OPTICAL SCIENCES

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA

TECHNICAL REPORT NO. 12

NARROWBAND OPTICAL HETERODYNE DETECTION

J. HANLON

S. F. JACOBS

January 1967

ABSTRACT

The technique of coherent detection has been used to explore the problems involved in detecting extremely low power levels. An input signal power level of 5×10^{-19} watts of 3.39μ radiation was detected with voltage S/N of 2, in good agreement with theory.

The major experimental problem was elimination of feedback from the local oscillator into the laser source. Narrowness of bandwidth was limited by instability in detector bias. Neither of these difficulties presents a fundamental limitation to a well designed receiver of light from a distant source.

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Introduction

Coherent or heterodyne detection of light is similar to the superheterodyne detection of radio waves. A weak, incoming signal-carrying beam is superimposed on a strong beam from a local oscillator. The nonlinear mixing of the fields on the surface of a photodetector results in a photoelectric current which may be interpreted as a beat between components of the electromagnetic field. The process has two important attributes: noise-free amplification of the weak signal beam, and post-detection electrical filtering of unwanted frequencies to extremely narrow bandwidths (much narrower than can be obtained by predetection optical filtering). In addition, phase- and frequency-modulated carriers can be demodulated.

With the advent of the laser, coherent detection of light became conveniently possible. However, the requirements for ideal performance are severe:

1. The local oscillator must not produce noise exceeding that which has been called "shot noise."
2. No significant wavefront distortions may be tolerated along the transmission path before the beams combine.
3. If narrowband filtering is to be exploited, a high degree of laser stability or control is necessary.

The latter two areas are today receiving considerable research attention. However, except for special applications, the complexities of coherent detection make it less practicable than incoherent detection (i.e., narrowband optical filter followed by photodetector). In the visible region, photomultipliers are capable of detecting a few photons per second, which is excellent performance. However, in the infrared, photodetectors of any type are presently too noisy for this kind of performance, and it is here that coherent detection appears to hold its greatest promise. Happily, the above-mentioned requirements for coherent detection are more easily met in the infrared than in the visible region of the spectrum.

The research reported in this paper concerns the detection of extremely low optical signal levels in the infrared region.

In 1961, an equation was published relating the power of the input signal ($\overline{P}_s$) to the signal-to-noise power ratio for coherent detection. This relationship was verified experimentally by several workers down to levels of 3×10^{-14} watts. It was assumed that lower input signal power levels would also give predictable values of signal-to-noise power ratio. But lower input powers had not actually been tested. Furthermore, it was not known what difficulties might be inherent in detecting such very low values of $\overline{P}_s$.

In the present work, input signal power levels as low as 5×10^{-19} watts were detected. It was found that the measured signal-to-noise power ratios still coincided with the predicted values.

The main problems in detecting very low input signal power turned out to be (1) optical feedback from the local oscillator into the laser and (2) overall system instability. The former can be prevented by adjusting the experimental apparatus. The latter requires careful system design.

Previous Work

Considerable work has been done to verify that the signal-to-noise power ratio achievable by means of coherent detection agrees with the expression[1]

$$S/N_{power} = \frac{\eta \ \overline{P}_s}{h\nu \ \Delta f},$$

where η is the detector quantum efficiency, $\overline{P}_s$ is the average input signal power, $h\nu$ is the energy per photon, and Δf is the receiver bandwidth. Good agreement has been found at relatively high levels of $\overline{P}_s$.[2,3]

It is of further interest to investigate the difficulties encountered in detection of the smallest $\overline{P}_s$ that is feasible--for example, narrowbanding to the order of 1 cps. To date, all measurements have been limited, by one thing or another, to values of $\overline{P}_s$ considerably greater than could have been reached by a more fortunate choice of components. Using essentially the arrangement shown in Figure 1, Jacobs and Rabinowitz[2] detected a $\overline{P}_s$ of 10^{-13} watts with a bandwidth of 1 cps. The resulting S/N agreed with the equation above and demonstrated, at $\lambda = 1.15\mu$, detection two orders of magnitude below the detector's incoherent NEP (noise equivalent power). However, as far as low $\overline{P}_s$ was concerned, the choice of PbS detector ($\eta = 2.3 \times 10^{-5}$) was unfortunate. Recently, Goodwin and Pedinoff[3] used an InAs photodiode ($\eta \simeq 0.3$) and a Debye-Sears modulator both to physically separate and to offset the frequency of the signal beam with respect to the local oscillator beam. They reported detection of 3×10^{-14} watts with $\Delta f = 10$ kc (five orders of magnitude below the detector's incoherent NEP). The limitation on narrow bandwidth was probably inhomogeneity in the modulator.

