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**SYLVANIA ELECTRONIC SYSTEMS  
WESTERN DIVISION**

**TEN MICRON  
WIDEBAND DETECTOR**

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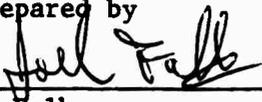
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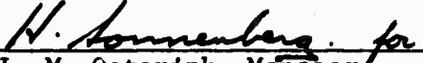
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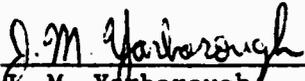
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## Section I

### INTRODUCTION

The object of this program is to provide parametric image conversion of thermal radiation from the 8-13 micron spectral region to the visible or near infrared. Previous experiments have converted 10 micron laser radiation to the visible and near infrared and have converted simple images from the near IR to the visible. No image visualization in the 8-13 $\mu$  region by parametric frequency conversion techniques has yet been reported.

Detection of 8-13 micron thermal images is viewed as a culmination of a three-part experimental program which has been initiated with the mixing of 10.6 micron CO<sub>2</sub> and 1.06 micron Nd:YAG radiation. Coherent mixing experimentation has been followed with initial experiments directed toward detection, via parametric frequency conversion, of a hot black body source. Thermal imaging experiments will follow these efforts.

This report, a summary of results obtained during the first six months of the program, is organized in the following manner: Section II describes the properties of proustite applicable to frequency conversion techniques and summarizes the results of a theoretical investigation of parametric upconversion of CO<sub>2</sub> radiation to the near infrared. Section III describes our CO<sub>2</sub> and Nd:YAG experimental mixing efforts. Section IV details a theoretical investigation of thermal imaging including a discussion of expected upconverted power and resolution.

## Section II

### UPCONVERSION AND PROUSTITE

Proustite, known for many years as naturally occurring crystal, was first artificially synthesized in 1966 at the Royal Radar Establishment in England<sup>1</sup>. Beginning with the work reported by Hulme and others in 1967, the properties of proustite have been the subject of several experimental investigations. Proustite has been used for frequency doubling of the CO<sub>2</sub> laser<sup>2</sup>, for upconversion<sup>3</sup> of CO<sub>2</sub> as well as for parametric oscillation<sup>4</sup>.

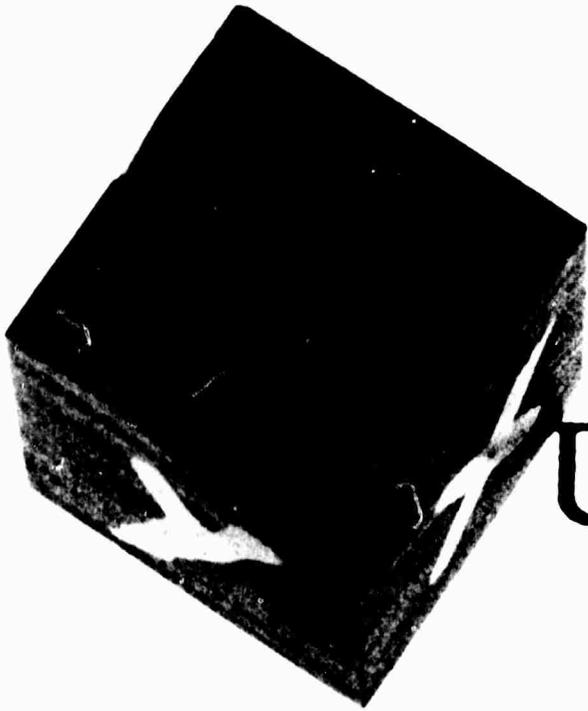
Crystalline proustite belongs to crystal space group R3<sub>c</sub> and is transparent from 6000Å to 13 microns. Although the optical quality of presently available crystals is good, scattering centers are visible in all samples we have examined to date. A typical piece of proustite, grown at the Royal Radar Establishment in the United Kingdom, is shown in Figure 1.

Proustite's second order nonlinear coefficients, among the largest of all synthetically produced crystals, are greater than twice those of lithium niobate<sup>1</sup>. In spite of proustite's large nonlinearity, its usefulness for non-linear optics is limited by its lack of resistance to damage by intense laser light.

We have observed a 5 watt, unfocused, multimode cw Nd:YAG laser cut in half a thin polished piece of proustite (see Figure 2). Further, we observe that a repetitively Q-switched Nd:YAG laser with a peak density of 500 kW/cm<sup>2</sup> causes pitting of a polished proustite sample. These damage thresholds are at least on order of magnitude worse than those previously reported.<sup>5</sup>

### UPCONVERSION IN PROUSTITE: THEORY

Two different orientations are possible for Nd:YAG pumped, 8-13 micron, upconversion in proustite.



USTITE

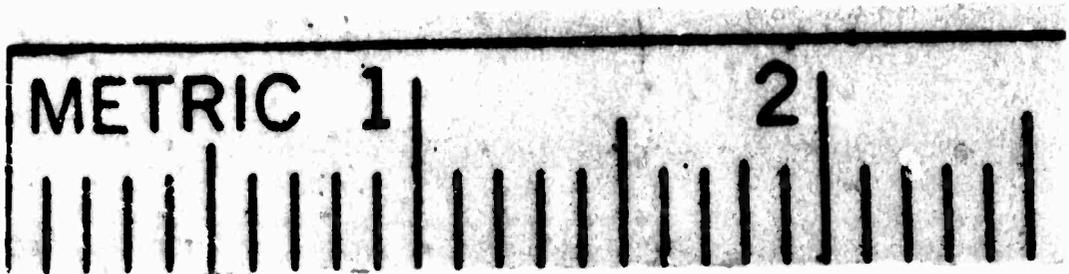


Figure 1. A proustite cube, as received from the Royal Radar Establishment, United Kingdom.



Figure 2. Damage to a thin slab of proustite.

The proustite cracked into two pieces as a result of the heating due to a 5 watt multimode Nd:YAG laser. Photo magnification is approximately 15.

