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INFRARED UPCONVERSION FOR ASTRONOMICAL APPLICATIONS

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ABSTRACT

The performance of an upconversion system is examined for observation of astronomical sources in the low to middle infrared spectral range. Theoretical values for the performance parmeters of an upconversion system for astronomical observations are evaluated in view of the conversion efficiencies, spectral resolution, field of view, minimum detectable source brightness and source flux. Experimental results of blackbody measurements and molecular absorption spectrum measurements using a lithium niobate upconverter with an argon-ion laser as the pump are presented. Estimates of the expected optimum sensitivity of an upconversion device which may be built with the presently available components are given.

1. Introduction

Upconversion of infrared radiation into visible spectrum by parametric interaction in a nonlinear crystal has received a great deal of attention in recent years. The upconverted radiation may be detected with relatively high sensitivities with no requirement for any cryogenic cooling, thus making it an attractive technique for detection and imaging of remote infrared sources.

The theory of parametric interactions in a nonlinear medium is now well developed[1] and a large number of experiments on various nonlinear materials covering the spectral range 1-10 μm have been reported. A summary of the published results of some upconversion experiments is provided in Table 1.

The possibility of applying the upconversion technique to astronomical observations has long been realized[13,14]. However, in practice it has received very little attention mainly due to the relatively low conversion efficiency, and therefore low sensitivity, with which upconversion so far has been possible. With the development of high power lasers and the availability of better nonlinear materials this situation now seems to be changing, and sufficiently high conversion efficiencies have been reported to make the upconversion process a useful technique for astronomy (see Table 1).

Since astronomical sources are constant during the period of observation, a C.W. system, if it has sufficient sensitivity, is advantageous. A figure of merit for an upconverter-spectrometer is given by the product (duty cycle x quantum efficiency); for broad band detection the product (duty cycle x quantum efficiency x band-width) is useful. Additional requirements for imaging extended sources are a reasonably large field of view and a large aperture for good spatial resolution[15]. For astrophysical applications, tunability (with wavelengths within an atmospheric window for ground based observations) and spectral resolution capable of identification of molecular and atomic species are important instrumental requirements. Most of the above requirements can be theoretically satisfied by upconversion using currently available components.

Astronomical observations using the upconversion technique have recently been reported when thermal radiation from the Moon, Venus and several stars was detected by Gurski et al.[11]. In this device, lithium iodate was used as the nonlinear medium and Nd:YAG laser as the pump, for observations in the 4 μm spectral region.

The purpose of this paper is to evaluate the performance of an upconversion system for spectroscopic and imaging observations of astronomical sources in the low to middle infrared spectral region. This evaluation is based on the experimental results of a temperature tuned lithium niobate-upconversion system with an argon-ion laser as the pump, which was built to investigate its performance in the 2.7-4.5 μm band. Theoretical calculations for the performance parameters of this upconversion device, such as conversion efficiencies as a function of the pump power, the spectral resolution and the field of view over the 2.7 - 4.5 μm band are given. With an evaluation of the system conversion efficiency of a practical device, estimates of the sensitivity of the system are given in terms of the minimum detectable source brightness and flux. We compare these quantities with the source brightness and the flux radiance of a black body at various temperatures. To evaluate the usefulness of the upconversion technique, we compare the sensitivity of an upconversion device with a direct detection device such as an interferometer. Finally, we present the experimental results for a temperature tuned lithium niobate upconverter which are based on black-body measurements and absorption spectra of methane. An estimate of the expected optimum sensitivity of this upconversion device which may be built with the presently available components is given.

2. Theoretical Considerations

The discussion given in this section is limited to upconversion devices based on parametric interactions in a nonlinear bireferingent medium[1]. Upconversion devices employing two-photon absorption processes in alkali metal vapors which have been reported recently[16] are not considered here explicitly, althougn this technique may turn out to have certain valuable advantages.

In an upconversion device (Fig. 1) infrared radiation from the source at frequency ω_{ir} is mixed in a nonlinear crystal with an intense beam at frequency ω_p from a pump laser. If the nonlinear susceptibility is sufficiently large an interaction between the two waves occurs and results in generation of both sum ($\omega_s = \omega_p + \omega_{ir}$)

and difference frequency($\omega_d = \omega_p - \omega_{ir}$) waves. One of the two frequencies can be "phase matched", that is made to interact constructively with phases matched as it propagates over the length of the crystal, which is in general many coherence lengths.

An upconversion device employs phase matching between the infrared, pump and sum frequency waves, so that the following two conditions are satisfied:

$$\omega_s = \omega_p + \omega_{ir} \tag{1}$$

$$\vec{k}_s = \vec{k}_p + \vec{k}_{ir} \tag{2}$$

where k's are the propagation vectors of the three waves. The phase matching condition for the sum frequency wave (2) may be satisfied by requiring that the change in phase over the length of the crystal ℓ is

$$|\Delta k| = \left| \vec{k}_s - (\vec{k}_p + \vec{k}_{ir}) \right| \leq \pi/\ell \tag{3}$$

This condition limits the spectral resolution and the field of view of the upconverter and will be further examined later.

The basic theory of upconversion in a nonlinear medium has been given, following a classical approach by Armstrong et al. [1,17] and also in a quantum mechanical formulation by Louisell et al. [18]. Verification of the theory has also been provided by a number of experiments on various nonlinear materials (e.q. $LiNbO_3$, $LiIO_3$, Proustite, HgS.) covering a spectral range for upconversion from 1 - 12.5 μm (Table 1). In this section we discuss the theoretical concepts which are relevant to an understanding of an upconversion system for application to observation of astronomical sources.

Assuming a unique polarization of the three waves such that the phase matching condition $\Delta k = o$ is satisfied in a nonlinear crystal of length ℓ with an effective nonlinear coefficient d, a solution of Maxwell's equations leads to a simple expression for the photon conversion efficiency for the infrared photons N^{ir} [1]

$$\eta_q = \frac{N^s(\ell)}{N^{ir}(o)} = \sin^2 (\beta\ell)^2 \tag{4}$$

and a corresponding power conversion equation

$$\eta_{uc} = \frac{P^s(\ell)}{P^{ir}(o)} = \frac{\omega_s}{\omega_{ir}} \sin^2 (\beta\ell) \tag{5}$$

with

$$\beta = \frac{1}{2}\left(\frac{\omega_{ir}\,\omega_s}{n_{ir}\,n_p}\right)^{\frac{1}{2}} d\, E_p \tag{6}$$

$$= \left(\frac{\omega_{ir}\,\omega_s\, Z_o^3\, d^2}{2\, n_{ir} n_p n_s}\;\frac{P_p}{A}\right)^{1/2} \tag{7}$$

where the n's are refraction indices of the crystal for the three waves, $Z_o = (\mu_o/\epsilon_o)^{1/2}$ and P_p/A is the pump power density in the crystal. For small values of conversion efficiency $\beta\ell \ll 1$,

$$\eta_q \simeq \left(\frac{\omega_{ir}\,\omega_s\, Z_o^3}{2\, n_{ir} n_p n_s}\right) d^2\, \ell^2\, \frac{P_p}{A} \tag{8}$$

$$\eta_{uc} = \left(\frac{\omega_s^2 \, Z_o^3}{2 \, n_{ir} n_p n_s}\right) d^2 \, \ell^2 \, \frac{P_p}{A} \tag{9}$$

The conversion efficiency is thus proportional to the squares of the nonlinear coefficient and the length of the crystal, and is directly proportional to the pump power density.

The pump laser output, which usually has the form of a Gaussian beam, is focussed at the center of the crystal with a beam waist w_o to optimize the efficiency. Apart from the possibility of damage to the crystal by the high pump power density, and the field of view considerations to be discussed later, the beam waist is also limited by the requirement that pump wave remain a plane wave over the interaction region. This is satisfied by making the confocal parameter b equal to or greater than the crystal length ℓ. The beam waist is related to b by the equation,[20]

$$b = \frac{2\pi \, w_o^2}{\lambda} \tag{10}$$

where λ is the wavelength. For a Gaussian pump beam, the effective area of the beam, which becomes the effective area of the upconversion detector A_{uc},

$$A_{uc} = \frac{\pi \, w_o^2}{2} \tag{11}$$

The choice of the nonlinear material is governed mainly by three considerations. The first is the spectral range, which is determined by the transparency of the crystal for the infrared, the pump laser and the sum frequency waves. The second is the efficiency of up-conversion, which as seen from Eq. 8, is a maximum for the highest-value of nonlinear coefficient and the greatest length of the crystal. Useful crystal length, however, is limited in the case of angle phase matching by the divergence of the upconverted beam from the pump beam [20]. The third consideration is the spectral bandwidth and field of view of the upconversion device which are dependent upon the phase matching method employed in the material.

The phase matching condition (3) in an upconversion device employing a nonlinear medium is satisfied by using the bireferingence characteristics of the medium. Upconversion devices employing optical waveguides which do not require a bireferingent material to satisfy the phase matching condition are not considered in this paper.

In a bireferingent material, waves may propagate as ordinary and extraordinary rays, which correspond to two different polarizations of the electric field vector with respect to the optic axis. The referactive indices (or propagation constants) of the two types of waves show different variations with the temperature of the crystal and the angle of propagation with respect to the optic axis. The range of frequencies and directions over which the phase matching condition $\Delta k \leq \pi/\ell$ remains approximately satisfied determine the spectral resolution and the field of view of the upconversion device.

