NRL Report 7154

Applications of Optical Parametric Upconversion to IR Viewing Systems

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October 13, 1970

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ABSTRACT

The use of parametric upconversion to convert IR images to the visible has been demonstrated by several investigators. This technique has possible application in real-time systems with IR active viewing, and also as a means of producing IR holograms for recording three-dimensional information. For these applications, special consideration must be given to resolution, conversion efficiency, laser pump and illuminator powers, image identification, atmospheric transmission, and nonlinear materials. Resolution is determined by the optical system employed, and it is a function of the mode structure of the pump radiation and the size of the nonlinear crystal. Conversion efficiency depends on the mode of operation, which in turn determines peak pump intensity. Available nonlinear materials and lasers currently limit the design of a practical system to a few optimum combinations. Image identification is a problem of object reflectivity, both spectral and diffuse, in the IR operating range, which is limited by atmospheric transmission. Considering all these factors, an IR viewing system is possible employing a Nd:YAG laser, HIO_3, and low-light-level TV.

PROBLEM STATUS

This is an interim report on one phase of the problem; work on this and other phases is continuing.

AUTHORIZATION

NRL Problem N01-14
Project XF-52545002-03

Manuscript submitted July 7, 1970.

APPLICATIONS OF OPTICAL PARAMETRIC UPCONVERSION TO IR VIEWING SYSTEMS

INTRODUCTION

Optical parametric upconversion has been demonstrated by a number of authors (1-4) as a means of converting infrared (IR) radiation to the visible. More recently, it has been shown that IR images can be upconverted to the visible while maintaining the image information (5-10). The basic upconversion process involves intense laser "pump" radiation incident on a crystal with a nonlinear (NL) susceptibility simultaneously with IR radiation. The result of the parametric mixing process is visible radiation. It is required for efficient conversion that

$$\omega_P + \omega_{IR} = \omega_S \tag{1}$$

and

$$\vec{k}_P + \vec{k}_{IR} = \vec{k}_S, \tag{2}$$

where the subscripts P, IR, and S refer to pump, infrared, and signal, respectively, and ω and k are the corresponding frequencies and wavevectors. The latter expression is the so-called phase-matching condition. It can be satisfied by making use of birefringence in an appropriate NL crystal to cancel the effect of normal dispersion. The wavevector mismatch as expressed in Eq. (2) must in general hold to a part in 10^4 or 10^5, i.e., $\Delta k = |\vec{k}_S - (\vec{k}_P + \vec{k}_{IR})| \leq 2\pi/L$, where L is the length of the NL crystal. Among other things this severely limits the spectral bandwidth of the IR radiation which can be upconverted. In general, λ_{IR} is limited to about 10Å, in the 2-micron range (2). The spectral bandwidth can be increased by a factor of about 50 in special cases (11), but in all cases parametric upconversion can be classified as a narrow-band process.

Due to the spectral-bandwidth limitation on the IR radiation, application of parametric image upconversion appears to be more appropriate to an active system as opposed to a passive system, which depends, for example, on blackbody radiation. The active system would use an IR laser as an illuminator. In certain cases an active system may be objectionable, but there are nevertheless many possible advantageous applications. This report will address the characteristics, both advantages and problem areas, associated with an active IR image parametric upconverter.

The first and probably most important advantage of a parametric upconverter is its low noise. The inherent noise in the upconversion process is due to the production of photons at the upconverted wavelength via non-phase-matched processes, e.g., the upconversion of parametric fluorescence (12,13). This noise is negligible in comparison with the dark-current noise of an image intensifier which may be used in conjunction with the upconverter (14). Since photomultipliers and image intensifiers have extremely low dark noise as compared to semiconductor detectors, the upconverter is the superior detector in the low-intensity, dark-noise-limited applications (14). Hence, despite the fact that semiconductor detectors have a higher quantum efficiency than photomultipliers, their higher figure of spectral noise equivalent power (NEP_λ) means they have a poorer spectral detectivity, $D^*_\lambda = \sqrt{\Delta f}/NEP_\lambda$, where Δf is the bandwidth of the detector. The frequency bandwidth requirements for image up-conversion are much less than for a fairly high-capacity communication channel. This bandwidth factor also works to the advantage of the image upconverter. As an example, Kleinman and Boyd (14) give the case of 10.6μ radiation upconverted to 6729Å (difference frequency) in HgS with a 6328Å pump of 0.1 W. In this case, $NEP_{6729Å} = 4 \times 10^{-16} (Hz)^{-1/2}$, or referred to 10.6$\mu$, $NEP_{10.6\mu} = 2.8 \times 10^{-12} W(Hz)^{-1/2}$. Further, the upconverter is shown to be superior to direct detection with a photoconductive device for $P_{10.6\mu} < 5.9 \times 10^{-11}$ W. With more pump power and/or better NL crystals, this limit would be even larger.