In the first configuration, termed type I or EOO phase matching, the far IR radiation propagates as an ordinary wave, the pump as an extraordinary wave and the upconverted signal as an ordinary wave. In the second, termed type II or EEO phase matching, the pump and far infrared wave are extraordinary, the upconverted signal ordinary.<sup>6</sup>

For efficient parametric upconversion the familiar conservation of momentum and energy relations must be satisfied, i.e.,

$$\omega_{\text{pump}} + \omega_{\text{far IR}} = \omega_{\text{signal}} \quad (1)$$

$$\vec{k}_{\text{pump}} + \vec{k}_{\text{far IR}} = \vec{k}_{\text{signal}} \quad (2)$$

where  $\omega_{\text{far IR}}$ , the far IR frequency is to be upconverted to  $\omega_{\text{sig}}$  the signal frequency. For a Nd:YAG pumped, 8-13 $\mu$ , upconverter these relationships can be satisfied with a proustite crystal cut with its length close to 20 degrees from the crystalline optic axis. The exact "phase matching" angle is dependent on whether type I or type II phase matching is used and is easily determined experimentally.<sup>6</sup>

The upconversion efficiency of a parametric upconverter is proportional to the square of the relevant nonlinear coefficient and is different for type I and type II phase matching. It is easily shown that the effective nonlinear coefficient for type I phase matching is given by

$$d_{\text{eff}} = d_{31} \sin \theta - d_{22} \cos \theta \sin 3\phi \quad (3a)$$

while for type II matching

$$d_{\text{eff}} = d_{22} \cos^2 \theta \cos 3\phi \quad (3b)$$

where  $\theta$  and  $\phi$  are the angles, the crystal z and x axes respectively make with the crystal length.<sup>7</sup> Noting, that for proustite,  $|d_{22}| = 1.6 |d_{31}| = 2.3 \cdot 10^{22} \text{ mks}^1$  and recalling that  $\theta = 20$  degrees<sup>6</sup>, is required for phase matching, the effective nonlinear coefficients may be maximized by appropriate choice of  $\phi$ . For type I phase matching, the effective nonlinear coefficient

is maximized by choice of  $\phi = -30$  degrees and is given by

$$d_{\text{effective maximum}} = 1.84 d_{31} = 2.66 \cdot 10^{-22} \text{ mks}$$

while for type II phase matching,  $d_{\text{effective maximum}}$  is achieved with  $\phi=0$  and is given by

$$d_{\text{effective maximum}} = 1.39 d_{31} = 2 \cdot 10^{-22}$$

Hence, the type I upconverter can be designed to utilize a nonlinear coefficient 1.33 times that of the maximum possible with type II phase matching.

For the type I phase matched upconversion of a Gaussian laser beam, an exact theoretical analysis exists. This analysis, which can be used to predict the performance of the EOO upconverter, takes into account the effects of losses, double refraction and arbitrary focusing. We summarize the theoretical predictions for the EOO-type I, proustite, Nd:YAG pumped, 10.6 micron upconverter. For a complete description of the arguments that lead to the equation below the reader is referred to several excellent papers by Boyd and Kleinman.<sup>8,9</sup>

Briefly, Boyd and Kleinman's results predict that the power output of such a 10.6 micron upconverter is given by

(4)

$$\frac{P_s}{P_{10.6 \text{ microns}}} = 1.42 \cdot 10^{-9} P_p \ell h(\beta, \xi) \text{ cgs}$$

where  $\beta = 12.5 \ell^{1/2}$

where  $P_s$ ,  $P_{10.6}$ ,  $P_p$  are the powers of the 0.967 micron wavelength signal, the 10.6 micron radiation and 1.06 micron Nd:YAG laser, respectively.  $\ell$  is the crystal length,  $\xi$  the focusing parameter of the Nd:YAG and  $\text{CO}_2$  beams,  $\beta$  is a walkoff parameter and  $h(\beta, \xi)$  which describes the effects of focusing, is given from the graph of Figure 3.

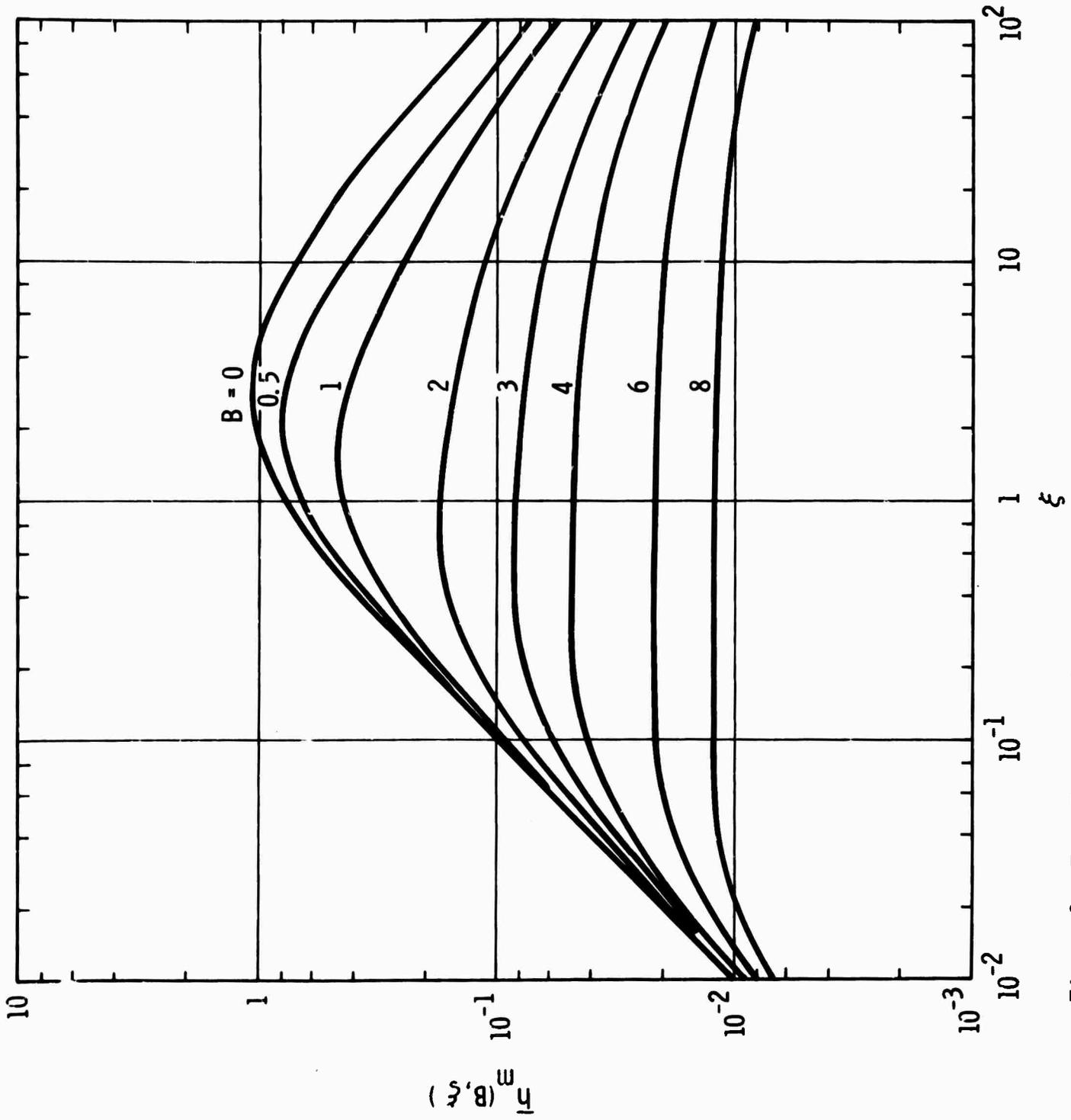


Figure 3. Type I parametric upconversion. The effects of focusing and double refraction.  $\xi = \ell/b$  where  $b$  is the Nd:YAG and CO<sub>2</sub> confocal parameter. For the proustite upconverter  $\beta = 12.5 (\ell)^{1/2}$ .