There are two general techniques used to achieve phase matching (see for example Ref. 20). In the first, called temperature phase matching, the propagation direction is usually chosen to be normal to the optic axis of the crystal. The difference between the refractive indices for the two polarizations transmitted by the crystal is a maximum for propagation in this direction, and the magnitude of the indices vary with crystal temperature. Condition (3) can then be satisfied for a given combination of ω_p and ω_{ir} by varying the temperature of the crystal. The second, called angle phase matching, uses the variation of refractive indices with the angle between the direction of propagation and the optic axis at a fixed crystal temperature to satisfy (3). The dispersion of the crystal is responsible for the bandwidth which is upconverted, and this can be substantially increased, for a given ω_p and ω_{ir}, if $\left(\frac{\partial k_s}{\partial \omega} - \frac{\partial k_{ir}}{\partial \omega} \right) = 0$, since the bandwidth

$$\Delta\omega = \frac{\pi}{2\ell \left(\frac{\partial k_s}{\partial \omega} - \frac{\partial k_{ir}}{\partial \omega} \right)} \qquad (12)$$

The field of view, $\alpha \frac{1}{\ell}$ and small for collinear propagation, can be increased by using non-critical phase matching, where the pump and IR propagation directions are not collinear. These techniques of varying the bandwidth and field of view are sometimes useful, but for astronomical applications the small field and spectral sensitivity can be exploited. Thus, either basic phase matching method can be used to produce a tunable, narrow band, high sensitivity detector such as our experimental example described below. With non-critical phase matching, when a wide spectral bandwidth is upconverted simultaneously, the upconverter signal can be dispersed giving better spectral resolution [21].

An upconvertion device based on temperature tuned $LiNbO_3$ crystal appears particularly useful because of its relatively high nonlinear coefficient, long crystal lengths ~ 5 cm and its ability to withstand high power densities. A temperature tuned experimental device using $LiNbO_3$ and an argon ion laser has been built by Smith and Mahr [14] and is also the basis of the present experiment which is described in section 4. Some expected performance characteristics of this upconverter are presented here to evaluate its usefulness for astronomical observations.

The power upconversion efficiency for a $LiNbO_3$ crystal of 5 cm length as a function of the pump power is shown in Fig. 2, assuming a pump beam waist w_o = 100 μm. The expected system power conversion efficiency, which includes various factors leading to a degradation in the sensitivity of the system discussed in section 3, is also shown. Power conversion efficiencies ~ 0.1 may be achieved with P_p ~ 10W and > 1 for P_p ~ 100W.

The spectral resolution $\Delta\lambda/\lambda$, the acceptance angle of the upconverter θ_{uc} and the corresponding solid angle Ω_{uc} were calculated (Eq. 12 and Ref. 20) and are shown in Figs. 3 and 4 as a function of the wavelength for w_o = 100 μm. The optimum spectral resolution, $\frac{\Delta\lambda}{\lambda}$ of such a system is seen to be ~ 4×10^{-4}. The resultant $A\Omega$ is of the order of the diffraction limited value $A\Omega = \lambda^2$. The temperature tuned $LiNbO_3$ upconverter is thus a relatively high spectral resolution and a high spatial resolution device.

The data presented in Figs 3 - 4 assume a pump beam waist $w_o \sim 100\ \mu m$. For astronomical observations, the solid angle Ω_T corresponding to the field of view (FOV) of the telescope is limited by the requirement $A_T\Omega_T = A_{uc}\ \Omega_{uc}$. For a given crystal length, lower values of w_o increase the conversion efficiency (Eqs. 9,11) but decrease the $A\Omega$ product of the upconverter which determines the effective field of view of the telescope. The effect of varying the beam waist w_o on the FOV of a telescope with $1m^2$ area is shown in Fig. 5. The variation of conversion efficiency with w_o for various pump powers is also shown on the same figure. High spatial resolution with high conversion effieiency is obtained for the lower values of the beam waist, while larger FOV with lower conversion efficiency is obtained for higher values of the beam waist.

3. Sensitivity of an Infrared Upconverter

It has long been apparent that an upconverter is inherently a low noise device and could be very suitable for the detection of weak signals such as those from astronomical sources[13]. Theoretically, assuming high conversion efficiency, the sensitivity of an upconverter is limited only by the phototube dark current shot noise, and the minimum detectable power for one second of integration time approaches the NEP of the phototube. When the quantum conversion efficiency appproaches unity, as discussed below, the minimum detectable power for one second of integration time may be smaller than the NEP of the phototube due to the power conversion gain. In the present status of upconverters, however, the conversion efficiencies are generally still considerably less than unity, and additional sources of noise usually degrade the sensitivity significantly. In this section we estimate the sensitivity of an upconverter device for astronomical observations.

The main sources of noise at the phototube of an upconversion system is the shot noise, due to average cathode signal current I_c, dark current I_d, and a background induced current I_b, which includes any contribution from the unrejected radiation from the pump laser, and also any parametric noise generated in the crystal.[22,23] The mean-squared amplitude of the shot noise current at the output of the photomultiplier is[24]

$$\bar{I}_N^2 = 2\, eG^2\, (I_c + I_d + I_b)\, \Delta\nu \qquad (13)$$

where G is the gain of the phototube and $\Delta\nu$ is the bandwidth. The meansquared modulated ir signal corresponding to an upconverted signal power P^s at ω_s at the output of the photomultiplier is

$$\bar{I}_s^2 = 2\left(\eta_{cath}\, \frac{e\, P^s\, G}{h\, \nu_s}\right)^2 \qquad (14)$$

$$= 2\left(\eta_{cath}\, \eta_q\, \frac{e\, P^{ir}\, G}{h\, \nu_{ir}}\right)^2 \qquad (15)$$

A signal to noise ratio can be defined from (13) and (14) as

$$\frac{S}{N} = \frac{\bar{I}_s^2}{\bar{I}_N^2} = \frac{\left(\eta_{cath}\, \eta_q\, e\, P^{ir}/h\nu_{ir}\right)}{e\,(I_c + I_d + I_b)\Delta\nu} \qquad (16)$$

The average cathode signal current I_c may be assumed to be much smaller than the dark current and may thus be ignored in (16). The "minimum detectable" infrared power is defined by setting (16) equal to unity giving,

$$P_{min}^{ir'} = \frac{h\nu_{ir}\left[(I_b + I_d)\,\Delta\nu\right]^{\frac{1}{2}}}{\eta_{cath}\,\eta_q\,e^{\frac{1}{2}}} \quad \text{watts} \qquad (17)$$

The infrared noise equivalent power of the upconverter system is thus:

$$(NEP)'_{ir} = \frac{h\nu_{ir}\,(I_b + I_d)^{\frac{1}{2}}}{\eta_{cath}\,\eta_q\,e^{\frac{1}{2}}} \quad \text{W-Hz}^{-\frac{1}{2}} \qquad (18)$$

In writing equations (16) - (18) it is assumed that the upconverted signal is transmitted with no loss through the filter required to reject the pump laser beam. Equations (17) and (18) may be alternatively expressed in terms of the minimum detectable power and the $(NEP)_{PM}$ of the phototube at the upconverted frequency introducing

$$P_{min}^{s} = \frac{h\nu_s\,(I_d\,\Delta\nu)^{\frac{1}{2}}}{\eta_{cath}\,e^{\frac{1}{2}}} \qquad (19)$$

and

$$(NEP)_{PM} = \frac{h\nu_s\,I_d^{\frac{1}{2}}}{\eta_{cath}\,e^{\frac{1}{2}}} \qquad (20)$$

in (17) and (18) and using the relation $\eta_{uc} = (\nu_s/\nu_{ir})\,\eta_q$ we have:

$$P_{min}^{ir'} = \frac{P_{min}^{s}}{\eta_{uc}\,\eta_b} \quad \text{Watts} \qquad (21)$$

or

$$(NEP)'_{ir} = \frac{(NEP)_{PM}}{\eta_{uc}\,\eta_b} \qquad W\text{-}Hz^{-\frac{1}{2}} \qquad (22)$$

The background induced noise degrades the sensitivity of the upconverter system and is introduced here as an efficiency factor.

The quantity $\eta_b = (1 + I_b/I_d)^{-\frac{1}{2}}$ (23)

is a measure of the extent to which the pump laser radiation and noise generated by parametric process or impurities in the crystal has been eliminated. Additional factors η_i which degrade the sensitivity of an upconverter when used for observation of astronomical sources may also be introduced here.

Total system efficiency η_{sys} can be expressed as a product function,

$$\eta_{sys} = \Pi_i\, \eta_i \qquad (24)$$

where the η_i's, to be included are due to:

(i) Power conversion efficiency η_{uc}, defined by (21).

(ii) Background radiation and noise η_b, defined by (23).

(iii) Optical loss factor η_{optics}, which is the combined transmission coefficient of all optical components in the infrared and upconverted radiation paths.

(iv) Polarization factor $\eta_{Pol} = 1/2$, since only one polarization is upconverted.

(v) Beam mismatch and misalignment factor η_{beam}, to account for any mismatch between the beam waists and misalignment of the pump laser and the infrared signal beams. This is included because it may not be possible to exactly match an upconverter to an existing telescope.

(v) A factor η_{chop} due to any chopping of the IR signal.