There are additional advantages of the upconverter. The parametric process does not require cryogenic temperatures, and in fact can work at room temperature. Second, a parametric upconverter is a very simple device, with few parts. Third, with IR radiation it is possible to improve visibility through haze. With a pulsed illuminator and a gated upconverter, it is possible to discriminate against scattered light due to haze, fog, and dust; at the same time, images only of objects at a specific range can be seen. Another advantage is the fact that parametric upconversion is an inherently fast process. Real-time viewing of fast events, such as a moving target, can take place. Besides the possible application of parametric upconversion to IR viewing systems, it can be used to record three-dimensional information. IR holograms have been made in the laboratory with the aid of a parametric upconverter (15,16). In principle it should be possible to obtain three-dimensional records of distant objects with invisible IR radiation. The longer wavelength has the added advantage of reducing the stability requirements for holography. Finally, the principles of parametric upconversion are directly applicable to any IR wavelength and thus provide possibilities for wavelength diversity as new lasing lines in the IR become available and as suitable nonlinear crystals are matched to them.

PARAMETRIC UPCONVERTER PROBLEM AREAS

Several problem areas associated with upconversion must be worked on before it can successfully be employed in practical devices and systems. These areas generally might be listed as resolution, conversion efficiency, laser pump and illuminator powers, image identification, atmospheric transmission, and NL materials. Each of these areas are discussed in relation to the current experimental progress in the various research fields.

In order to maintain a maximum amount of image information during the upconversion process, it is necessary to maximize the resolution inherently associated with the upconversion process. For given directions of propagation for the pump and IR radiation, the upconverted radiation will have a direction determined by a phase-match condition. In general, the upconverted image of an IR point source is a disc with diameter D, (17) as shown in Fig. 1. The distance of the image behind the NL crystal is given by an equation similar to the thin-lens equation of geometrical optics (18). The diameter of this disc determines how close a second IR point source can be to the first and still be resolved in the upconverted image. The quantity D is a function of the thickness of the nonlinear crystal and also of the mode structure and divergence of the pump radiation. However, the form of the functional dependence is determined by the optics of the upconverter (17). Minimum D (maximum resolution) is obtained with a single-mode pump source, with diffraction-limited divergence, and with the IR image optically at infinity with respect to the NL crystal. In this case the resolution is independent of the crystal thickness and is not limited by the upconversion process. To obtain comparable resolution with the image focused in the NL crystal, the crystal thickness must be reduced, and hence the conversion efficiency is lowered. With the IR image at a finite distance from the NL crystal, as shown in Fig. 1, maximum resolution is

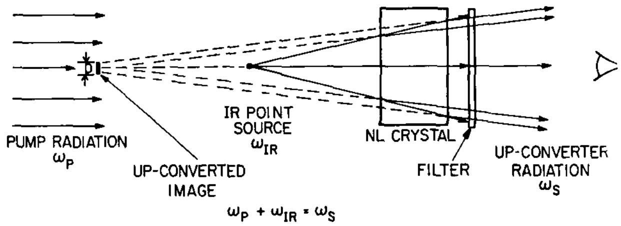

Fig. 1 - Basic schematic drawing of optical parametric upconversion. The ω_{IR} radiation from a point source at frequency IR is upconverted in the NL crystal by parametric mixing with the pump radiation of frequency ω_P. The upconverted radiation at frequency ω_S is passed through the high-pass filter, and an upconverted image of the IR point source is observed.

obtained with the pump source at the same distance optically from the NL crystal as the IR image. However, the resolution tends to degrade as one moves away from the center of the IR image.