For a one centimeter length piece on proustite, with loosely focused CO<sub>2</sub> and Nd:YAG beams, ( $\xi = 10^{-2}$ ) equation 4 predicts an upconverted power of approximately  $10^{-4} P_{10.6} P_p$ . For example, for 100 mW of CO<sub>2</sub> and YAG power incident upon the proustite we would expect roughly  $10^{-6}$  watts of upconverted signal at 0.9670 microns.

For type II phase matching no exact analysis exists and the simplest way to predict the upconverted power of a CO<sub>2</sub>, Nd:YAG mixing experiment is to use an analysis based on the assumption that the CO<sub>2</sub>, YAG and upconverted signal propagate as plane waves. This approach neglects walkoff and diffraction, but should, in general, give reliable predictions of upconverted power if the nonlinear crystal lies in the near field region of loosely focused Nd:YAG and CO<sub>2</sub> laser beams.

Subject to these assumptions, it is predicted that the power output of a type II phase matched CO<sub>2</sub>, Nd:YAG mixing experiment will be given by

$$\frac{P_s}{P_{10.6}} \approx 2.4 \cdot 10^{-7} \ell^2 \frac{P_p}{A_p + A_i} \quad (5)$$

where  $A_p$  and  $A_i$  are the areas of the Nd:YAG and CO<sub>2</sub> beams, respectively

or for  $\ell = 1$  cm  
and

$$A_p = (3 \cdot 10^{-2})^2 \pi \text{ cm}^2 \text{ and } A_i \approx A_p$$

$$\frac{P_s}{P_{10.6}} = 3.510 \cdot 5 P_p$$

or for  $P_p = P_{10.6} = 0.1$  watts

$P_s = 3.5 \cdot 10^{-7}$  watts, or about 1/3 that for type I phase matching

### Section III

#### UPCONVERSION IN PROUSTITE: EXPERIMENT

As a first step toward image upconversion of thermal radiation as well as to provide experimental verification of the theory presented in Section II of this report, we have mixed the output of a CO<sub>2</sub> laser operating at several wavelengths near 10 microns with the output of a 1.06 Nd:YAG laser.

Mixing was accomplished in proustite using type II or EEO phase matching. Although type I phase matching should provide better upconversion efficiency and is better theoretically understood, the ready availability of a crystal oriented for type II phase matching led us to begin our upconversion study with an experimental investigation of type II mixing. Presently, crystals are being prepared for an experimental study of type I phase matched upconversion. For our initial type II mixing experiments, upconversion was accomplished with the CO<sub>2</sub> laser operating at 9.6 microns, 10.2 microns and 10.6 microns. The particular wavelength CO<sub>2</sub> wavelength to be upconverted was selected by rotation of the proustite crystal. Subsequent experimentation utilized a CO<sub>2</sub> laser partially filled with SF<sub>6</sub> to suppress oscillation in all but the 10.6 micron CO<sub>2</sub> line. Single line operation of the CO<sub>2</sub> laser by this method was only partially successful and the laser often oscillated in two spectral lines near ten microns.

The angular acceptance of the upconversion process was measured, yielding a value close to that previously reported in the literature.<sup>7</sup>

Upconversion was achieved with the Nd:YAG laser operating in both cw and Q-switched modes. Typical cw Nd:YAG powers incident on the proustite crystal were 50-300 mW while average CO<sub>2</sub> powers were 50-150 mW. When the Nd:YAG laser was Q-switched, the average power was 200 mw, with peak powers of 500 watts. As expected, Q-switching the Nd:YAG laser significantly increased the peak power of the upconverted signal, while reducing the possibility of damage to the proustite crystal by limiting the average power incident upon it.

Experimentation with focusing of the Nd:YAG laser as well as the CO<sub>2</sub> laser was undertaken. Lenses of focal lengths 75 cm and 10 cm were used for the CO<sub>2</sub>, lenses of 50 cm and 25 cm focal lengths were used for the Nd:YAG. As expected the unconverted power increased with stronger focusing and was usually strong enough to be seen with an uncooled 7102 phototube.

Considerable effort was made to extend the minimum detectable signal to its lowest possible value. Provision was made for cooling our type 7102 photomultiplier to dry ice temperature (-68°C). Such cooling decreased its noise equivalent power from about 10<sup>-13</sup> watts at room temperature to about 3·10<sup>-15</sup> watts at -68°C (1 sec integration time). Provision was made for beam steering of both the CO<sub>2</sub> and YAG laser beams as well as adjusting the angle and position of the proustite crystal. A schematic diagram of our latest experimental setup is shown in figure 4. The CO<sub>2</sub> laser beam, chopped at 1 KHz, is focused by a 10 cm focal length mirror upon the proustite crystal. The Nd:YAG, focused by a 25 cm lens, passes through a hole in the CO<sub>2</sub> mirror, and onto the proustite. The 0.967 micron output is detected using phase sensitive detection with typically one second integration time. Three bandpass filters and a polarizer prevent both the CO<sub>2</sub> and the YAG radiation from entering the detector. A KCl reflector and teflon attenuator provide CO<sub>2</sub> powers, at the proustite input face, variable from 1 microwatt to 100 milliwatts. Focusing as shown provides approximately equal CO<sub>2</sub> and Nd:YAG beam areas measured to be approximately 1.03·10<sup>-2</sup> cm<sup>2</sup>, or CO<sub>2</sub> and Nd:YAG focusing parameters of approximately 3.0·10<sup>-2</sup> and 2.5·10<sup>-1</sup> respectively<sup>8</sup>. It might be desirable to focus the Nd:YAG tighter to optimize unconverted power by making the Nd:YAG focusing parameter more nearly equal to that of the CO<sub>2</sub> beam. This was not tried for fear of damaging the proustite at moderate (less than 50 mW) power levels with any stronger focusing.