The infrared noise equivalent power of the upconveter system including the degradation factors considered in defining the system efficiency thus may be written as

$$(NEP)_{ir} = \frac{(NEP)_{PM}}{\eta_{sys}} \qquad W\text{-}Hz^{-\frac{1}{2}} \tag{25}$$

and the minimum detectable power as

$$P^{ir}_{min} = \frac{(NEP)_{PM}}{\eta_{sys}\ \tau^{\frac{1}{2}}} \qquad \text{watts} \tag{26}$$

here τ is the integration time. The signal-to-noise ratio for an upconverter with a system efficiency defined as above is:

$$\frac{S}{N} = \frac{\eta_{sys}\ P^{ir}}{(NEP)_{PM}}\ \tau^{\frac{1}{2}} \tag{27}$$

For astronomical observations, and for comparison with direct IR detection techniques, it is useful to calculate the minimum detectable source radiance I^{ir}_{min} by dividing P^{ir}_{min} by the bandwidth and the A_{uc} Ω_{uc} product of the upconverter which gives:

$$I^{ir}_{min} = \frac{(NEP)_{PM}}{\eta_{sys}\ \Delta\nu_{ir}\ A_{uc}\ \Omega_{uc}\ \tau^{\frac{1}{2}}} \qquad W\ cm^{-2}\ Hz^{-1}\ str^{-1} \tag{28}$$

where $\Delta\nu_{ir}$ is the bandwidth of the upconverter discussed in section 2.

Alternatively, we may calculate the minimum detectable source brightness R^{ir}_{min} (photons sec^{-1} cm^{-2} str^{-1}) in the bandiwdth of the upconverter.

$$R^{ir}_{min} = \frac{(NEP)_{PM}}{\eta_{sys}\, h\nu\, A_{uc}\, \Omega_{uc}\, \tau^{\frac{1}{2}}} \quad \text{photons-sec}^{-1}\ \text{cm}^{-2}\text{-str}^{-1} \tag{29}$$

We may also write an expression for the minimum detectable flux F^{ir}_{min}, a quantity commonly referred to in astronomical observations, as

$$F^{ir}_{min} = \frac{P^{ir}_{min}}{\Delta\nu_{ir}\, A_T}$$

$$= \frac{(NEP)_{PM}}{\eta_{sys}\, \Delta\nu_{ir}\, A_T\, \tau^{\frac{1}{2}}} \quad \text{W m}^{-2}\ \text{Hz}^{-1} \tag{30}$$

where A_T is the telescope area in m^2.

For comparison with source values, we calculate the source brightness and the flux radiated by black-body sources in the field of the upconverter from:

$$R^{ir}_{BB} = \frac{2}{\lambda^2} \frac{\Delta\nu_{ir}}{(e^{h\nu/kT}-1)} \quad \text{photons sec}^{-1}\ \text{cm}^{-2}\ \text{str}^{-1} \tag{31}$$

and

$$F^{ir}_{BB} = \frac{2hc}{\lambda^3} \frac{\Omega_T}{(e^{h\nu/kT}-1)} \quad \text{W m}^{-2}\ \text{Hz}^{-1} \tag{32}$$

Assuming a telescope area of 1 m^2, and values of A_{uc} Ω_{uc} and $\Delta\nu_{ir}$ for the $LiNbO_3$ upconverter discussed in Section 2, plots of R^{ir}_{BB}

and F_{BB}^{ir} are shown as a function of wavelength for given black body source temperatures. The minimum detectable values of R_{min}^{ir} and F_{min}^{ir} for $\tau = 1000$ sec for various values of $(NEP)_{ir} = (NEP)_{PM}/\eta_{sys}$ are shown as horizontal lines. The tuning range of the $LiNbO_3$ device investigated experimentally is shown by the dashed lines. With a system NEP of $\sim 10^{-14}$ W $Hz^{-\frac{1}{2}}$, a signal equivalent to $\sim 260^{o}K$ black body radiation can be detected. It can be seen that the upconversion technique can yield highly sensitive detection of infrared radiation if reasonably high system efficiencies η_{sys} can be achieved.

When used as a narrow band or broad band ir imaging system or as a spectrometer, how does the sensitivity of upconversion system, expressed in terms of signal to noise ratios or minimum detectable source brightness R_{min}^{ir}, compare with that of a direct detection system? Considering an interferometer, for example, the signal to noise ratio is

$$\frac{S}{N} = \frac{\eta_{in} P^{ir}}{(NEP)_d} \tau^{\frac{1}{2}} \tag{33}$$

where η_{in} expresses the system losses in an interferometer and $(NEP)_d$ is the noise equivalent power of the detector. From an infrared source with intensity I^{ir} (W cm^{-2} Hz^{-1} str^{-1}) the power received by the interferometer is:

$$P^{ir} = I^{ir} (\Delta\nu)_{in} (A\Omega)_{in} \tag{34}$$

and the power received by the upconverter is

$$P^{ir} = I^{ir} (\Delta\nu)_{uc} (A\Omega)_{uc} \quad (35)$$

From (27) and (31) - (34), a comparison of the S/N ratios for an upconversion device with a direct detection system is given by

$$F = \frac{(S/N)_{uc}}{(S/N)_{in}} \quad (36)$$

$$= \frac{\left[(NEP)_d/\eta_{in}\right]}{\left[(NEP)_{PM}/\eta_{sys}\right]} \frac{(\Delta\nu)_{uc}}{(\Delta\nu)_{in}} \frac{(A\Omega)_{uc}}{(A\Omega)_{in}} \quad (37)$$

It is assumed there that τ is the same in both cases; and any multiplexing advantage that may be achieved with an interferometer is not considered. The ratio F depends upon the mode of operation of the upconverter discussed in Section 2. The critical phase matching mode provides higher spectral resolution and also high spatial resolution ($A\Omega \sim \lambda^2$). The non-critical phase matching mode on the other hand, has a large $A\Omega$ product and a large spectral bandwidth. In the latter case a subsequent dispersion device can provide a higher spectral resolution. If we assume that the upconverter is operated in a mode which is most suitable for observation of a particular source and that the last two ratios in (37) are unity, the ratio F is

$$F = \frac{(NEP)_d/\eta_{in}}{(NEP)_{PM}/\eta_{sys}} \quad (38)$$

$$= \frac{(NEP)_{in}}{(NEP)_{ir}} \quad (39)$$

where $(NEP)_{in}$ is the effective system NEP of the interferometer. An upconversion system thus becomes more sensitive than a direct detection device if $(NEP)_{ir} < (NEP)_{in}$. With the presently achieved value (section 4) of $(NEP)_{ir} \sim 2 \times 10^{-14}$ W Hz$^{-\frac{1}{2}}$, an upconversion system already appears to be as sensitive as a direct detection system employing the best detectors presently available.

4. Experimental Results

An experimental upconversion system was built to investigate the performance parameters or a practical device and determine its feasibility for astronomical observations in the low to middle infrared.

The instrument uses a temperature-tuned, 90° phase matched lithium niobate crystal obtained from Chromatix as the nonlinear medium and a Spectra-Physics Model 170 argon ion laser as a pump. The experimental system is shown in Fig. 8. An intense CW 5145Å argon ion laser beam, filtered to reject both laser plasma light and fluorescence, is combined at the beamsplitter with a beam from an infrared source which may be chopped. The combined coaxial beams are focused into a 5 cm long temperature controlled $LiNbO_3$ crystal. Phase matching is obtained by adjusting the temperature of the crystal. Continuous tuning of the IR radiation can be obtained from 2.7 - 4.5 μm by varying the crystal temperature through the range 180-400°C. The upconverted output radiation, which contains the spectral information of the IR, is thus tuned from ~ 0.43 μm to ~ 0.46 μm.

Since the plane of polarization of the upconverted radiation is perpendicular to that of the pump light, a combination of prism polarizer and pump light filters are used to reject the pump beam. Noise from scattered light and possible upconversion of thermal radiation from the oven and crystal was further rejected by chopping the IR source. The filtered upconverted light is then detected by an EMI type 9789A photomultiplier tube, followed by either a phase sensitive detector or a photon counter.

Measurements of system sensitivity were performed by detection of unpolarized black body radiation from a calibrated source. Results were obtained using both phase sensitive detection and photon counting techniques. In Fig. 9 the black body power incident upon the upconversion system within its field of view of $\sim 1.5^{o}$ and its spectral bandwidth of 1.8×10^{-3} μm at 3.3 μm is plotted as a function of lock-in amplifier output. The black body reference temperatures corresponding to the observed powers are also shown. All measurements except for the two lowest values were made for 1 sec. integration time. The two points at lowest power were obtained at 30 sec. integration and the minimum detectable power was seen to be 3×10^{-15}W in 30 sec. corresponding to 308°K. This gives a measured NEP for the system at 1.6×10^{-14} W-Hz$^{-\frac{1}{2}}$.

The black body power measurements using photon counting technique are shown in Fig. 10. They are somewhat worse but within a factor of 2 of those obtained for phase sensitive detection.

The system power conversion efficiency η_{sys} (Eq. 24) can be calculated from the photon counting results by

$$\eta_{sys}\,(exp) = \frac{\lambda_{ir}}{\lambda_s}\,\frac{1}{\eta_{cath}}\,\frac{\text{no. counts}}{\text{no. IR photons in}} \tag{40}$$

The average value of η_{sys} for the experimental upconversion system based on photon counting results was found to be $\sim 6.6 \times 10^{-4}$. From the phase sensitive detection measurements, however, η_{sys} was calculated (Eq. 25) to be $\sim 8 \times 10^{-4}$.

To demonstrate the use of an upconversion system as a spectrometer for remote spectroscopic observations capable of identification of molecular or atomic species, absorption measurements were made on cells containing various gases of astrophysical interest. Gas cells of 10 cm length were placed in front of a 1300°K black body source and detected in absorption by observing the upconverted visible radiation.

Molecular spectra of methane, ethane and HCL were obtained around 3.3 μm by tuning the temperature of the $LiNbO_3$ crystal. The vibrational-rotational spectrum of the ν_3 band of methane is shown in Fig. 11 where it appears superimposed over the transmission profile of the pump light filter. The P, Q, and R branches of the band are clearly visible and the line positions are in excellent agreement with previously published data[25]. From the measured linewidth of ~ 2.7 cm^{-1} we obtained a spectral resolution $\sim 9 \times 10^{-4}$. This was subsequently improved to 6×10^{-4}. These measurements demonstrate our upconversion spectrometer to be capable of spectroscopic observations on weak sources with sufficient resolution for identification of the absorbing or radiating molecular or atomic species.

