractive optical beam combiner is reported in the following. The transmitter laser consisted of a very narrow linewidth, single mode Nd:YAG unidirectional nonplanar ring oscillator whose $\lambda = 1.06\mu m$ output beam was phase modulated using a custom fabricated integrated optic phase modulator. Part of the transmitter laser light was diverted and used as the phase coherent local oscillator light, so the results of these measurements represent receiver performance that can be obtained with a "perfect" local oscillator. The next section presents a simplified theoretical analysis of how the receiver with the photorefractive beam combiner operates and indicates why only certain phase modulation formats can be used. Expressions for receiver bit error rate (BER) calculations and signal-to-noise ratios (SNR) are also presented. The last section gives the details of the experimental measurements made and performance observed.

2 Theoretical Description

In two-wave mixing in photorefractive media, the mutual coherence between the local oscillator (pump) and received signal beams forms an interference pattern inside the photorefractive material which in turn creates an internal space charge electric field that modulates the refractive index via the linear electrooptic (Pockels) effect.[4] Once the refractive index grating has reached steady state, the optical power emerging from the beam combiner in the signal beam direction can be written as [3]

$$P_s(t) = P_s(0)\cos^2(\delta) + m_0 P_s(0)\sin^2\delta + 2\sqrt{m_0}P_s(0)\sin\delta\cos\delta\cos\phi_m(t) \qquad (1)$$

In equation (1), $P_s(0)$ and $m_0 P_s(0)$ represent, respectively, the signal and pump beam optical powers incident on the photorefractive material, $\phi_m(t)$ the phase modulation impressed on the signal beam, and the grating coherent combining effects are characterized by a rotation angle, δ. Optical absorption inside the material has been neglected but is easily included simply by replacing $P_s(0)$ by $P_s(0)exp(-\alpha d)$ where d is the propagation distance through the photorefractive medium and α the optical power absorption coefficient in cm^{-1}. The only restriction on the phase modulation waveform is that it be such that the time average value of the fringe visibility at any point inside the photorefractive medium is nonzero. Stated another way, the Fourier transform of the phase modulated optical signal light must not be zero at the optical field carrier frequency. This means suppressed carrier phase modulation formats cannot be used. This restriction arises from the form of the time development of the internal space charge field which may be written as [5]

$$E_{sc}(z,t) \propto \int_0^t e^{-(t-t')/\tau_g} A_p^*(z,t')A_s(z,t')dt' \qquad (2)$$

where $A_p(z,t)$ and $A_s(z,t)$ are the complex amplitudes of the two optical fields which are assumed to be plane waves of identical optical center frequencies and τ_g is the grating formation time. Since (2) is a convolution, the Fourier transform of $E_{sc}(z,t)$ is such that

$$\mid E_{sc}(\omega)\mid^2 \propto \frac{\tau_g^2}{1+(\omega\tau_g)^2}S_{A_pA_s}(\omega) \qquad (3)$$

In (3), $S_{A_pA_s}(\omega)$ is the modulus squared of the Fourier transform of the temporal phase variations between $A_p(z,t)$ and $A_s(z,t)$ computed as

$$S_{A_pA_s}(\omega) =\mid \mathcal{F}\{exp(j\phi_p(t) - j\phi_s(t) - j\phi_m(t))\}\mid^2 \qquad (4)$$

In the absence of phase modulation on the signal beam ($\phi_m(t) = 0$), mutual temporal coherence between the pump (local oscillator) and signal optical fields causes $\phi_p(t) = \phi_s(t)$ and $S_{A_pA_s}(\omega) = \delta(\omega)$. This renders the steady state value of the internal space charge field a maximum and produces the maximum amount of two beam coupling. In the presence of phase modulation, $\mathcal{F}\{exp(j\phi_m(t))\}$ must be nonzero for values of ω such that $\omega\tau_g \le 1$ or else the space charge field will be greatly reduced in strength, or even vanish altogether. On this basis, a good phase modulation format would have substantial power at the carrier frequency, i.e. $S_{A_pA_s}(\omega = 0) \gg 0$, and distribute the rest at frequencies for which $\omega\tau_g \gg 1$.

Since equation (1) is a consequence of the thick volume index of refraction grating diffracting only light that satisfies the Bragg condition set by the grating spacing, the time scale of the phase modulation process must not be so short that the optical signal field is substantially spectrally broadened.

This would begin to be significant only at modulation rates well above 10 Gigahertz. It should also be noted that in a conventional homodyne optical receiver the information bearing term is of the form $\cos(\phi_{sc}(t) - \phi_{lo}(t) + \phi_m(t))$ where $\phi_{sc}(t)$ and $\phi_{lo}(t)$ are the carrier phases of the signal and local oscillator, respectively. The receiver phase tracking loop must maintain their difference at some set value. With photorefractive beam combining, the dynamic nature of the grating will automatically "track" on their difference, always forming in relation to the intensity maxima of the fringe pattern, provided the phase difference changes slowly compared to the grating formation time.