The typical Nd:YAG pump power for the experiment shown schematically in Figure 4 was 60 mW. Detection of 80 milliwatts of CO<sub>2</sub> incident upon the proustite crystal was accomplished with a signal to noise ratio of greater than 2·10<sup>5</sup>, leading to an expected minimum detectable signal power of

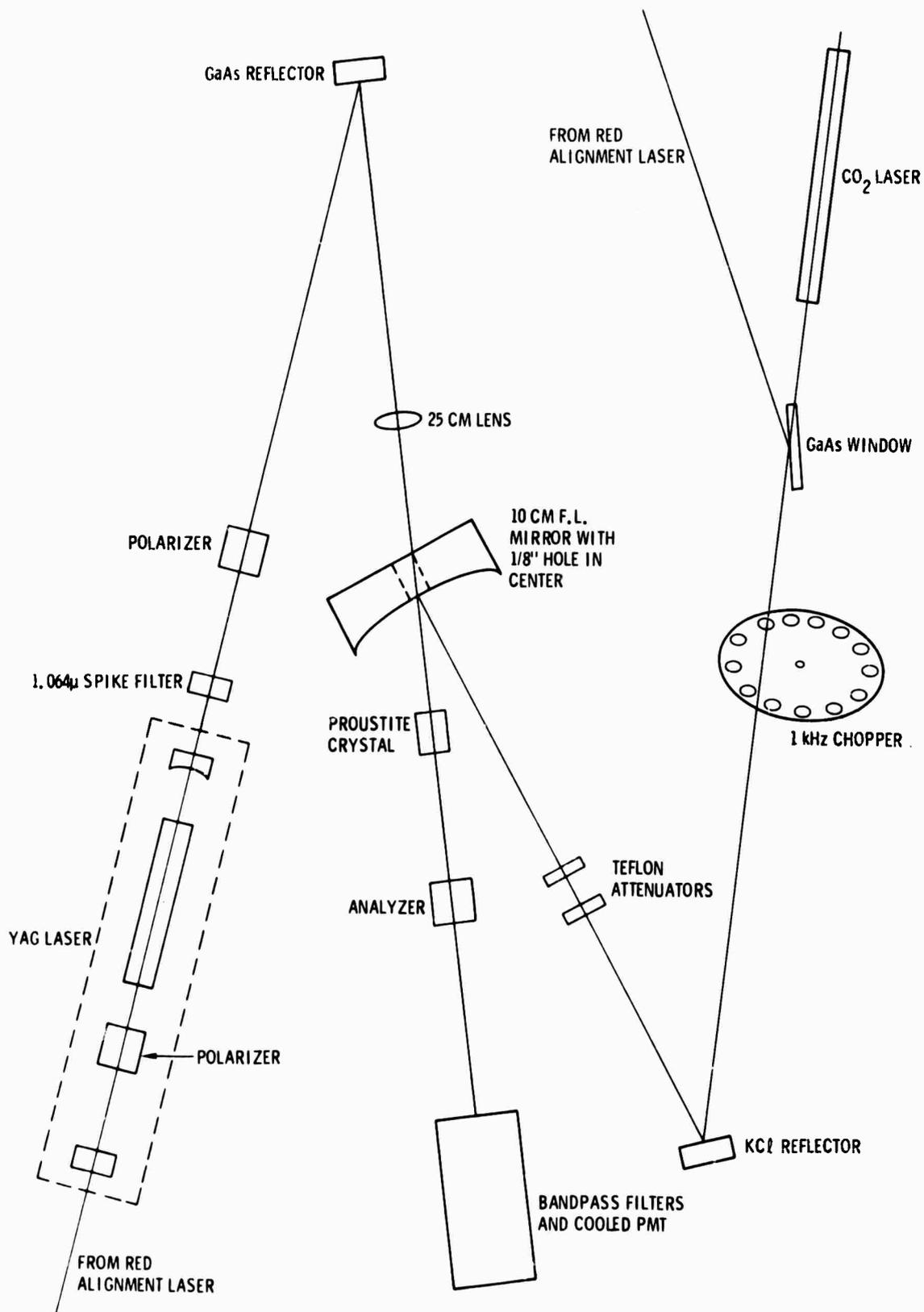


Figure 4. A schematic diagram of the parametric upconverter.

approximately 0.5 microwatts. Detectability of about 1 microwatt of  $\text{CO}_2$  was verified by inserting teflon attenuators in the  $\text{CO}_2$  beam to reduce its power to the microwatt level. To date, 1 microwatt represents the least  $\text{CO}_2$  that we have been able to upconvert. More efficient upconversion should be possible using type I upconversion coupled with the use of a small diameter, low noise, cooled S-1 phototube. Figure 5 shows a photograph of our experimental setup. Figure 6 shows typical upconverter output waveforms.

Very preliminary experimentation has been undertaken in an attempt to replace the  $\text{CO}_2$  source within incoherent blackbody radiation. Direct substitution of  $1000^\circ\text{K}$  blackbody source for the  $\text{CO}_2$  laser in the experiment shown in Figure 4, was attempted. Attempts at upconversion of the hot source were unsuccessful. A careful attempt to repeat this experiment will be made shortly.