Discussion:

The experimental results reported here are based on an upconversion system the sensitivity of which has been optimized using available optical components. These results already make an upconversion system an attractive instrument for astronomical observations as a spectrometer or as an imaging device with a sensitivity which approaches the background limit. However, for spaceborne observations which are detector limited, it is of interest to ask, what ultimate improvements in the sensitivity of a temperature tuned $LiNbO_3$ upconverter pumped by an argon-ion laser may b expected?

To make a realistic estimate of the achievable sensitivity, we may discuss several practical problems which tend to limit the sensitivity of an upconverter.

(i) Rejection of pump laster light: After upconversion process in the crystal, the pump laser light and plasma emission and any difference frequency light has to be rejected while transmitting the upconverted signal with minimum attenuation. Interference filters, polarizers, and diffraction gratings can be used for this purpose. Spatial separation of the pump and upconverted beam before filtering helps minimize any scattering of the intense pump light. In the present system, with the components available to us, maximum rejection efficiency was achieved with a polarizer-filter combination, with the optical transmission factor $\eta_{optics} \sim 0.08$.

Optical components are available to improve this by at least a factor of 2.5. A differaction grating arrangement, although more complicated, can be used together with filters orprism polarizers to obtain maximum rejection efficiency.

(ii) Additional noise sources: With temperature phase matching, special care has to be taken to eliminate any upconverted thermal emission from the oven or the heated crystal. Upconverted radiation from impurities in the crystal or "tracks" caused by high intensity pump laser beams or lack of oxygen may introduce an additional source of noise. These noise sources could be minimized by selecting a good quality crystal, insuring a sufficient supply of oxygen, and by undertaking steps such as inserting a pinhole aperture stop after the oven, chopping the IR signal and using phase sensitive detection. An optimum signal to noise can thus be obtained which is limited only by the photomultiplier dark current.

(iii) Beam focusing: For a given pump power, the conversion efficiency can be maximized by focusing the pump beam to the smallest possible beam waist (Eq. 9) such that its plane wave characteristic is maintained over the length of the crystal. An optimum conversion efficiency is obtained when the confocal parameter b (inside the crystal) is of the order of the crystal length. For a 5 cm long crystal the optimum beam waist - w_p is thus $\simeq$ 50 μm (Eq. 10). This of course assumes that the IR beam is also a plane wave and is focused within the interaction region of 50 μm radius. If this condition is not satisfied, such as is the case in observing exeneded objects (e.g. planets, interstellar clouds), the optimum beam waist for maximum conversion efficiency is the IR beam waist w_{ir}. There is no gain in reducing the pump beam waist w_p below w_{ir}.

For observation of stellar sources, on the other hand, when the full IR emission can be focussed into the diffraction limit of a large elescope, optimum beam focusing may be utilized. In this case, the diffraction limit of the telescope may be matched to the 100 μm pump beam diameter and the crystal conversion efficiency thus maximized. A further improvement by a factors of 4 could thus be achieved in the conversion efficiency and the $(NEP)_{ir}$ reported here by reducing the pump beam waist from the presently used value of ~ 100 μm to the optimum value of ~ 50 μm.

(iv) Pump power: Conversion efficiency is directly proportional to the pump power. Presently available gas lasers (e.g. Ar^+ ion) can deliver up to 8 W single mode 5145 Å radiation of which 4 W can be made incident on the crystal. Utilization of this full power would improve our presently reported results based on 1 W incident power, by a factor of 4. An intra-cavity upconverter has the further potential of at least an order of magnitude gain in power and thus η_{sys}. Such a device has been shown possible by Voronin et al [12] at 10.6 μm and Campillo and Tang [26] at 1-2 μm.

Based on the above considerations and assuming an intra-cavity upconverter, it is estimated that the system power conversion efficiency

η_{sys} may be improved by a factor ~ 100 to $\eta_{sys} \sim 10^{-1}$. Using the best available photomultiplier tube (NEP $\sim 10^{-18}$ W-Hz$^{-\frac{1}{2}}$) would give an infrared upconversion system with $(NEP)_{ir} \sim 10^{-17}$ W-Hz$^{-\frac{1}{2}}$. Such a system would be background limited for ground-based astronomical observations, and photomultiplier dark noise limited for spaceborne observations.

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LIST OF FIGURES

9. Sensitivity measurements using phase sensitive detection.

10. Sensitivity measurements using photon counting.

11. Upconverted absorption spectrum of methane.

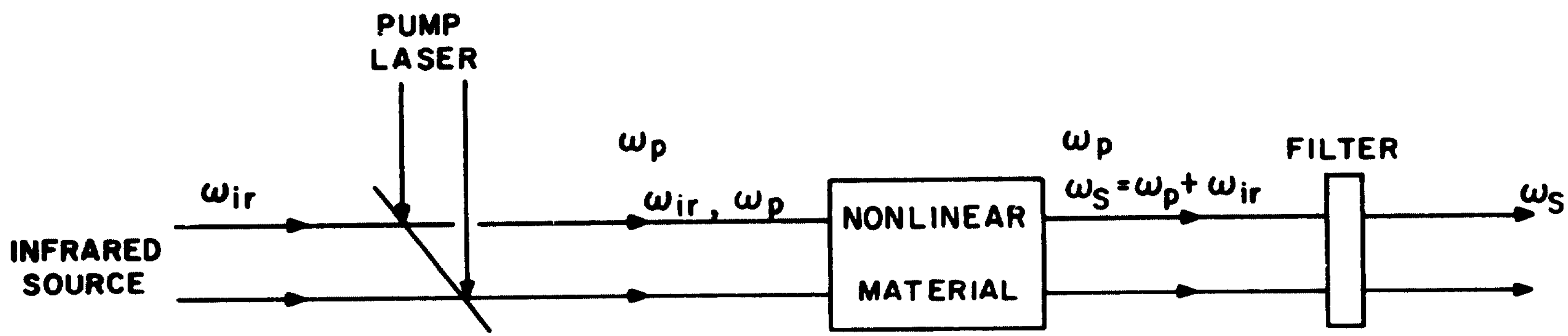
TABLE I

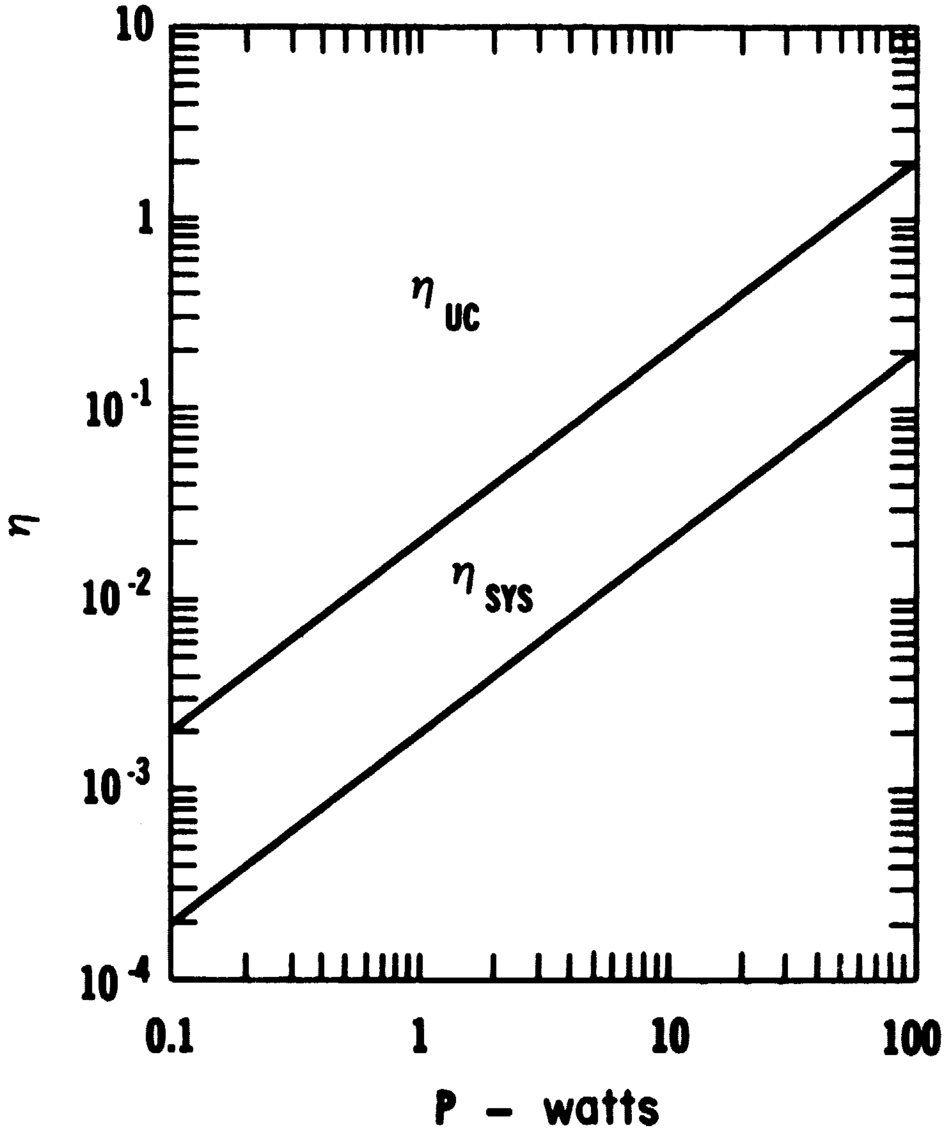
DATE	EXPERIMENTER	PUMP	MEDIUM	WAVE-LENGTH	PHASE-MATCH	C.W. PUMP	SYSTEM PHOTON-CONVERSION EFFICIENCY(η_{SQ}) SENSITIVITY/PUMP POWER	REMARKS	REF.
1967	Miller & Nordland	He-Ne	Lithium Niobate	3.39μm	Angle	Yes	3×10^{-8}W/(4.3mW)	Extrapolated to S/N=1 at 10^{-11}W input Phase sensitive detection	2
1967	Midwinter & Warner	Ruby	Lithium Niobate	1.7μm	Temperature	No	$\eta_{SQ} \sim 1\%$	First use as Spectro meter. Excess noise observed.	3
1968	Warner	Ruby	Proustite	10.6μm	Angle	No	$\eta_{SQ} = 1.4\times10^{-6}$	Detection of CO_2 Laser	4
1968	Midwinter	Ruby	Lithium Niobate	1.6μm	Temperature	No	$\eta_{SQ} = 10^{-7}$	Detection of Image	5
1968	Boyd, Bridges & Burkhardt	He-Ne	HgS	10.6μ	Angle	Yes	NEP=8×10^{-6}WHz$^{-\frac{1}{2}}$	Difference Frequency generation	6
1969	Midwinter	Nd-YAG	Lithium Niobate	2.0-3.5μm	Noncritical	No	--	Used black-body source	7
1971	Falk and Yarborough	Nd-YAG	Proustite	6.5-12.5μm	Angle	No	--	Detection of 300°K black-body	8
1972	Lucy	Ruby	Proustite	10.6μm	Angle	No	$\eta_{SQ} = 6\times10^{-6}$	Detection of image-Excess noise observed	9
1973	Gurski	Ruby	Lithium Iodate	3.4μm	Angle	No	High peak η_{SQ} Low Duty cycle	External resonator used	10