Another important aspect in resolution considerations is the size of the angular aperture in which IR can enter the NL crystal and still be upconverted. Resolution in upconversion is conveniently measured in resolvable lines per milliradian of angular aperture for phase-matched upconversion. Hence, a large angular aperture means that the total number of resolvable lines is also large. Warner (19) has shown that noncritical phase matching offers the largest angular aperture. This situation exists when the wavevector surface corresponding to $(\vec{k}_P + \vec{k}_{IR})$ is tangent to the surface corresponding to $\vec{k}_S$ in phase space. The fact that good resolution has been demonstrated experimentally with different optical systems (7,9,15,20) indicates that resolution should not be considered a major problem for the application of upconversion to an IR viewing system. It is, however, an important consideration which enters into design criteria.

In order to have wide practicality, the upconversion process should efficiently convert low-intensity IR images to the visible. In the upconversion process, the amount of upconverted light is proportional to the NL susceptibility squared, the length of the NL crystal, the pump intensity, and the IR intensity. The number of NL crystals available is limited, and these are discussed later. Peak pump intensity can be increased, as mentioned previously, by employing a pulsed sytem. Consider, for example, the pump and illuminator to be synchronously pulsed at a rate of n pulses per second and each with a pulse duration of ϵ seconds, yielding a peak intensity for these two sources of $\langle I_P\rangle/n\epsilon$ and $\langle I_{IR}\rangle/n\epsilon$, respectively, where $\langle I_P\rangle$ and $\langle I_{IR}\rangle$ represent average intensity levels. In this mode of operation the intensity of upconverted light is increased by a factor of $1/n\epsilon$ over the CW case. This factor can be important for a laser such as a CW-pumped YAG, where the average power output is almost the same for CW operation or for Q-switching at a high repetition rate. In practice, a photon conversion efficiency of 1 percent has been demonstrated for a pulsed high-intensity ruby pump source (2). Another possibility for high efficiency is to place the NL crystal in the pump laser cavity to take advantage of the increased intensity. This approach has not been reported yet.

Assuming an efficiency for the upconverter of about 1 percent and a minimum detectable intensity of visible light (with the aid of low-light-level TV) on the order of 10^{-12} W/cm^2 (21), an estimate can be made of the pump and illuminator powers. The 1 percent efficiency with presently available NL crystals requires peak pump powers near

1 MW/cm²(2), which is easily obtained at high repetition rate with either ruby or Nd:YAG lasers. The power seen by a receiver from a distant diffusely reflecting object is approximately

$$P_{rec} = \frac{(0.07)\ Ar\sigma}{\alpha_{1/2}^2\ d^4}\ P_{ill}, \qquad (3)$$

where A is the object area, r its reflectivity, d the object's range, $\alpha_{1/2}$ the half-angle divergence of the illuminator beam, σ the area of the receiver, and P_{ill} the illuminator power. For an object of area about 78 yd² at a range of 2000 yd with a reflectivity of 1 percent, an illuminator divergence of $\alpha_{1/2}$ = 50 milliradians, and a receiver area of about 0.78 yd², the ratio P_{rec}/P_{ill} in Eq. (3) is on the order of 10^{-12}. In this case a minimum peak illuminator power of 100 watts is required. This power is easily obtainable. The situation is obviously improved when the illuminator divergence is decreased or the peak power increased.

The reflectivity of most materials changes quite markedly in the IR. In fact, at 10μ most materials are either good spectral reflectors or good absorbers. There are relatively few good diffuse reflectors. This means that reflectivity will in general be very low, and if there are spectral reflections it may be difficult to identify the image of the illuminated object. Tables 1 and 2 list the spectral reflectivity of several common materials. This problem may mean that a compromise may have to be made on how far into the IR the illuminator can be and how easily an object can be identified. Of course a related problem is the location of transmission windows in the atmosphere.