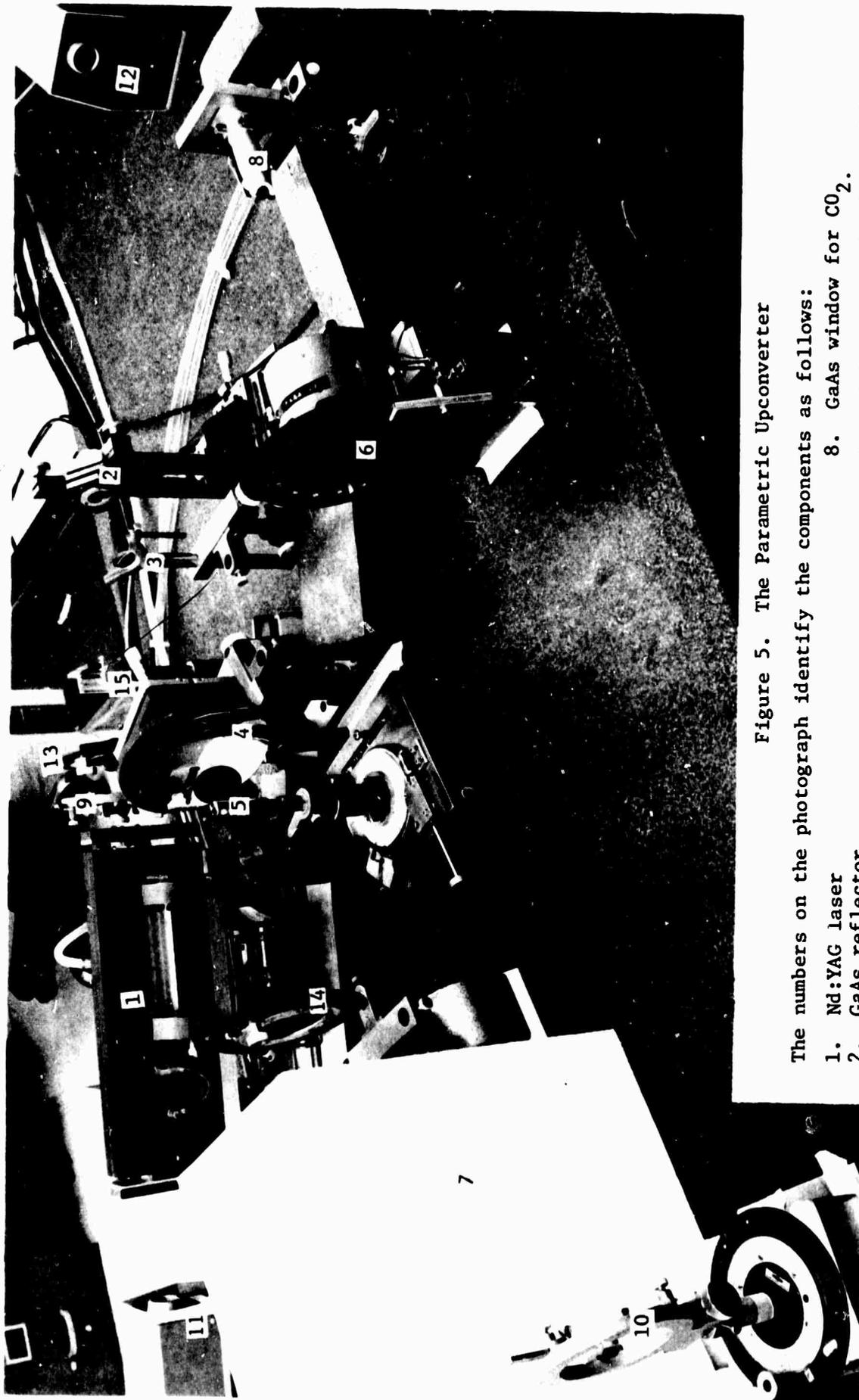


Figure 5. The Parametric Upconverter

The numbers on the photograph identify the components as follows:

- |                                    |                                      |
|------------------------------------|--------------------------------------|
| 1. Nd:YAG laser                    | 8. GaAs window for CO <sub>2</sub> . |
| 2. GaAs reflector                  | 9. Nd:YAG narrow bandpass filter     |
| 3. Nd:YAG focusing lens            | 10. KCl reflector                    |
| 4. CO <sub>2</sub> focusing mirror | 11,12. Alignment lasers              |
| 5. Proustite crystal               | 13. Polarizer                        |
| 6. 1 KHz chopper wheel             | 14. Analyzer                         |
| 7. Cooled PMT and bandpass filters | 15. 3 db Nd:YAG attenuator           |



Figure 6. Type II parametric upconverter output waveforms.

For this photo, the Nd:YAG laser output was chopped at a 1 KHz. CO<sub>2</sub> input radiation was about 10 mW, Nd:YAG radiation about 100 mW. Upper trace is upconverted signal, lower trace is the Nd:YAG waveform. The signal power is of the order of several nanowatts.

## Section IV

### THERMAL IMAGING: THEORY

In this section we will consider the theoretical requirements for viewing thermal images in the 10 micron region via parametric up-conversion. Expressions will be derived for the power and resolution to be expected from a parametric blackbody image upconverter constructed using a Nd:YAG laser and proustite nonlinear crystal. It will be shown that resolution of a thermal image upconverter depends on background temperature, detector quantum efficiency, as well as on the emissivity of the thermal source to be upconverted.

It has long been known that all solids radiate. The power that a solid radiates is strongly dependent of its temperature and is given by Planck's formula<sup>10</sup>

$$\frac{dP_i}{dAd\Omega d\lambda} = \frac{2 hc^2 \epsilon_\lambda}{\lambda_i^5 \left[ \exp \frac{hc}{\lambda_i kT} - 1 \right]} \quad (6)$$

where  $\frac{dP_i}{dAd\Omega d\lambda}$  is the power radiated per unit area, solid angle and wavelength,

$c$  the velocity of light,  $h$  Planck's constant,  $k$  Boltzmann's constant, and  $T$  the solid's temperature in degrees Kelvin. The body's spectral emissivity,  $\epsilon_\lambda$ , is the ratio of the energy radiated by a solid at temperature  $T$  to the energy radiated by a perfect radiator or so-called "blackbody".  $\epsilon_\lambda$  will in general be a function of wavelength. For purposes of the discussion that follows we will assume that  $\epsilon_\lambda = 1$ , i.e., in the ensuing discussion we will consider upconversion of the 8-13 $\mu$  thermal radiation of a blackbody. For a solid at room temperature (300<sup>o</sup>K) the peak of the blackbody spectral distribution is near 10 microns and the power radiated per unit area, solid angle and wavelength is  $9.8 \cdot 10^6$  mks.

It is interesting to note that in the 8-13 micron range the total power radiated by a  $1 \text{ cm}^2$  blackbody at room temperature is in excess of several milliwatts. Detection of thermal radiation in the 8-13 micron region by parametric techniques requires that a substantial portion of this radiated energy be upconverted to a region of the spectrum where relatively sensitive detectors exist. In Section II we have found that the signal output power,  $P_s$ , of such a parametric upconverter is given by

$$P_s = K \ell^2 \frac{P_p P_i}{A_p + A_i} \quad (7)$$

where  $A_p$ ,  $A_i$  are the areas of the pump and 8-13 micron beams respectively and where  $K$  is a material parameter. Combining equations 6 and 7, it is easily shown that the incremental output of a thermal imaging upconverter is given by

$$dP_s = K \ell^2 \frac{P_p}{A_p + A_i} \frac{2hc^2 A_i}{\lambda_1^5 \left[ \exp \frac{hc}{\lambda_1 kT} - 1 \right]} \text{sinc}^2 \frac{\Delta k \ell}{2} d\lambda_1 d\Omega_1 \quad (8)$$

where  $\text{sinc} \frac{\Delta k \ell}{2} = \frac{\sin \frac{\Delta k \ell}{2}}{\frac{\Delta k \ell}{2}}$

is an asynchronism factor which accounts for the fact that all wavelengths of thermal radiation will not be perfectly phase matched for upconversion.

$$\Delta k = \overline{k_p} + \overline{k_i} - \overline{k_s}, \text{ can be easily shown to be given by } \Delta k = b\Delta v_1 + g\phi^2, \quad (15)$$

where  $b$  and  $g$  are constants of the parametric process and  $\phi$  is the internal angle between an incremental upconverted ray and the pump, and

$$\Delta v_1 = c\Delta \left( \frac{1}{\lambda_1} \right).$$

A good estimation of the total upconverted power may be obtained by integrating equation 8. Assuming that the terms multiplying the sinc<sup>2</sup> function are slowly varying over the range where the sinc function is appreciable, we find that the total power output expected from a thermal upconverter can be written

$$P_s = \frac{2hc^2}{\lambda_i^5 \left[ \exp \frac{hc}{\lambda_i kT} - 1 \right]} \frac{2\lambda_i^2}{cb\ell} \Delta\Omega_i A_i \frac{K\ell^2 P_p}{A_p + A_i} \quad (9)$$

Equation 9 may be viewed as  $P_s = [\text{Power radiated/ Bandwidth} \times \text{Solid angle} \times \text{Area}] \times [\text{Bandwidth}] \times [\text{Solid Angle}] \times [\text{Area}] \times \text{Gain}$ , where  $\frac{2\lambda_i}{cb\ell}$  is seen

to be an equivalent bandwidth for the parametric upconverter.