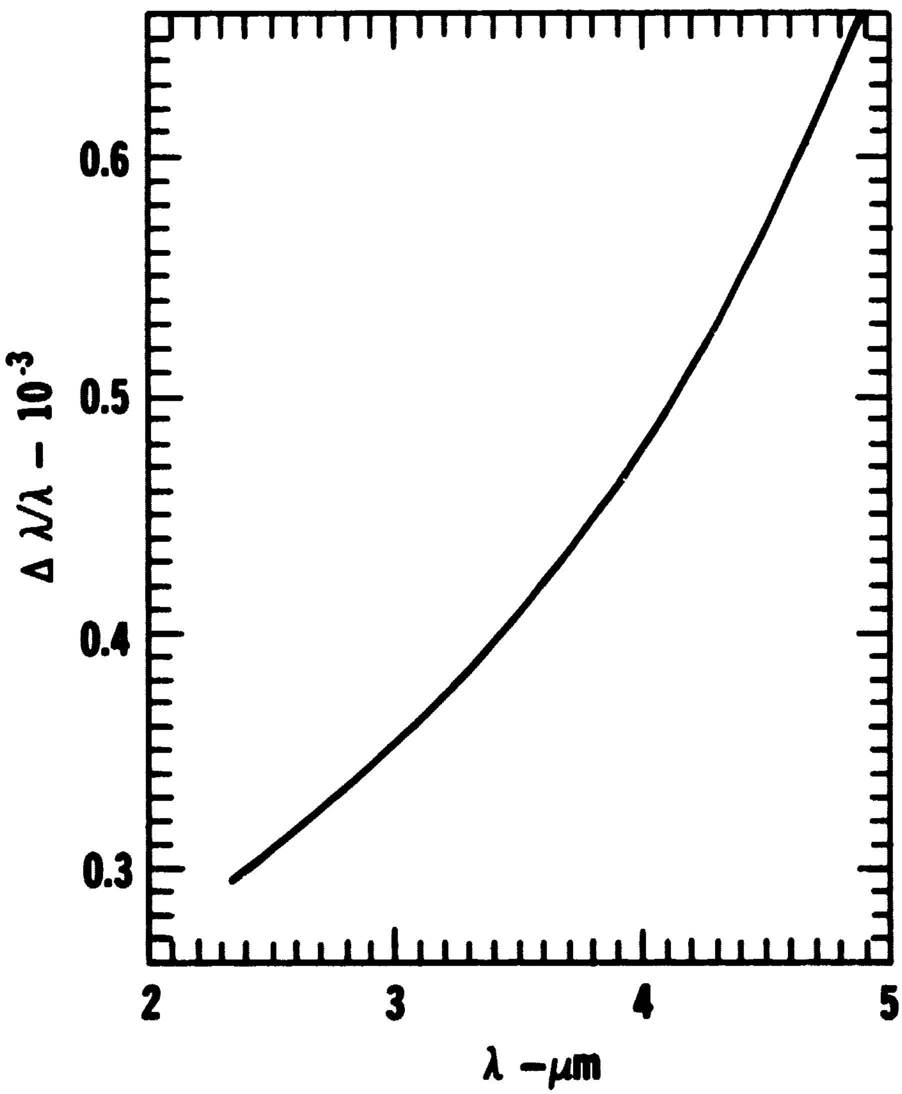
TABLE I (continued)

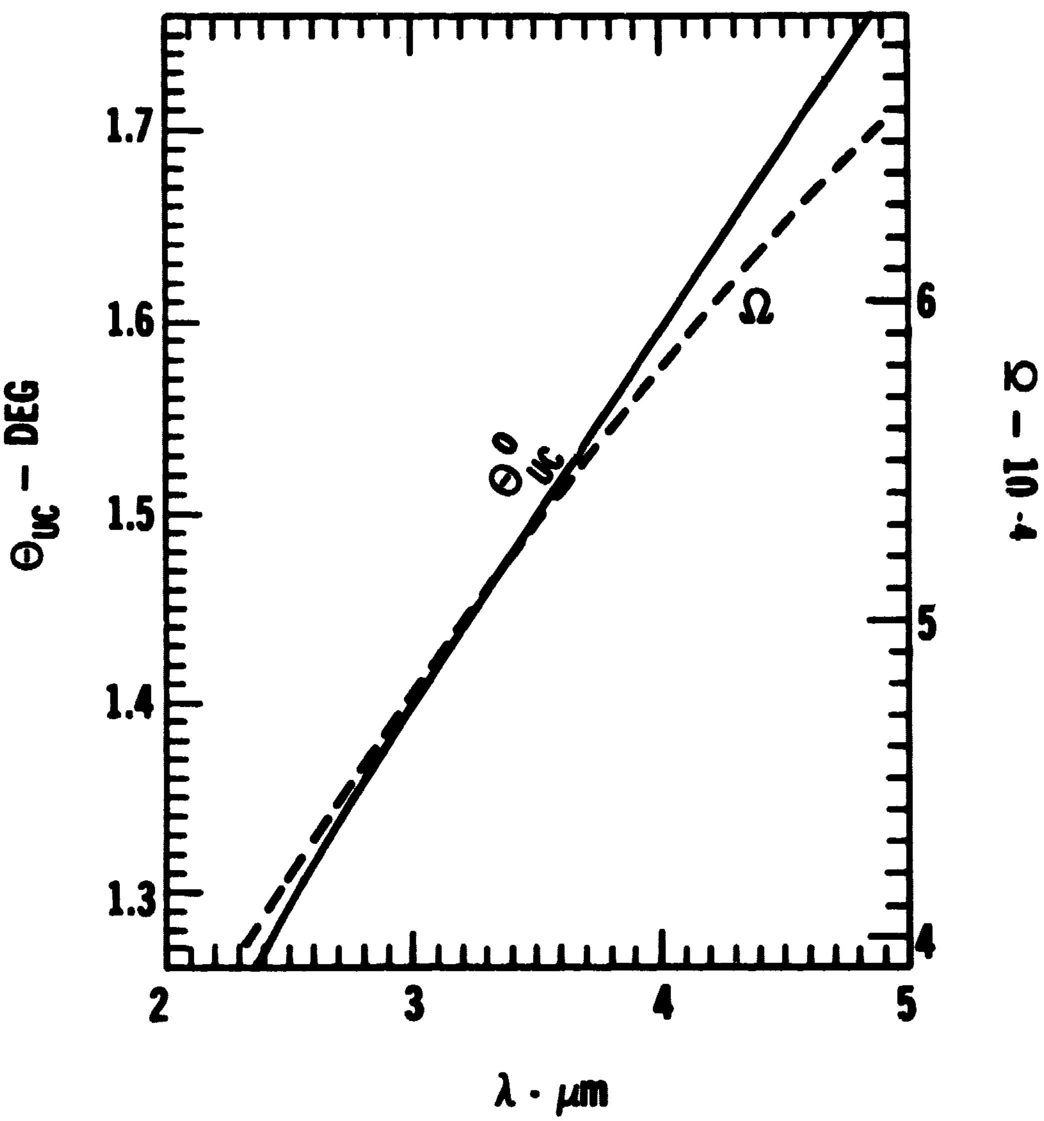
DATE	EXPERIMENTER	PUMP	MEDIUM	WAVE-LENGTH	PHASE-MATCH	C.W. PUMP	SYSTEM PHOTON-CONVERSION EFFICIENCY(η_{SQ}) SENSITIVITY/PUMP POWER	REMARKS	REF.
1974	Gurski, Epps, Moran	Nd:YAG	Lithium Iodate	3.2-5μm	Angle	No	$\eta_{SQ} \sim 10^{-5}$	First astronomical observations	11
1974	Voronin et al	Nd:YAG	Proustite	10.6μm	Angle	No	$\eta_{SQ} \sim 1.5 \times 10^{-3}$	Intra Cavity System	12
1975	Abbas, Kostiuk, Ogilvie	Argon	Lithium Niobate	2.7-4.5	Temperature	Yes	$1.6 \times 10^{-14} WHz^{-1}/1W$ $\eta_{SQ} \sim 10^{-4}$	Present work	--