In the present study, the above work is extended to the relatively narrow bandwidth of 0.5 cps, where a signal level of 5×10^{-19} watts has been detected with the theoretically predicted S/N power ratio of 4.

Equipment and Method

Figure 1 shows the arrangement used in the present work.

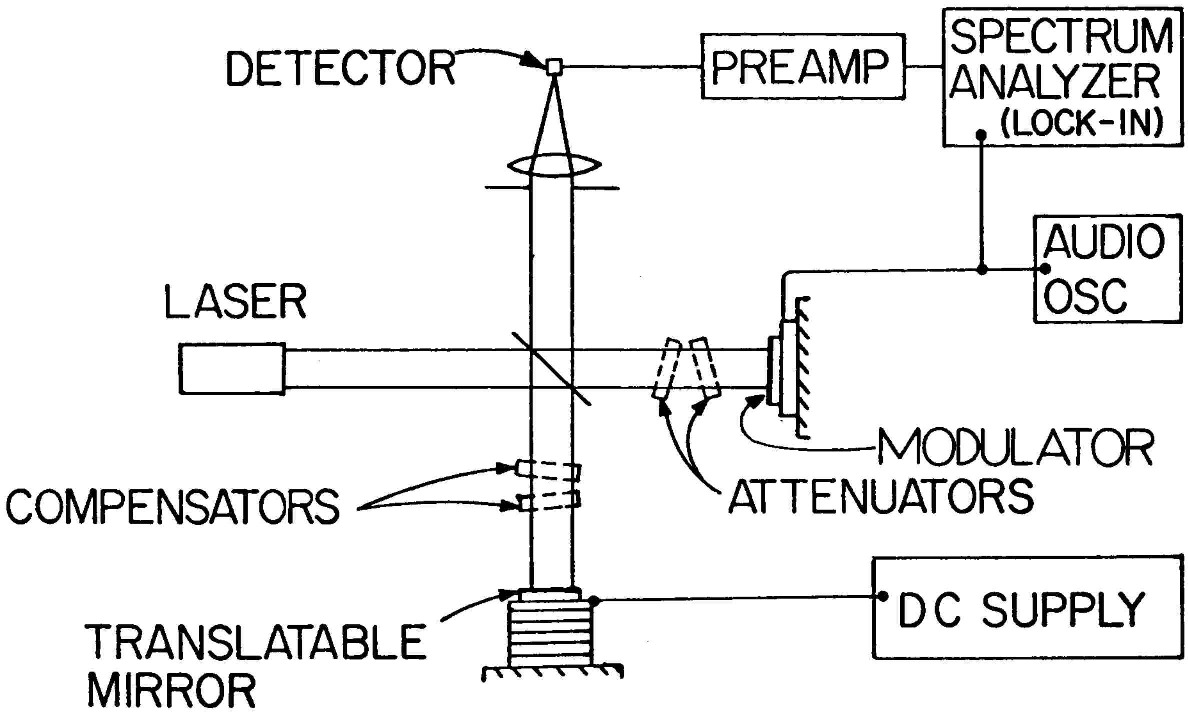
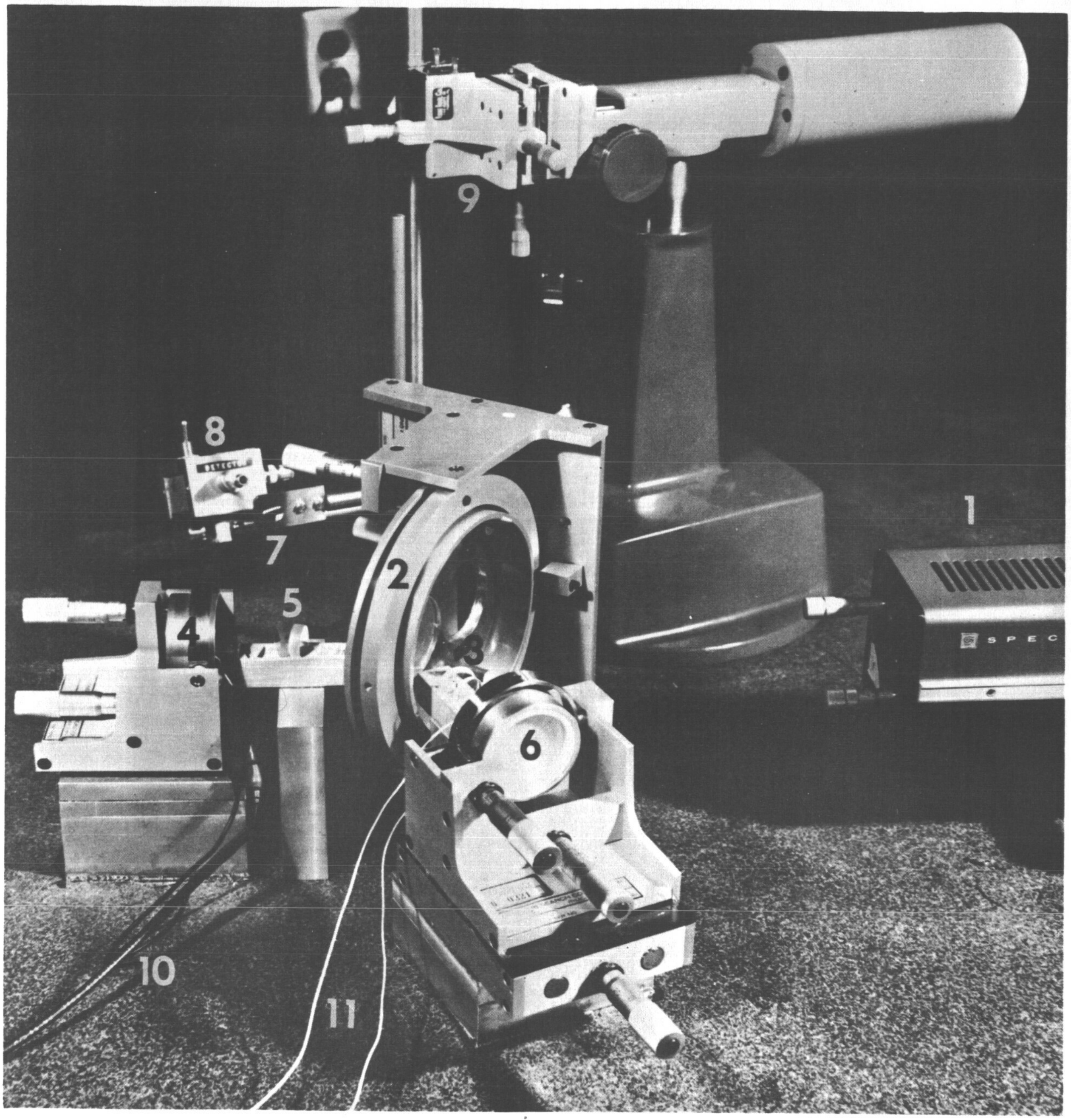


