AIP Applied Physics Letters

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Citation: Applied Physics Letters **31**, 440 (1977); doi: 10.1063/1.89733
View online: http://dx.doi.org/10.1063/1.89733
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/31/7?ver=pdfcov
Published by the AIP Publishing

from each other. Because the D2 detector element is small compared to the separation between the two focal spots of the probing beam, only the probing beam is monitored, when D2 is centered on the focal spot of the probing beam.

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An infrared upconverter for astronomical imaging[a)]

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(Received 5 July 1977; accepted for publication 28 July 1977)

An imaging upconverter has been constructed which is suitable for use in the study of the thermal 10-μm radiation from astronomical sources. The infrared radiation is converted to visible radiation by mixing in a 1-cm-long proustite crystal. The phase-matched 2-cm^{-1} bandpass is tunable from 9 to 11 μm. The conversion efficiency is 2×10^{-7}, and the field of view of 40 arc seconds on the sky contains several hundred picture elements, approximately diffraction-limited resolution in a large telescope. The instrument has been used in studies of the sun, moon, Mercury, and VY Canis Majoris.

PACS numbers: 42.80.Qy, 42.65.Cq, 95.85.Gn, 95.75.Mn

There has long been interest in utilizing upconversion as a means of converting images from infrared wavelengths to the visible region where convenient image storage devices (such as photographic films) are readily available.[1] This letter describes an imaging upconverter with sufficient sensitivity that it has been used to study the thermal 10-μm radiation from several astronomical objects. This represents the first successful application of imaging upconversion to astronomy and, while of limited efficiency, demonstrates the promise of such devices when larger nonlinear optical responses are developed.

The requirements on an upconversion system for astronomy are different from those for some other purposes in that the primary needs are a good time-averaged conversion efficiency and diffraction-limited angular resolution over a field of view. Thus, the high conversion efficiencies obtainable by pulsed techniques are not necessarily advantageous, and efficiency must also be compromised in order to obtain a number of converted picture elements. Fortunately, most astronomical applications require only a rather small field of view at the telescope, but wave-front distortion must be avoided in order to approach the maximum resolution allowed by diffraction from the telescope aperture. In addition to these qualities, good spectral resolution is sometimes needed for astronomical applications.

The upconversion process is well understood,[2] and only a brief description of it will be given here. The apparatus is shown in Fig. 1. Infrared radiation is collected with an $f/56$ optical system, which is arranged so as to form an exit pupil at the center of a 1-cm-long nonlinear proustite crystal. The infrared radiation is collimated at the crystal, so that each point in the image space of the upconverter is represented at the crystal by a plane wave of a distinct propagation direction. The infrared signal is then mixed with a 0.25-W 0.7525-μm wavelength krypton ion laser beam. A simple grating monochromator was constructed to spectrally separate the laser frequency from the broadband light of the laser discharge tube. A grating monochromator was selected for this purpose in order to avoid the problem of fluorescence which accompanied the use of glass filters. The laser beam is injected into the cone of infrared radiation through a hole in the infrared collimating mirror.

The laser and infrared beams mix in the proustite crystal, generating an optical signal at the sum frequency. Type-II phase matching[3] is used to avoid an absorption feature for the ordinary ray at 10 μm in proustite. The upconverter can be conveniently angle tuned from 9 to 11 μm. The quantum conversion efficiency of infrared photons into visible-frequency photons is given by[4]

$$\eta=\frac{512\pi^5 d_{\mathrm{eff}}^2 l^2 I_L}{n_{\mathrm{IR}} n_L n_S \lambda_S \lambda_{\mathrm{IR}} c}\left(\frac{\sin\frac{1}{2}l\Delta k}{\frac{1}{2}l\Delta k}\right)^2, \qquad (1)$$

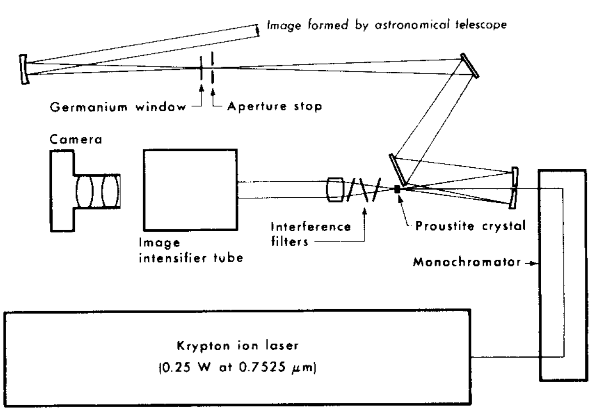

FIG. 1. Optical layout of the 10-μm imaging upconverter.