From equation 9, we see that for  $A_p \ll A_i$  the detected signal power is independent of area of either the pump or 8-13 micron beam. Hence, it is advantageous to use pump and far-IR beams as large as possible so that any possible crystal damage is avoided.

It has been noted elsewhere<sup>11</sup> that to avoid chromatic aberration in image upconversion the greatest possible blackbody solid angle that can be accepted by the parametric upconverter is determined by the requirement that all 8-13 micron radiation to be upconverted be well collimated in the nonlinear crystal. This condition limits the maximum acceptable thermal radiation solid angle to  $\frac{4n_i \lambda_i}{\ell}$ . Hence, if we upconvert thermal radiation with solid angle as great as  $\frac{4n_i \lambda_i}{\ell}$ , we find from equation 9 that the maximum usable upconverted power<sup>2</sup> is independent of both beam area and crystal length.

We have evaluated this maximum usable upconverted power for the 1.06 micron Nd:YAG proustite system where the output signal wavelength will be near 0.95 microns. Table I shows expected power output as a function of the temperature of the object to be imaged.

TABLE I: 8-13 MICRON TYPE II IMAGE UPCONVERSION EXPECTED POWERS

T(°K)	Signal Power per watt of pump (picowatts) $\lambda_s \approx 0.95\mu$
300	0.2
400	0.6
500	1.3
600	2.1
700	3.1
800	4.0
900	5.7
1000	6.8

We note that for type I upconversion that the expected powers tabulated above would be approximately doubled. Further, since the damage resistance of proustite limits useful Nd:YAG powers to about a watt, the powers per watt of pump tabulated in Table I are the maximum expected upconverted powers.

If blackbody radiation is to be detected, detector noise must be lower than those powers given in Table I. At present, the only available image detector for the 0.95 micron wavelength region is a S-1 photocathode followed by one or more image intensifiers. The typical S-1 photosurface has an equivalent room temperature input noise of  $10^{-9}$  watts/cm<sup>2</sup> and hence at room temperature is useless as a detector. An S-1 photosurface, cooled to dry ice temperature has an equivalent input noise of approximately  $10^{-13}$  watts/cm<sup>2</sup> and hence provides marginal near infrared detection for the image upconverter.

For reliable detection of the near IR scene resulting from the parametric upconversion it is probably necessary to use a gated S-1 image tube. A gated tube, used with a pulsed Nd:YAG pump, will reduce the effective tube noise by the duty cycle of the gate. Improvement in noise performance of greater than 100 can be reasonably expected.

Thus far we have considered the power available in an upconverted thermal image but have said nothing about resolution to be expected from such a process. Resolution is limited by the discrete nature of the photons,

and the statistical fluctuations associated with their time of arrival at the parametric upconverter. This statistical distribution of photons results in a statistical distribution of near IR upconverted photons leaving the upconverter which in turn results in a statistically distributed number of photons at each resolution element of any detector used to view the output of the upconverter.

In the following paragraphs we examine the limiting resolution due to so-called "scintillation fluctuations" in the image conversion of a near IR scene to the visible via an image tube. We will apply our results to the experimental situation where the source of the near IR image is 10 micron blackbody radiation that has been upconverted to the near IR via a pro:stite, Nd:YAG system.

For mathematical convenience, we will consider scene to be viewed as consisting of a pattern comprised of light and dark squares, i.e., we will consider the output of an imaging detector to be partitioned into resolution elements as sketched in Figure 7. We will allow for the "dark" squares to be partially illuminated and define a contrast factor  $C$  such that the rate of production of photoelectrons in elements 1 and 2 are related by

$$\dot{n}_2 = (1-C) \dot{n}_1 \quad (10)$$

where  $C$  is always between zero and one.

The output signal may be calculated by computing the average difference in rate of photoelectron production of adjacent resolution elements. That is, an eye or camera distinguishes between adjacent monochromatic resolution elements by contrasting their different levels of illumination.

Noise due to the discrete nature of photoelectrons is calculated by considering the variance or rms difference in photoelectron production rates of two resolution elements. We assume as is the usual case for photon

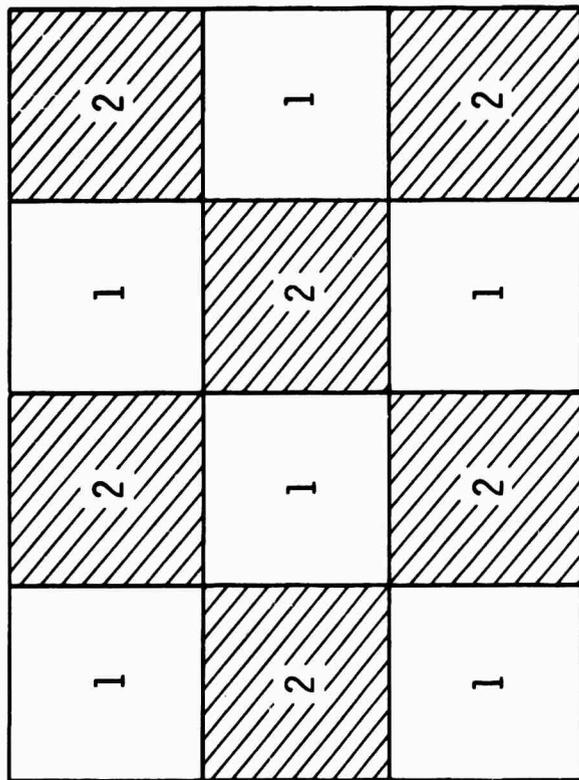


Figure 7. An upconverted scene. Dark squares produce (1-C) less photoelectrons than light squares.

or photoelectron counting, that the production rate of photoelectrons is Poisson distributed and take the photoelectron production of adjacent resolution elements to be independent. Further, we recall that for a Poisson distribution, the average production rate is equal to the mean square rate<sup>12</sup>. We may write the signal to noise ratio for detection of adjacent resolution elements, i.e., the scene signal to noise ratio as:

$$\frac{S}{N} = \frac{(\bar{n}_1 - \bar{n}_2) t}{[(\bar{n}_1 + \bar{n}_2)t]^{1/2}}$$

where  $n_1$  and  $n_2$  are the average rates of production of photoelectrons in resolution elements 1 and 2 respectively. The plus sign in the denominator of the expression is due to the fact that for independent production rates mean square values add.

Noting that the total average photoelectron current is given by

$$I = \frac{Me}{2} [\bar{n}_1 + \bar{n}_2]$$

where  $M$  is the total number of resolution elements and  $e$  is the charge on an electron, we may rewrite the signal to noise ratio in a useful form.

$$\frac{S}{N} = \frac{C}{2-C} \frac{[2It]^{1/2}}{Me} \tag{11}$$

We note that  $t$  appearing in the above equation is the integration time of the visible detector. Literature estimates of necessary signal to noise ratio for detectability, depend on the particular image, and are in the range of one to five.<sup>13,14</sup> For a given contrast  $C$ , and a given resolution  $M$  equation (11) determines the minimum  $(I) \cdot (t)$  product for satisfactory image resolution.