Table 1
Diffuse Reflective Power of Various Substances in the IR*

Material	Reflecting Power (percent)		
	0.95μ	4.4μ	8.8μ
Lampblack paint	3.4	3.2	3.8
Pigments:			
CuO	23.5	15.2	
Cr_2O_3	44.6	32.9	5.0
PbO		50.6	25.6
Fe_2O_3	41.0	29.9	3.7
$PbCrO_4$		41.2	4.74
Al_2O_3	87.7	20.8	2.34
ZnO	86.4	8.5	3.2
ZrO_2	84.1	23.2	5.1
SiO_2 (sandstone)	8.1	17.6	11.0
$CaCO_3$ (Indiana limestone)		20.3	5.0
SiO_2 (Quartz powder)	41.5	7.9	9.0
Slate		13.4	20.0
White paper	74.7	18.2	5.0

*Values taken from "Handbook of Chemistry & Physics" (39th ed.), p. 2745-6.

Table 2
Reflectivity of Various Metals in the IR*†

Material	Reflectivity (percent)		
	1.0μ	4.0μ	9.0μ
Antimony	55	68	72
Bronze	70	88	93
Copper	90	97	98
Iron	65	89	94
Magnesium	74	83	93
Nickel	72	91	96
Silver	97	99	99
Tungsten	62	93	95
Aluminum	71	92	98
Graphite	27	48	58
Silicon	28	28	28
Tin	54	72	84

*Normal incidence on polished surfaces.
†Values taken from "Handbook of Chemistry & Physics" (39th ed.), p. 2742-3.

Atmospheric transmission in the IR is mainly limited by the presence of water vapor. The principal components of the atmosphere, oxygen and nitrogen, do not absorb near IR radiation. Figure 2 shows absorption curves of water vapor, carbon dioxide, and ozone. Carbon dioxide and ozone are the only significant absorbers besides water vapor. Several windows are indicated between 1 and 13 microns. Beyond about 16 microns, atmospheric absorption is almost complete for any significant distance. Present possibilities for high-power illuminators are the CO laser in the 5 to 6 micron range, the CO_2 laser at 10.6 microns, and the Nd:YAG laser at 1.06 micron. The latter two lie in IR windows. There is an obvious need for more high-power lasers at other wavelengths, primarily in the 3.5 to 4.0 micron range and the 2.0 to 2.5 micron range. The 3.5 to 4.0 micron range would seem to offer a compromise between the disadvantages of 10.6-micron illumination and the advantages of long-wavelength illuminators.

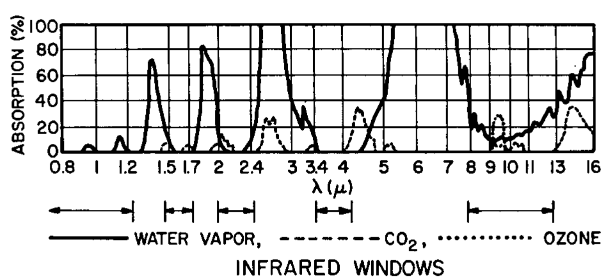

Fig. 2 - Plot of absorption as a function of wavelength in the IR for water vapor, CO_2, and ozone. Areas of low absorption correspond to transmission windows in the atmosphere.

Several NL materials are used today for upconversion. The major considerations are good optical quality and transmission in the range of wavelengths of interest, a high NL susceptibility, and a material which can phase match the desired process (17). Most promising at present are proustite, lithium niobate and barium sodium niobate, and lithium iodate. Proustite is transparent from 0.6 to 13 microns and has been used in 10.6-micron image upconversion experiments (4,20). The other materials mentioned are limited to about 4 or 5 microns in the IR. Obviously, the number of NL materials is very limited, and there is an urgent need for new materials to be developed and evaluated. An important consideration for both existing and new NL materials is the threshold for damage due to intense pump radiation. Any type of damage, whether surface or bulk, or optical damage that can be annealed away, such as in the case of $LiNbO_3$, limits the pump intensity in the upconverter. This in turn limits the conversion efficiency. Hence a damage-resistant NL crystal with a low NL coefficient may be capable of a higher conversion efficiency than a NL crystal with a large NL coefficient but a low damage threshold.