Figure 1. Experimental arrangement for measurement of S/N voltage in coherent detection.

The detector was an InAs photodiode (Philco L4530). The stability of the piezoelectric modulator made it possible to narrowband and coherently detect a signal beam power ten orders of magnitude below the detector's incoherent NEP. As in the preceding work, the method involved obtaining a single-frequency laser beam, free from excess noise and of sufficient power to generate a photocurrent whose shot noise exceeded all other system noise.



1 LASER
2 BEAM SPLITTER
3 COMPENSATORS
4 MIRROR
5 ATTENUATORS
6 MIRROR
7 FOCUSING LENS
8 DETECTOR
9 DETECTOR POSITIONER
10 WIRES FOR ELECTRICAL MODULATION SIGNAL
11 WIRES FOR ELECTRICAL PHASE ADJUSTMENT

Figure 2 shows the various noise levels present.

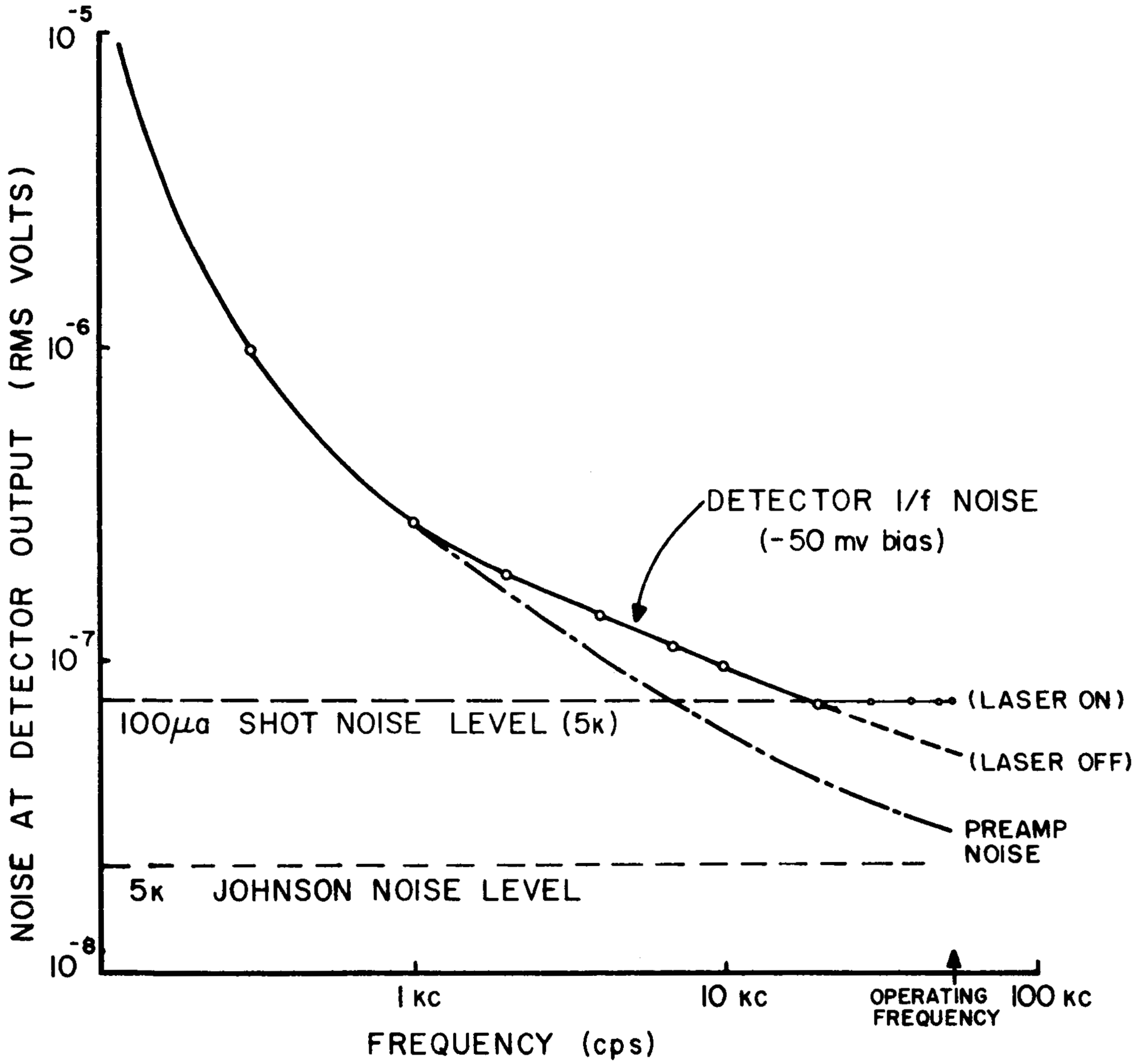


Figure 2. System noise spectrum (Δf = 6 cps).

At low frequencies, 1/f noise of the detector was the largest system noise; it lessened at higher frequencies, eventually dropping below shot noise beyond 20 kc. The maximum frequency was set by the available spectrum analyzer (Hewlett-Packard Model 302A).

The laser was He-Ne, operated at 3.39μ with rf excitation, in a 6-mm plasma tube. Diffraction output coupling[4] was used to obtain 500μ watts of single-mode power. The resonator consisted of an aluminized flat, separated 60 cm from a 60-cm-radius concave quartz reflector, the central 0.090-inch diameter of which was also aluminized.

By position-modulating the mirror with a piezoelectric transducer, 50 kc phase modulation was impressed on one beam. Signal power was varied by inserting attenuation A (plane parallel aluminized quartz reflectors, cocked 15° from normal to the beam). For phase angles $\theta < 0.2$ radians, the modulated signal beam power $\overline{P}_s$ is related to the unmodulated beam power $\overline{P}_o$ through the relation $\overline{P}_s = \theta^2 \overline{P}_o A$.

Phase modulation depth θ was measured, under conditions where $\overline{P}_s << \overline{P}_o$, by adjusting the interferometer for maximum AM signal (quadrature setting) and taking the ratio of this peak-to-peak signal to the difference between maximum and minimum DC levels (in-phase and out-of-phase settings). Because of curvature of the wavefronts it was necessary to keep the interferometer arms equal in length. This was done by placing clear, plane parallel optical compensators in the local oscillator beam each time an attenuator was inserted into the signal beam.