What does this minimum  $(I) \cdot (t)$  mean relative to the construction of a cw Nd:YAG-proustite 10 micron blackbody upconverter? It has been previously noted that upconversion of room temperature blackbody radiation in the Nd:YAG-proustite system produces  $\sim 2 \cdot 10^{-13}$  watts of near IR power for each watt of pumping 1.06 radiation. The only present photosurface available for use in an image tube for conversion of near IR to the visible in the S-1 photosurface. The S-1 photocathode has a near IR quantum efficiency of approximately 0.2%, i.e., it will produce  $1.5 \cdot 10^{-3}$  amps for each watt incident upon it. Thus we find that each watt of YAG incident on the Nd:YAG, proustite, the upconverter produces  $3 \cdot 10^{-16}$  amps in the S-1 photodetector. It is this photocurrent which determines the maximum resolution  $M$  possible for a detector with a given integration time  $t$ .

For blackbody radiation, contrast between adjacent elements can only be due to a temperature difference between the elements. Contrast, as defined by equation 10, may be determined from the Planck formula, Equation 6. For a scene minimum temperature of  $300^{\circ}\text{K}$  we find  $C = 2.07 \cdot 10^{-3} \Delta T$ , where  $\Delta T$  is the temperature difference between adjacent elements. Figure 8 shows the  $\Delta T$  required for resolution of  $M$  elements as a function of Nd:YAG energy,  $P_p \cdot t$ , incident on a proustite upconverter. In Figure 8, we have assumed use of a S-1 image tube to convert the near IR image to the visible.

For example, we consider an imaging system with  $10^4$  resolution elements. Taking the visible detector to be the eye, which has an integration time of approximately 0.2 seconds, and considering a  $\Delta T = 10^{\circ}\text{K}$  between adjacent resolution elements we find that the required Nd:YAG pump power for image resolution is 250 watts. Because of the damage properties of proustite, detailed in Section II of this report, such a system is probably not feasible. Therefore, for detection of a  $300^{\circ}\text{K}$  blackbody image with  $10^4$  resolution elements it is necessary to use a detector with longer integration time than the eye (e.g. film) or to develop a photosurface more sensitive in the near IR than the S-1.

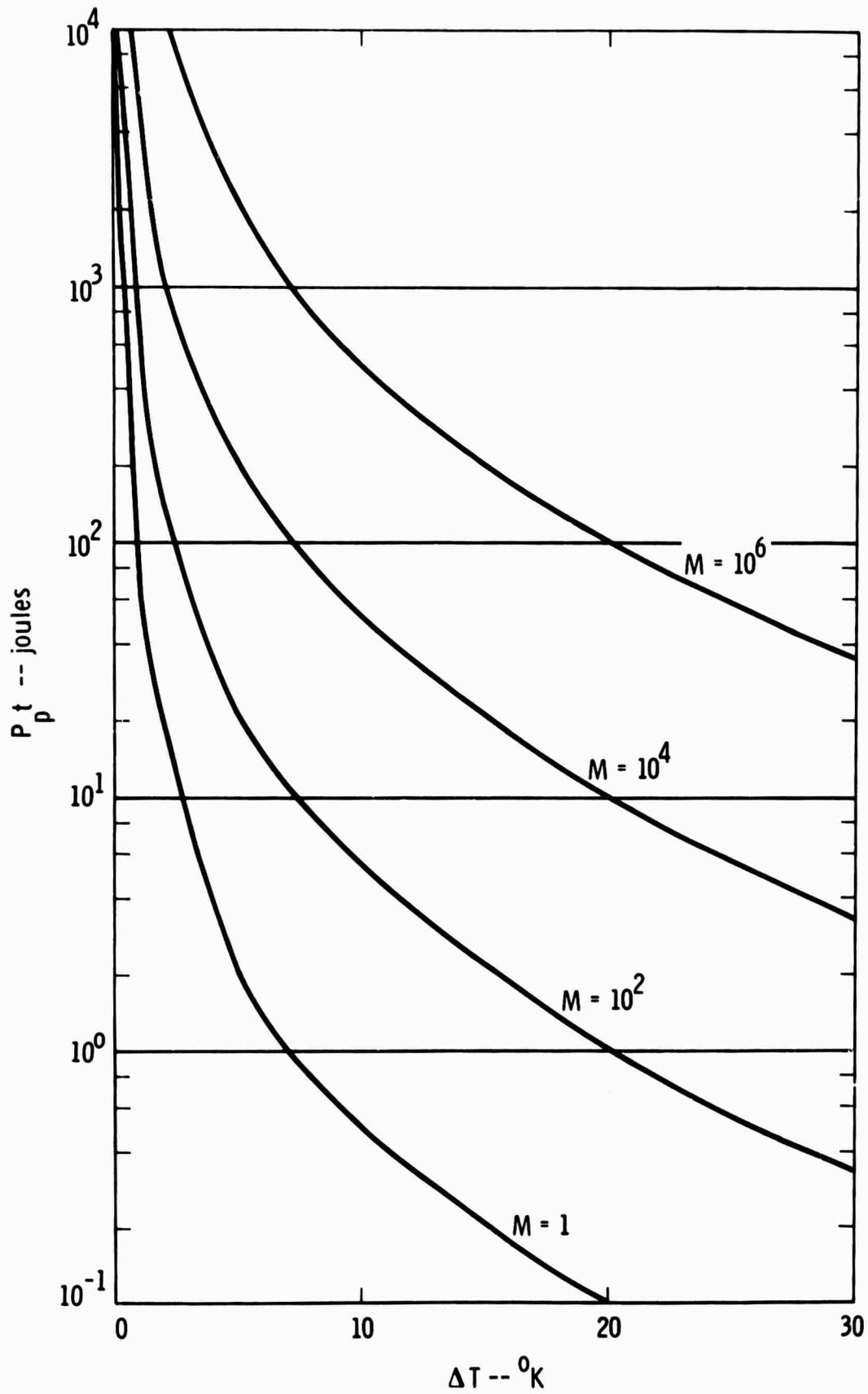


Figure 8.  $\Delta T$  required for the resolution of  $M$  elements as a function of Nd:YAG energy,  $P_p t$ .

We note that in general if a photosurface with greater efficiency than the S-1 could be developed, lower near IR powers would be required to overcome quantum fluctuations and hence lower Nd:YAG powers would be needed for the cw blackbody upconverter. In particular, a photosurface with a quantum efficiency of  $n$  percent would reduce the Nd:YAG energy required for a given resolution by  $\frac{n}{0.2}$  below that required for a S-1 tube. Alternately, for fixed Nd:YAG energy, resolution is improved by  $5n$  over that for a S-1 image tube. This argument presupposes that if such a high quantum efficiency tube could be developed, its noise would be negligible with comparison to the upconverted signal.