The grating coherent coupling properties are expressed through the angle δ which depends on the particular phase modulation format used. The form of (1) suggests that a good choice would restrict $\phi_m(t)$ to take on only the values 0 or π radians. If L binary source bits are represented as a single change of $\phi_m(t)$ from 0 to π in only one of 2^L time slots, with $\phi_m(t) = 0$ in all the other slots in the interval [0,T], where $T = 2^L \tau$, δ is given by the following expression, valid for $m_0 > 100$, $\kappa = (1 - 2\tau/T)$, and $m_0^{-1} exp(\Gamma d/2) - 1) < 1$.

$$\sqrt{m_0} \tan \delta = \kappa(exp(\Gamma d/2) - 1) \tag{5}$$

In the absence of phase modulation, the static two-wave photorefractive mixing gain, $P_s(d)/P_s(0)$, is given by $exp(\Gamma d)$ where the exponential gain constant, Γ is determined by the material properties of the InP:Fe photorefractive material. The simplest nontrivial example of this phase modulation format has L=2, with the choice L=1 unacceptable as it produces a signal optical field with no energy at the carrier center frequency. For L=2, $\kappa = 1/2$.

It is straightforward to show, from the Poisson nature of photodetection, that the maximum likelihood receiver for this signal format is a device which can determine the time slot for which $\phi_m = \pi$. If the photodetector output photocurrent is ac coupled and inverted, the receiver implementation is exactly the same as in a direct detection optical receiver for a Q=4 pulse position modulation signal format [6]. The difference is that in this homodyne receiver, the photocurrent shot noise level is higher for the time slots for which $\phi_m = 0$, whereas in the direct detection system the time slots which do not contain the light pulse have very low noise levels which result from just the photodetector load resistor thermal noise and residual background light.

In a conventional homodyne optical receiver, the local oscillator power is made sufficiently large that photodetector shot noise is dominant over load resistor thermal noise and a unity gain p-i-n photodiode is used as the photodetector. In this receiver design, it is necessary to use a photodetector with gain if the two-wave mixing gain cannot be made large enough to dominate thermal noise from the load resistor. The coherently combined optical power levels incident on the photodetector are however large enough that the output photocurrent is well described as a Gaussian process provided the receiver is operated at a reasonably high data rate. The receiver bit error rate for this L=2 modulation format may be expressed as the following in which the photodetector average gain and excess noise factor are given by G and F, respectively.

$$BER = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-u^2} erfc(\frac{\sigma_1}{\sigma_0}u + \sqrt{SNR})du \tag{6}$$

$$SNR = \frac{2(\eta P_s(0)/hf)T}{F(1 + C^2/m_0^2)(1 + \sqrt{m_0}/C)^2 + TN} \tag{7}$$

$$TN = \frac{(2KT/e^2 R_L)}{G^2\kappa^2(e^{\Gamma d/2} - 1)^2(\eta P_s(0)/hf)} \tag{8}$$

$$C = \sqrt{m_0}\kappa(exp(\Gamma d/2) - 1) \tag{9}$$

Equation (8) represents the effects of load resistor thermal noise. The denominator of (8) corresponds to $(\eta P_{lo}/hf)$ in a conventional homodyne receiver and indicates the beneficial effects of G and an "ac" photorefractive mixing gain, $\kappa(exp(\Gamma d/2) - 1)$, in reducing its adverse effects on receiver performance. The ratio σ_1/σ_0 in (6) is due to unequal shot noise levels. Its square can be expressed as $(F(1 - C)^2 + TN)/(F(1 + C)^2 + TN)$ which is usually close to unity. If thermal noise can be neglected relative to the photodetector shot noise, the receiver SNR is maximized if $\kappa(exp(\Gamma d/2) - 1) = m_0^{1/3}$ and receiver performance is optimal. For avalanche photodiode photodetectors, $F = k_{eff}G + (2 - 1/G)(1 - k_{eff})$ where k_{eff} is the ratio of the ionization coefficients of holes to electrons. Quantum limited performance is obtained if the denominator of (7) becomes unity. From numerical evaluation of (6), a BER of 10^{-6} requires a SNR of 13.7 dB, which corresponds to $\eta P_s(0)/hf)T = 12$ detected photons per symbol in the quantum limit for this signal format.