Final narrowband measurements were made using lock-in detection (Princeton Applied Research Model JB-6, with variable bandwidth). S/N voltages were measured with a detection time constant of 1 second.

Results

Figure 3 shows the S/N voltages measured at various values of $\overline{P}_s$.

Because S/N was actually measured in terms of voltage rather than power, the theoretical S/N is expressed in terms of voltage rather than power.

$$S/N_{voltage} = \sqrt{\frac{\eta \ \overline{P}_s}{h\nu \ \Delta f}}$$

As shown by the graph, the correlation is good between measured and theoretical values of S/N.

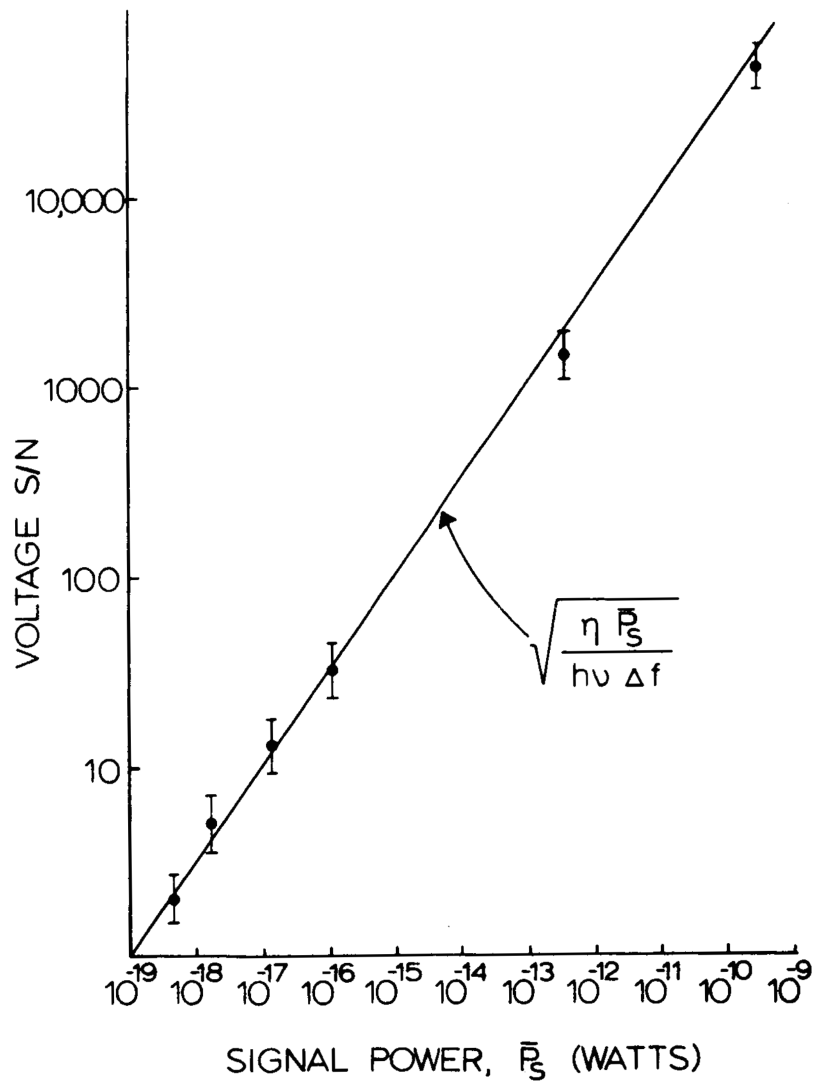


Figure 3. Measured and theoretical S/N voltages vs. incident signal beam power.

Discussion

The major problem encountered in achieving theoretical S/N was optical feedback from the local oscillator into the laser, which caused laser power fluctuations at the signal frequency. It was necessary to tilt the attenuators, the detector, and the laser optic axis sufficiently nonnormal to the interferometer mirrors so that no reflected light reentered the laser. This problem would not occur in a system with a distant signal source.

Longer time constants were precluded by the bias instability of the particular detector used. In order to assure that photocurrent shot noise was much greater than detector noise, and with limited local oscillator power available, it was necessary to keep the detector noise as small as possible. This was done by operating the detector back biased, close to zero volts (-50 mv), where noise is low but signal is very bias-dependent and hence unsteady. With either a lower system noise level (higher frequency operation or a quieter detector) or a more powerful local oscillator laser, the detector could be operated at larger negative bias levels where signal is nearly independent of bias or, alternatively, better regulation of bias voltage could be utilized for work at narrower bandwidths.

Acknowledgment

This work was partially supported by NASA.

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