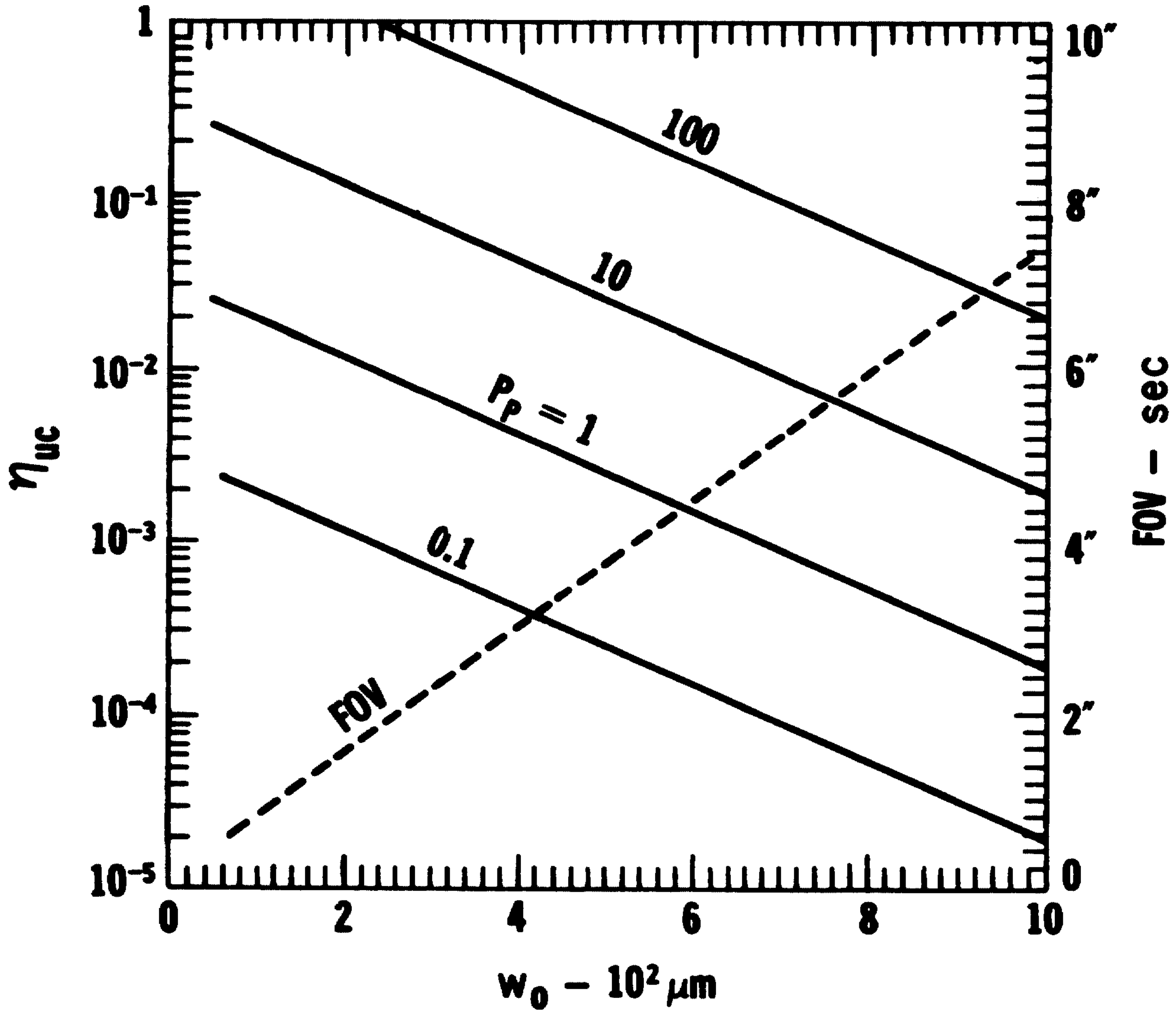
BASIC UPCONVERTER SYSTEM

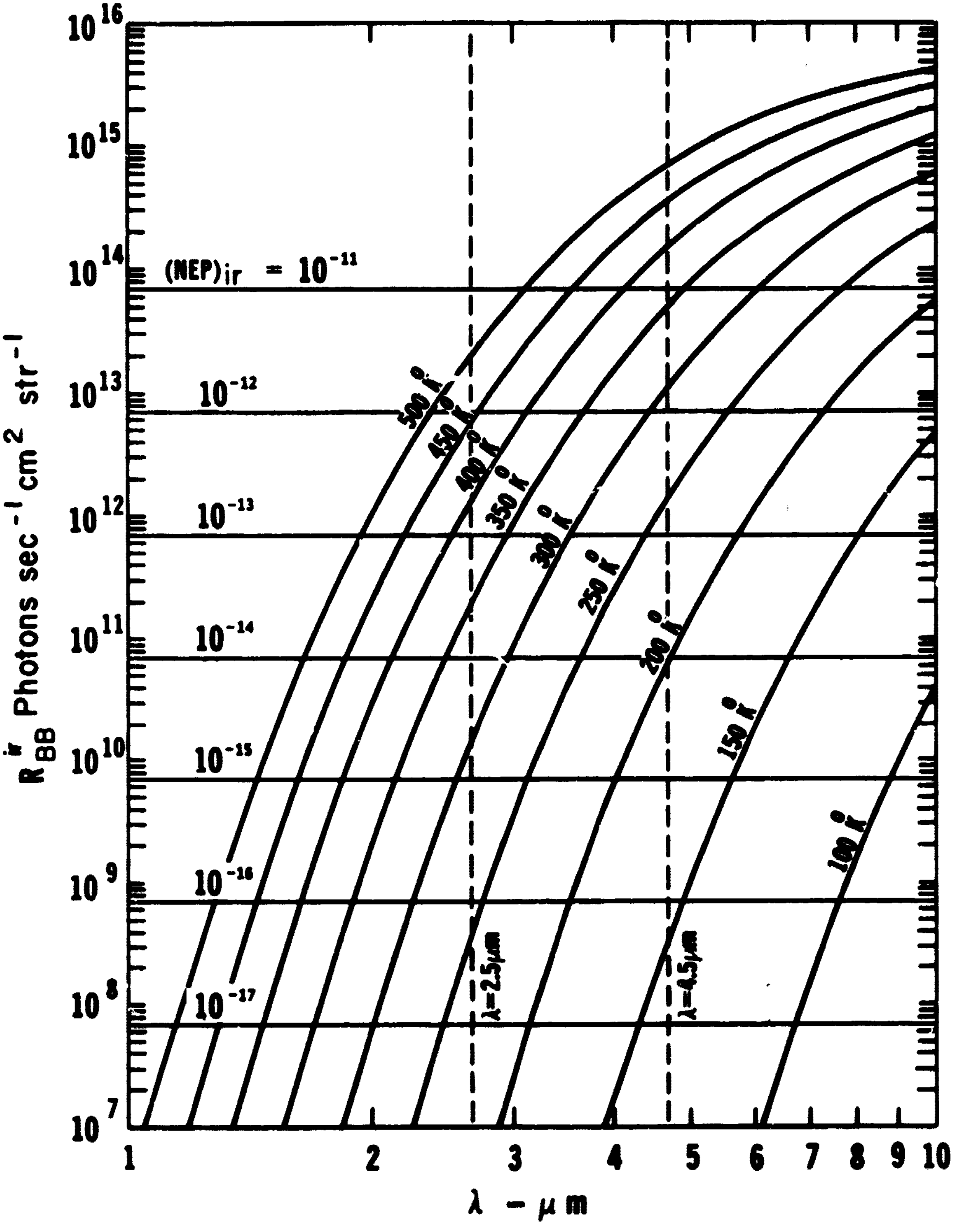



10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
η
η_{UC}
η_{SYS}
0.1
1
10
100
P - watts