3   Experimental Performance

Figure 1 shows a block diagram of the experimental setup. Light from a single mode, narrow linewidth Nd:YAG unidirectional nonplanar ring oscillator laser (Lightwave Electronics, Model 122) was divided into two parts by a 10:90 conventional optical beam splitter. Mirrors M1 and M2 directed the stronger component onto a 1 cm cube of InP:Fe where it acted as the "pump", or local oscillator component of the homodyne receiver. The weaker beam was coupled into and out of an integrated optic phase modulator using single mode optical fiber. Neutral density filters were used to simulate optical propagation loses by adjusting the received signal beam intensity. Both beams were s-polarized and brought to coincidence at the InP:Fe photorefractive crystal with an external full angle of about 6°, which yielded an internal refractive index grating spacing of about $10\mu m$. The pump beam fully illuminated the InP:Fe crystal and had an optical power density of about $10mW/cm^2$.
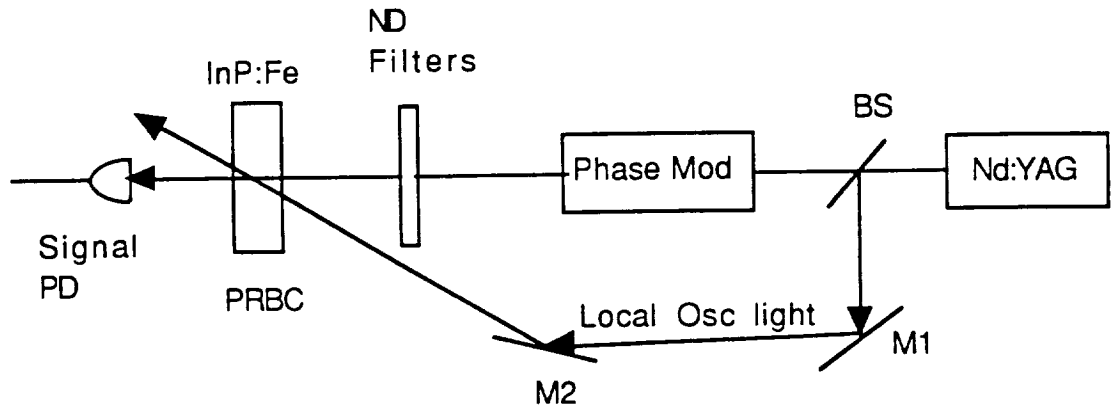

Figure 1.

The signal beam at the crystal had a TEM_{oo} spatial mode profile with a spot size of about 1 mm. A DC external electric field was applied to the crystal in the 001 direction to control the two-wave mixing gain [7]. The entrance and exit faces of the crystal were antireflection coated. The measured optical absorption coefficient, α, of the crystal was $0.5cm^{-1}$.

Experimentally measured bit error rates for the receiver described by (6)-(9) are shown in Figure 2. A complete description of the receiver electronics is given in [6]. The data was obtained using a Microwave Logic bit error rate test set and a pseudorandom sequence of input binary data 127 bits long. The InP:Fe photorefractive two-wave mixing gain was set such that $\kappa(exp(\Gamma d/2) - 1) = 2.13$ by applying a 7 KV/cm constant external electric field across the crystal.The grating formation time was measured to be about 0.2 msec which was more than adequate to track slow changes in the relative phases of the center frequency component of the two light beams caused by air currents in the two optical paths. The photodetector used was a $k_{eff} = 0.02$ silicon avalanche photodiode which was connected to a transimpedance preamplifier with $R_L = 5.6K\Omega$ load resistor and operated at average gain $G = 23$. Other relevant parameter values were $F = 2.5$, $m_0 \approx 3000$, $TN \approx 9$ (effective thermal noise temperature of load resistor was about $600°K$) at a $BER = 10^{-6}$, $T = 40 \times 10^{-9}s$ (source data rate = 50 Mbps), and $exp(\Gamma d) = 28$. The dashed curve in Figure 2 is the theoretically expected receiver performance computed from (6). The solid curve represents the best receiver performance that can be obtained if the denominator of the SNR expression (7) were unity (i.e. in shot noise limited operation with no excess photodetector noise).