PRACTICAL VIEWING SYSTEM

Based on the preceding discussion, the primary problem areas that remain for a successful application of parametric upconversion to a viewing system are (a) increased conversion efficiency by enhancing pump power and the quality of nonlinear crystals, (b) more high-power laser sources in the IR, particularly the 3.5 to 4.0μ range, (c) additional damage-resistant NL materials with large NL susceptibilities, and (d) limitation in image identification under IR illumination. Of these, conversion efficiency is probably the most important.

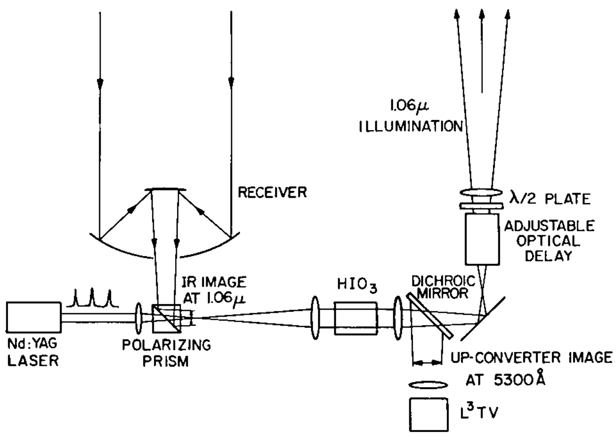

Fig. 3 - Basic IR viewing system using optical parametric upconversion: The Nd:YAG laser produces high-intensity pulses at a high repetition rate. This beam of radiation is expanded to fill the HIO_3, where it acts as "pump" radiation. The beam is then passed through an optical delay line and used as illumination at 1.06μ. The radiation collected by the receiver is combined with the pump radiation of opposite polarization with a polarizing prism, and the upconverted image is viewed with low-light-level TV.

A possible viewing system, using currently available lasers and materials, is shown in Fig. 3. This system employs a single high-repetition-rage Q-switched Nd:YAG laser operating at 1.06μ as both a pump and illuminator. The optics place the IR image at infinity with respect to the NL crystal taken to be HIO_3 . An extradordinary polarization pump is combined with an ordinary polarization signal by a polarizing prism. The upconverted image is viewed with a dichroic mirror and low-light-level TV. The unused pump radiation is sent through an optical delay line for synchronization and ranging and collimated to the desired degree, and its plane of polarization is rotated 90 degrees for use as the source of illumination. Such a system is at the present time feasible. It has fast response time for real-time viewing of rapid motion and requires no cryogenic temperatures. It employs no mechanical scanning and has a minimal number of parts. This system has not been built, so actual performance figures cannot be given and compared with IR scanning viewers.

The considerations presented in this report indicate the parametric upconverter may have an application to IR viewing systems in the instances where active viewing can be empolyed. However, maximum exploitation of this technique for practical and useful applications will require more work in the problem areas that have been outlined. In the next year, or at most two or three years, it seems fair to estimate that prototype systems should be available for test and evaluation in specific applications.

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

UNCLASSIFIED

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
APPLICATIONS OF OPTICAL PARAMETRIC UPCONVERSION TO IR VIEWING SYSTEMS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
An interim report on one phase of the problem; work is continuing.

5. AUTHOR(S) *(First name, middle initial, last name)*
R.A. Andrews

6. REPORT DATE October 13, 1970	7a. TOTAL NO. OF PAGES 11	7b. NO. OF REFS 21

8a. CONTRACT OR GRANT NO. NRL Problem N01-14 b. PROJECT NO. XF-52545002-03 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7154 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Naval Electronics Systems Command) Washington, D.C.

13. ABSTRACT
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DD FORM 1473 1 NOV 65 (PAGE 1)

S/N 0101-807-6801

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Optical Parametric Processes Upconversion Night Vision Quantum Optics						