[a)]Work partially supported by NASA Grants NGL 05-003-272 and NGR 05-003-452.

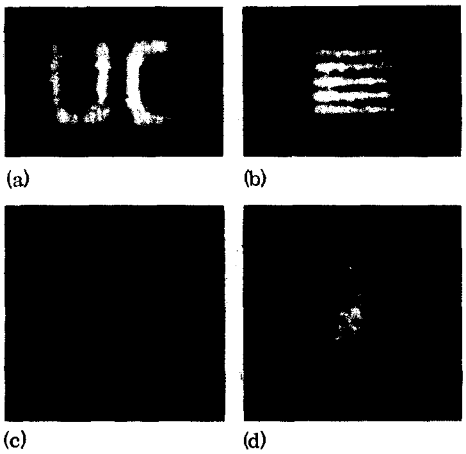

FIG. 2. Upconverted images of several laboratory test objects. (a), (b), and (c) show resolution test patterns. The smallest spacing in (c) is 1.3 times the diffraction limit. (d) shows a 1-min integration on a soldering iron operating at 100 °C.

where Δk is the propagation vector mismatch

$$\Delta k = |\mathbf{k}_S - \mathbf{k}_L - \mathbf{k}_{IR}|, \tag{2}$$

d_{eff} is a constant describing the strength of the nonlinear interaction, l is the length of the nonlinear crystal, n_{IR}, n_L, and n_S are the indices of refraction at the infrared, laser, and sum frequencies, respectively; λ_S and λ_{IR} are the vacuum wavelengths of the sum and infrared waves, and I_L is the laser power per unit area at the crystal. For perfect phase matching $\Delta k = 0$, and the term in parentheses in Eq. (1) is equal to its maximum value of unity. For type-II phase matching in proustite,[5] $d_{eff} = 5.5 \times 10^{-8}$ esu, and for this experiment $l = 1$ cm and $I_L = 3.5$ W/cm^2, yielding a value of 2.3×10^{-7} for η. Laboratory measurements indicate good order of magnitude agreement with this calculated conversion efficiency. The infrared bandpass of the upconverter is limited to the extent that the term in parentheses in Eq. (1) falls to zero as the infrared frequency is varied from its central phase-matched value. The bandpass can be calculated to be 2 cm^{-1}. This is sufficiently narrow to allow some spectrocopy of molecular bands in planetary atmospheres, but the upconverter was not used for spectroscopy in the present experiments. The field of view of the upconverter is quite large: 17° measured externally to the proustite crystal. The magnification of the telescope and coupling optics used in this study implies a field of 40 arc seconds on the sky. Slightly different infrared frequencies are upconverted at different points in the field of view, but this spread of 11 cm^{-1} is not an important effect for the thermal imaging work reported here.

Considerable effort was spent in perfecting this system in terms of angular resolution and sensitivity. The angular resolution of an imaging upconverter of the type described here should be limited only by the diffraction of the three waves through an aperture defined by the illuminated portion of the crystal. In our apparatus, a 1-mm exit pupil size was used, implying a diffraction limit of 0.69° for the infrared wave and giving 25 resolvable spots across the field. Diffraction-limited resolution was not quite achieved in this study due to a distortion of the wave fronts by laser-induced local heating of the proustite crystal. To first order, this distortion was a wave-front curvature ($R = 260$ mm at 225 mW) and could be corrected by refocusing the optical system, but a residual distortion remained that limited resolution to about 75% of theoretical. Resolution test patterns imaged with this apparatus are shown in Fig. 2.

Good sensitivity was obtained by a careful choice of sum-frequency detection methods. A set of five interference filters was used to pass the sum-frequency radiation while rejecting the intense laser beam. This set of filters has a transmission of 35% at 7000 Å and a transmission of less than 10^{-18} at the laser frequency. The sum-frequency signal is amplified by a three-stage image intensifier tube with an S-20 first-stage photocathode. The entire tube is cooled to -30 °C, thus lowering the dark count by a factor of 300 to a level of 0.1 photoelectrons/sec within the 3-mm field used by the upconverter. This background does not substantially limit the system performance. The output of the image intensifier is lens coupled at unit magnification to Kodak TRI-X film for short exposures and to Kodak IIa-D film for long exposures.