For example, a low noise near IR image converter whose photosurface has a quantum efficiency of 10%, could satisfactorily be used to form the usual image ( $10^4$  elements,  $\Delta T=10^{\circ}\text{K}$ ) previously described with Nd:YAG input powers of 5 watts.

## Section V

### SUMMARY AND CONCLUSIONS

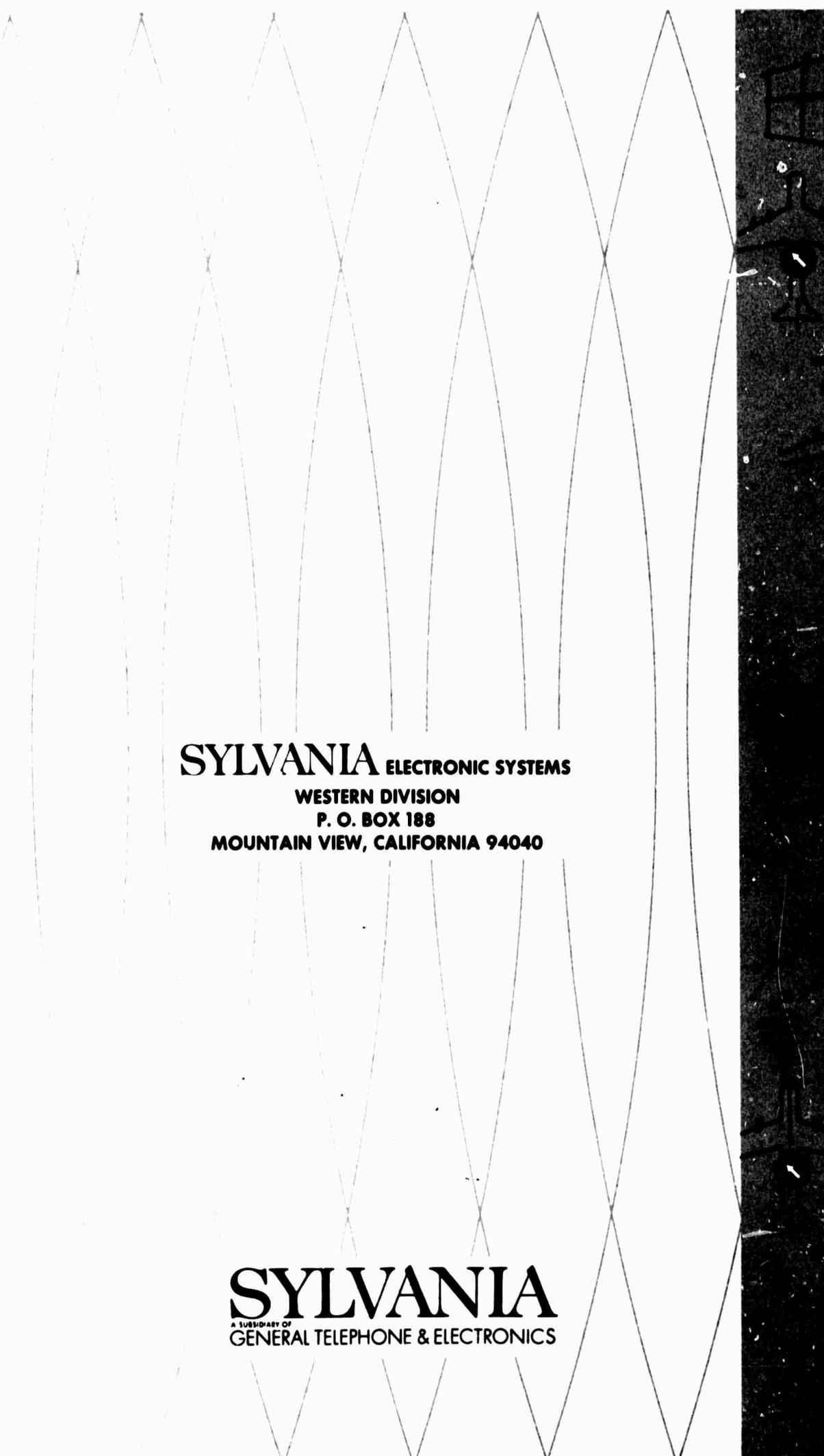
In the first six months of this program we have theoretically investigated upconversion of incoherent images and also experimentally studied coherent mixing. Ten micron  $\text{CO}_2$  light of power as low as a microwatt has been upconverted to 0.96 microns. An experimental study of the detection of a hot blackbody, via upconversion, has begun.

In the remaining six months of this program we intend to continue our study of incoherent upconversion directed toward the ultimate goal of image upconversion. The major problem hindering thermal imaging in the present Nd:YAG proustite system is expected to be image detection of the near infrared output of the upconverter. A state-of-the-art, gated, coolable, S-1, image converter tube is expected to be required. The low quantum efficiency, high noise of the S-1 photosurface is thought to present the major detection problem.

We will investigate methods of shifting the upconverted signal into the visible portion of the spectrum where tubes with substantially higher quantum efficiency exist. Methods under investigation to produce a visible image include changing the pump to ruby or operating the Nd:YAG pump at 0.946 microns. A detailed investigation of the consequences of such a wavelength shift will be made.

## REFERENCES

1. K. F. Hulme, O. Jones, P. H. Davies and M. V. Hobden, *Appl. Phys. Letters* 10, 133 (1967)
2. D. M. Boggett and A. F. Gibson, *Phys. Letter* 28A, 33 (1968)
3. J. Warner, *Appl. Phys. Letters* 12, 222 (1968)
4. E. O. Ammann and J. M. Yarborough, *Appl. Phys. Letter* 17, 233 (1970)
5. W. Bardsley, P. H. Davies, M. V. Hobden, K. F. Hulme, O. Jones, W. Pomeroy, J. Warner, *Opto-Electronics* 1, 29, (1969)
6. R. A. Andrews, *IEEE J. Quant. Elect.* QE-6, 68, (1970)
7. Y. Klinger and F. Arams, *Proc. IEEE*, 57, 1797 (1969)
8. G. D. Boyd and D. A. Kleinman, *J. Appl. Phys.*, 39, 3597 (1968)
9. D. A. Kleinman and G. D. Boyd, *J. Appl. Phys*, 40, 546, (1969)
10. A. Yariv, Quantum Electronics, (John Wiley, New York, 1967) P. 87
11. Proposal for Development of Infrared Image Upconversion Techniques. Contract N00014-70-C-0224.
12. See, for example, Papoulis, Probability, Random Variables, and Stochastic Processes, Pgs. 101, 145, 357, McGraw-Hill Book Co., (1965).
13. A. Rose, *J. Opt. Soc. Am* 38, 196 (1948).
14. J. S. Parton, J. C. Moody, *Image Intensifier Symposium*, Ft. Belvoir, Virginia, NASA SP-2 (1961).
15. R. L. Byer and S. E. Harris, *Phys. Rev.* 168, 1064 (1968)



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