4   Discussion

As can be readily seen from Figure 2, this receiver could only come within about 12 dB of the quantum limit, attaining a BER of 10^{-6} at 192 detected photons per symbol (96 photons per information bit). This corresponded to a received average signal optical power of about 30 nanowatts taking into account the 5 percent quantum efficiency of the photodetector and the 40 percent absorption loss in the photorefractive crystal. The denominator of (7) was 5.4 + 9 =14.4, instead of unity, which accounts for 11.5 dB of the departure from ideal performance. The use of a much better transimpedance preamplifier (one with $R_L \approx 100K\Omega$) would eliminate about 9.5 dB of the discrepancy. Reduction of the 5.4 to approximately unity is much more difficult as it requires substantially larger values of $\kappa(exp(\Gamma d/2) - 1)$. In fact, the performance of this receiver could not be optimized because the optimal value of grating rotation angle could not be reached with this particular sample of InP:Fe. At $m_0 = 3000$, a value of $\kappa(exp(\Gamma d/2) - 1) = 14.4$ is required to attain the optimal value of SNR which is far in excess of the value of 2.13 which was obtained. The low values of two-wave mixing gain were primarily due to too low a concentration of iron in the host photorefractive material . The APD photodetector gain, however, is much lower than in a direct detection receiver (typically several hundred at this source data rate) and the excess noise factor, F, is not the major factor limiting receiver performance. The 0.5 dB departure from theoretically expected receiver performance is most likely due to the fact that the slot clock recovery circuits in the receiver were optimized for a direct detection Q=4 PPM receiver in which the noise levels in the slots that do not contain the optical pulse are very low. In this homodyne receiver, however, the slots for which $\phi_m(t) = 0$ have the highest noise levels. Figure 2 does demonstrate that the basic concept of using a photorefractive material as a coherent optical beam combiner in a homodyne optical communication receiver is sound and leads to easily implementable receivers that give quite good performance.
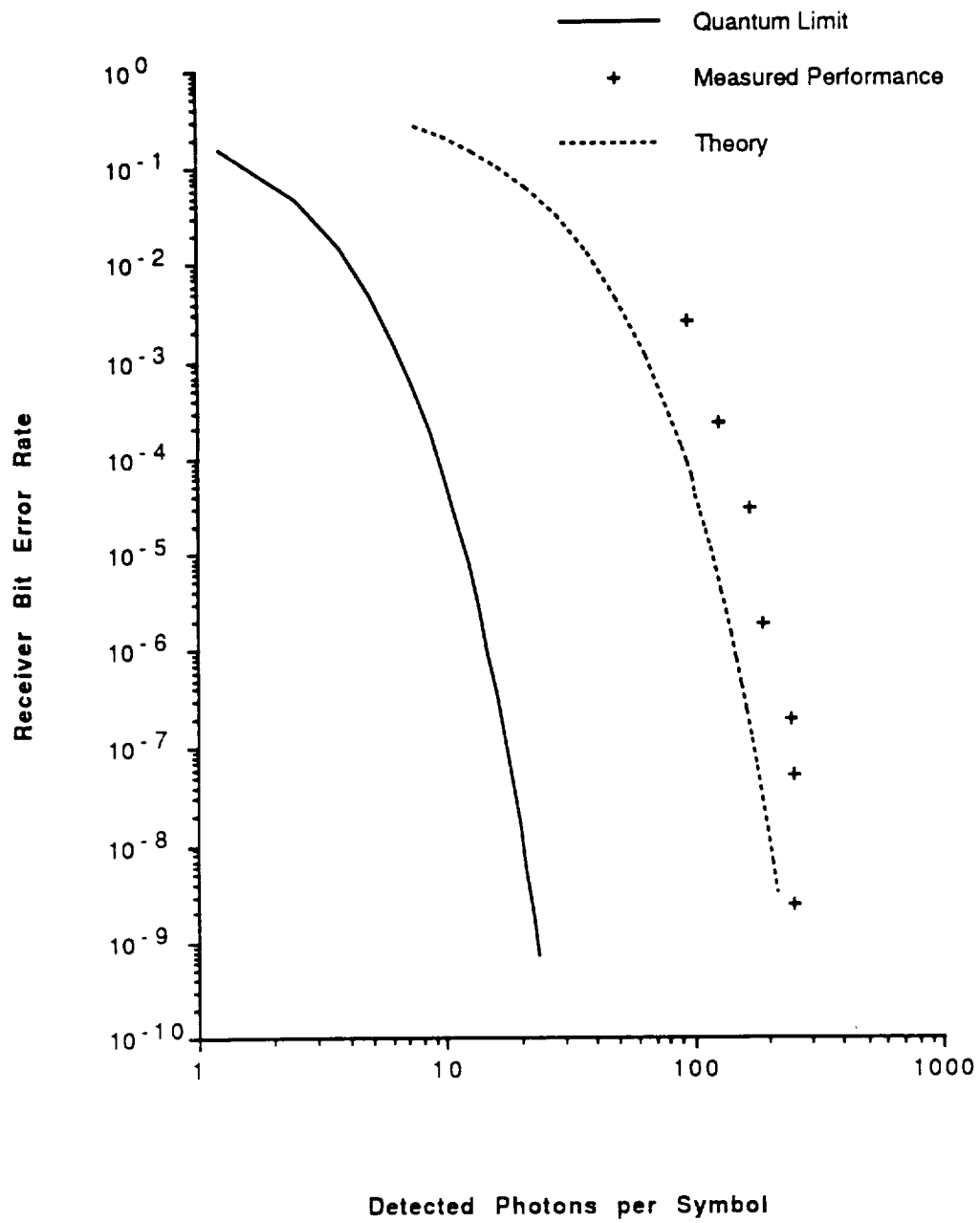
Figure 2.

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