In laboratory sensitivity measurements conducted at a somewhat different infrared f number, we have detected a 100 °C blackbody against a 25 °C background in 8 sec of integration; a limiting temperature difference of 25 °C obtained from a 50 °C source against a 25 °C background was detected in 2 min of integration. While it is difficult to define an NEP for an imaging system, especially when the final detector is photographic, we note that each resolution element of our 500-element field can be considered a detector with an NEP of the order of 3×10^{-10} W/Hz$^{1/2}$.

A limitation to the sensitivity of this instrument results from a background signal at the sum frequency which is of comparable intensity to the signal from a room-temperature blackbody and probably comes from

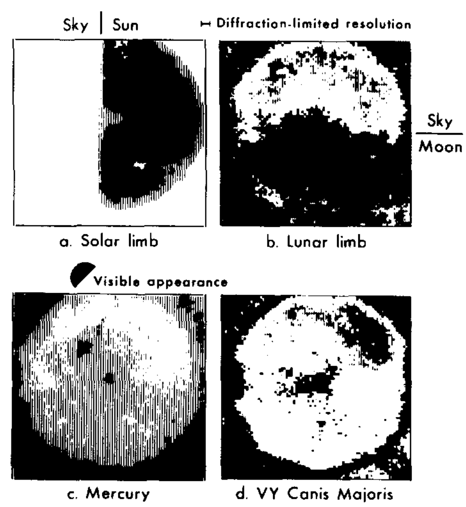

FIG. 3. Infrared images of a number of astronomical objects. Computer generated plots of digitized photographic negatives are shown. In each case the field of view is round, and a spurious spot is introduced at the center of the field from the hole in the collimating mirror shown in Fig. 1.

such a source. The background is of narrow wavelength band and is linearly polarized, and thus appears to be upconverted infrared radiation. It is likely that the entire background results from the upconverted radiation from two sources: thermal emission from the proustite crystal and room-temperature blackbody radiation injected into the signal beam by the high-reflectivity (20% at 10 μm) surfaces of our proustite crystal. However, we cannot rule out some contribution from more exotic effects such as that of Smith and Townes.[6]

As an astronomical instrument, the upconverter was mounted at the focus of the 1.5-m McMath solar telescope of Kitt Peak National Observatory, yielding a field of view of 40 arc seconds and an angular resolution of 2.5 arc seconds. Thermal radiation from the sky and telescope did not appreciably increase the system background. Infrared pictures of the sun, moon, Mercury, and the dust cloud surrounding the star VY Canis Majoris have been obtained.

We were able to detect the sun in 1 sec of integration, although 30-sec integrations were frequency used to provide high signal-to-noise ratios. A number of observations were made of the solar limb, one of which is shown in Fig. 3(a). No surface features such as spicules or prominences were seen. The sharpness of the image of the solar limb can be used to obtain a quantitative measure of atmospheric "seeing" (loss of angular resolution due to atmospheric turbulence) in the 10-μm region. Such a study, which will be published separately, shows considerable improvement in angular resolution at the infrared wavelength. Pictures were taken of sunspot regions, but the images of the sunspots were of marginal significance because nonuniformities in the response of the upconverter were comparable to the expected signal decrease (~10%) in a sunspot region.

The thermal radiation from the ~400 K subsolar point of the moon provided a more demanding test of upconverter sensitivity. We were able to detect this signal in 4-min integrations. The imaging properties of the upconverter were demonstrated by taking pictures of the lunar limb, one of which is shown in Fig. 3(b). The apparent raggedness of the limb is a result of only a modest signal-to-noise ratio.

Mercury's surface temperature reaches about 650 K, and thus Mercury's small hot disk is an ideal object for imaging studies. A 12-min integration on Mercury is shown in Fig. 3(c); the response from the presumably hottest region near the subsolar point is exaggerated in our 10-μm pictures.

Figure 3(d) shows a marginal detection of VY Canis Majoris, a star surrounded by a thick dust cloud which intercepts much of the stellar flux, reradiating it in the infrared. Sources such as VY Canis Majoris are believed to have sizes of about one arc second and nonspherical shapes,[7] and thus would provide exciting objects to study with imaging upconverters of only slightly better sensitivity than the one described here. Suggested methods for improving the performance of astronomical upconverters are published separately.[8]

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