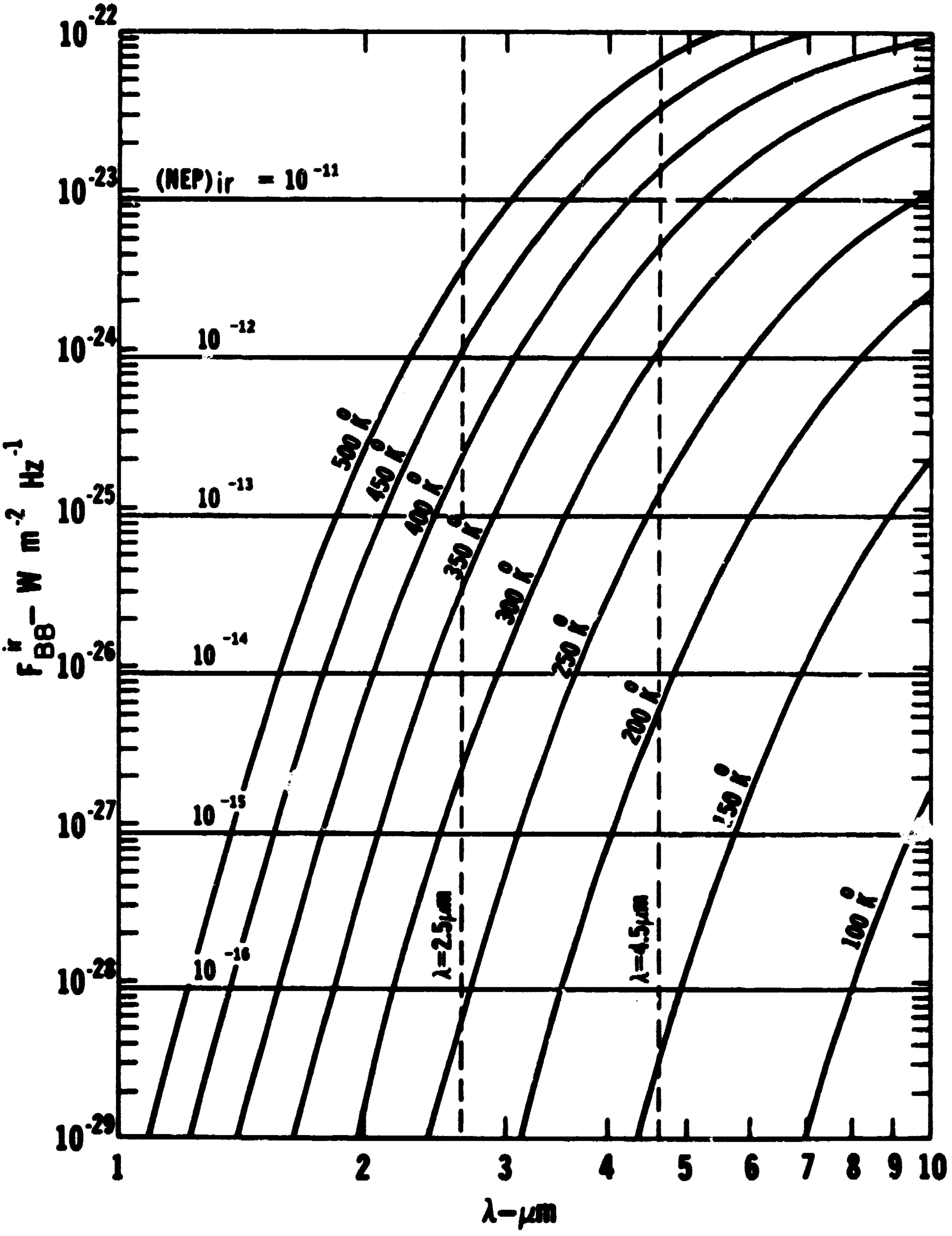

0.6
0.5
0.4
0.3
Δ λ/λ – 10^-3
2
3
4
5
λ –μm


Θ_UC – DEG
1.7
1.6
1.5
1.4
1.3
Ω – 10-4
6
5
4
Ω
Θ°_UC
2
3
4
5
λ · μm

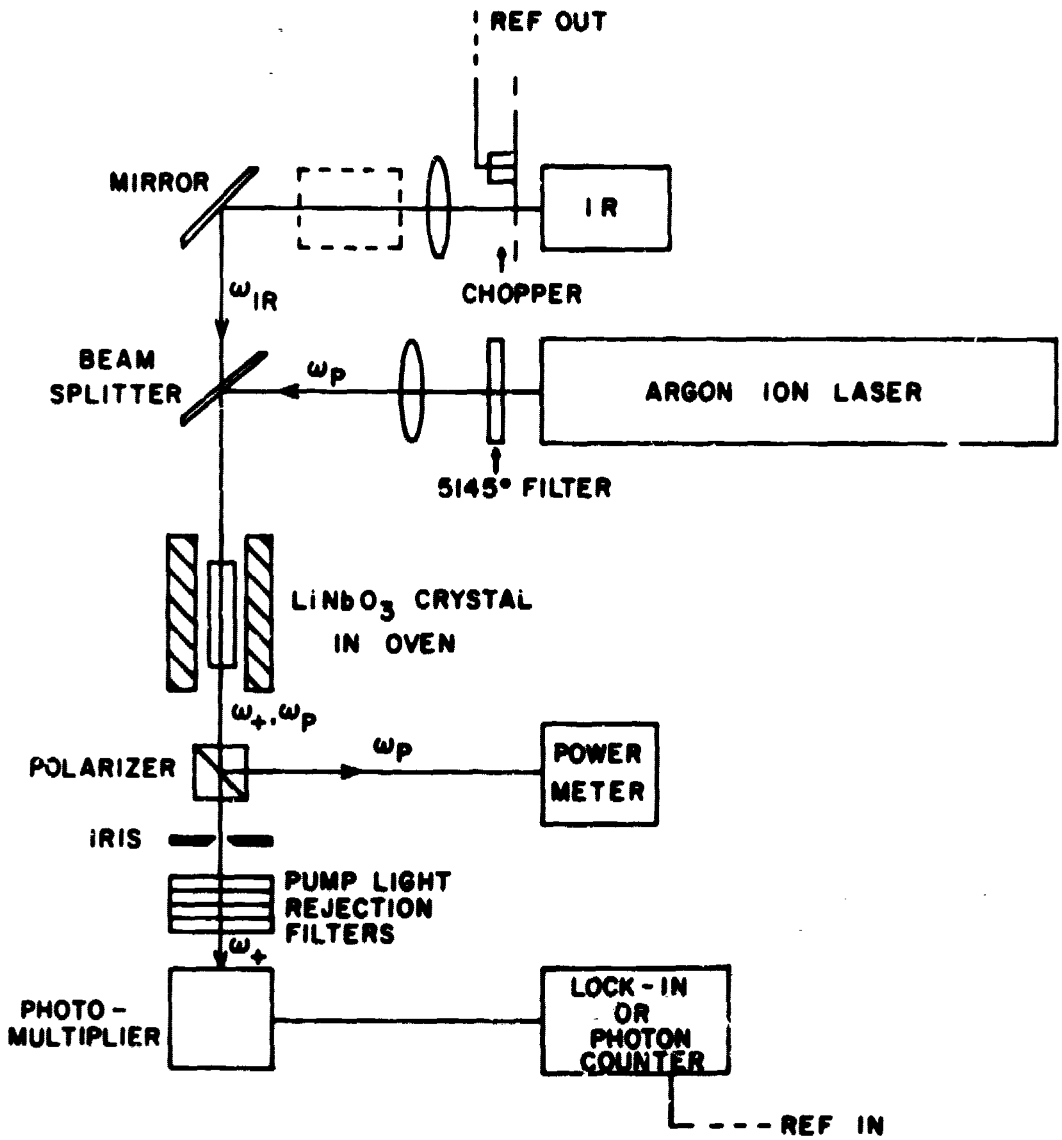

1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
η_uc
0
2
4
6
8
10
w₀ – 10² μm
10″
8″
6″
4″
2″
0
FOV – sec
100
10
P_P = 1
0.1
FOV



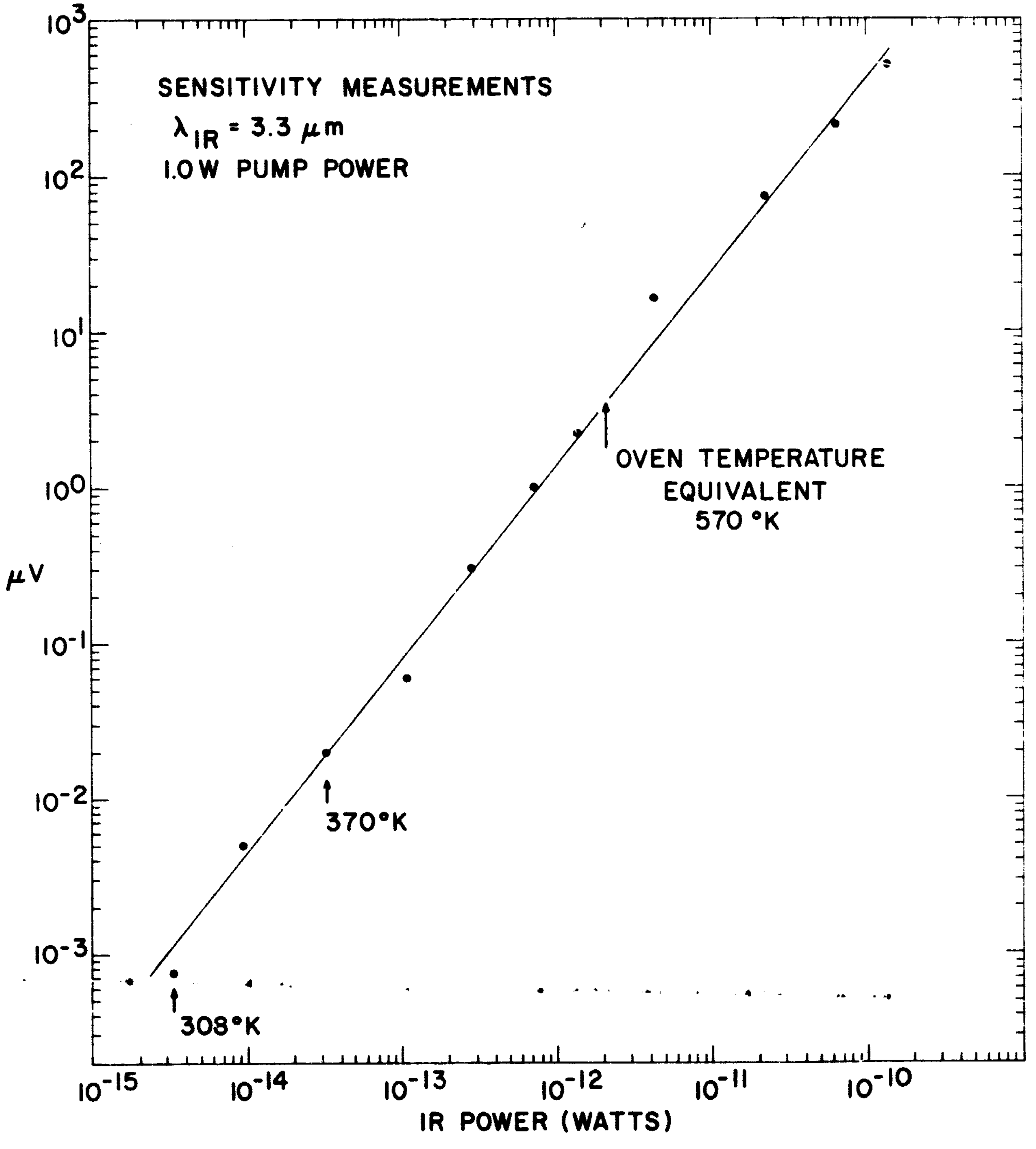
R^{ir}_{BB} Photons sec^{-1} cm^{2} str^{-1}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
(NEP)ir = 10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
500 °K
450 °K
400 °K
350 °K
300 °K
250 °K
200 °K
150 °K
100 °K
λ=2.5μm
λ=4.5μm
1
2
3
4
5
6
7
8
9
10
λ - μm

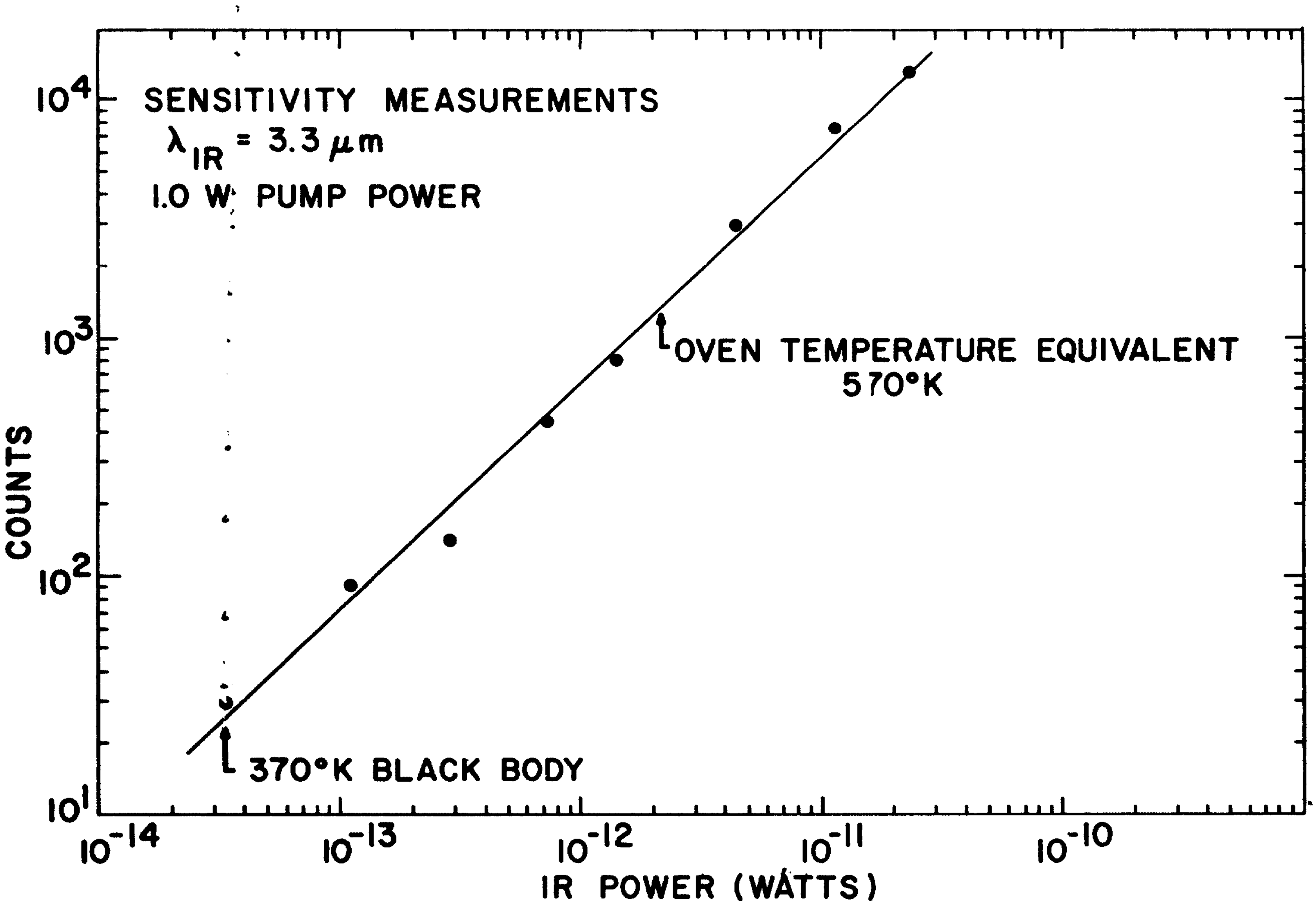


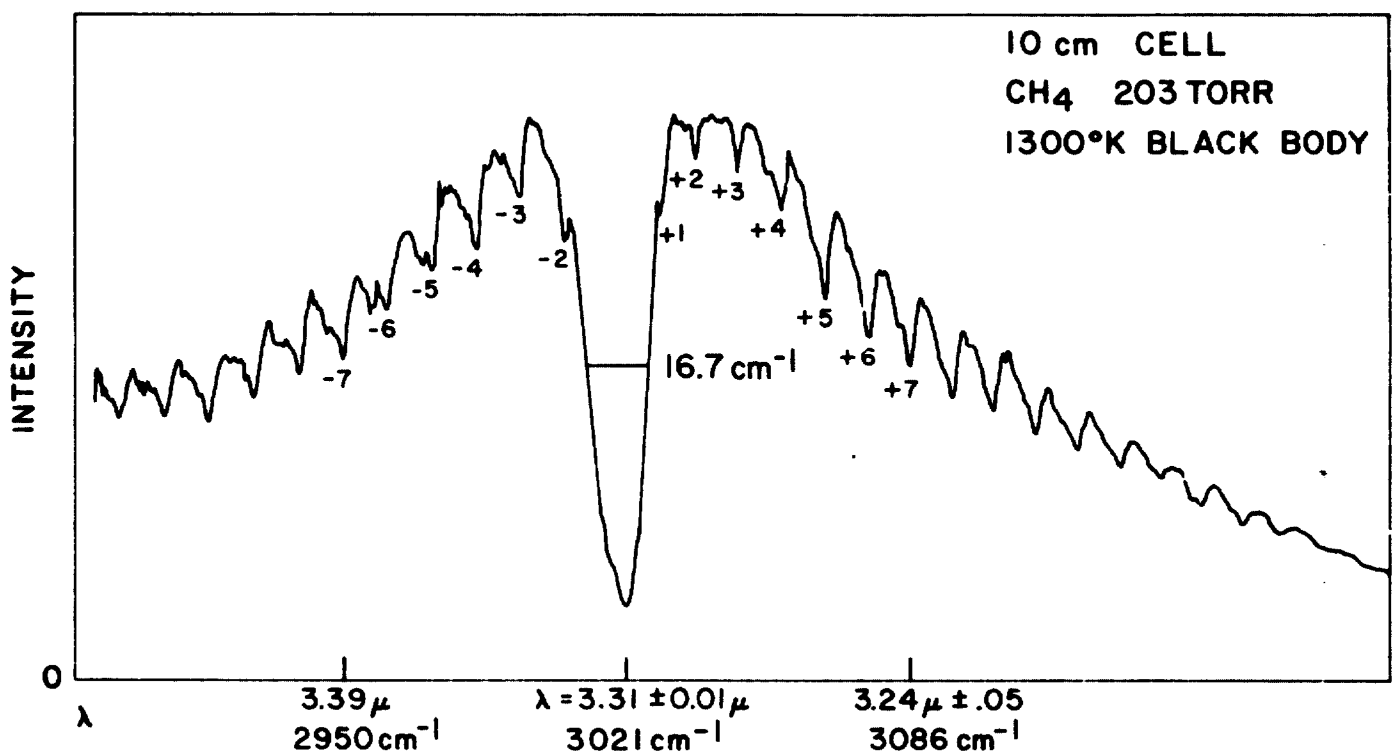
(NEP) ir = 10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
500 °K
450 °K
400 °K
350 °K
300 °K
250 °K
200 °K
150 °K
100 °K
λ=2.5μm
λ=4.5μm
F_{BB}^{ir} — W m^{-2} Hz^{-1}
λ—μm
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
1
2
3
4
5
6
7
8
9
10



UPCONVERSION SPECTROMETER


SENSITIVITY MEASUREMENTS
λ_{IR} = 3.3 μm
1.0 W PUMP POWER
OVEN TEMPERATURE EQUIVALENT 570 °K
370°K
308°K
μV
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
IR POWER (WATTS)


SENSITIVITY MEASUREMENTS
$\lambda_{IR} = 3.3\,\mu m$
1.0 W PUMP POWER
OVEN TEMPERATURE EQUIVALENT
570°K
370°K BLACK BODY
COUNTS
10^4
10^3
10^2
10^1
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
IR POWER (WATTS)


10 cm CELL
CH4 203 TORR
1300°K BLACK BODY
INTENSITY
0
λ
3.39 μ
2950 cm⁻¹
λ = 3.31 ± 0.01 μ
3021 cm⁻¹
3.24 μ ± .05
3086 cm⁻¹
16.7 cm⁻¹
-7
-6
-5
-4
-3
-2
+1
+2
+3
+4
+5
+6
+7