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# NONLINEAR EFFECTS IN IMAGE FORMATION

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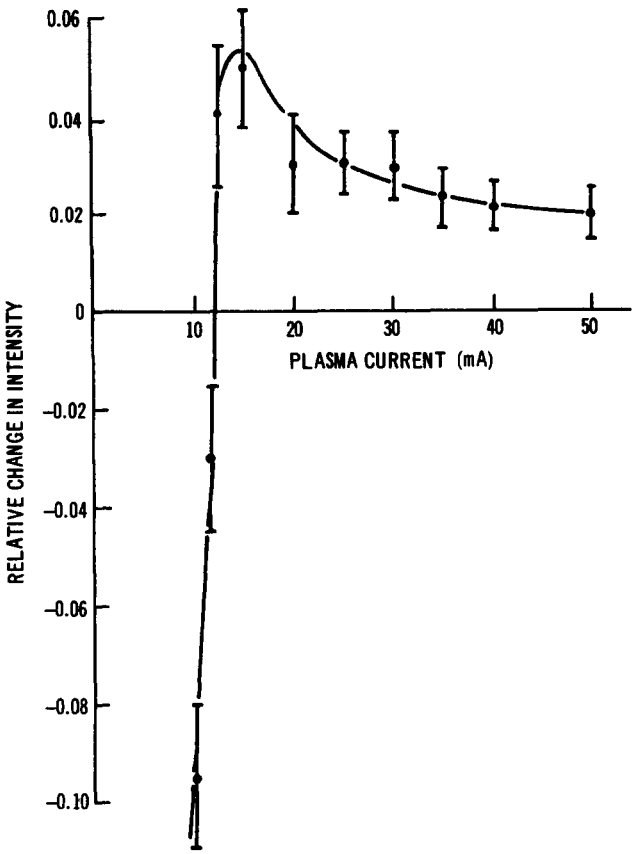


**Fig. 2. Relative change in the intensity of the $N_2$ transition at 3576 Å with discharge current, stimulated by the laser radiation field. Plasma gas mixture: $CO_2$ – 17%, $N_2$ – 17%, He – 66%, total pressure 6 torr.**

results. Similar experiments were also carried out in a pure $CO_2$ plasma where the current changes are much larger. It was established that in this case, the current change undergoes a definite switch in polarity as the current is reduced below a value which depends on the pressure. At the higher current values the polarity is positive (opposite to that of the case of the ternary gas mixture). Experiments are currently being carried out to determine the correlation between the gain properties and the current and side-light characteristics of a laser plasma. In this work spectroscopic measurements at longer wavelengths are also being made.

The authors express their appreciation to Dr. A. I. Carswell for many helpful discussions concerning this investigation, and the technical assistance of D. Coulter and J. I. Wood is gratefully acknowledged.

[1] A. L. Waksberg and A. I. Carswell, *Appl. Phys. Letters* **6**, 137 (1965).

[2] A. L. Waksberg and A. I. Carswell, RCA Victor Report No. TM 7-801-018 (1965).

[3] G. Moeller and J. Dane Rigden have also observed these effects and have interpreted them solely in terms of gross temperature changes of the plasma, *J. Quantum Elect.* **2**, 365 (1966).

[4] A. I. Carswell (unpublished).

[5] Optical pumping from the lower to the upper laser level decreases the optical cascading into the ground state. This results in an effective net incremental gain in the upper laser level from the ground state.

# NONLINEAR EFFECTS IN IMAGE FORMATION

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(Received 6 February 1967)

The use of nonlinear effects in image processing is discussed, particularly in connection with holography. A new type of microscope, called a holoscope, is described which permits true three-dimensional magnification.

We report here a group of new nonlinear imaging phenomena which we have investigated experimentally and analytically, as well as some speculations about applications. Detailed experimental and theoretical accounts of this work will be published elsewhere.[1]

It has been well known since the work of D. Gabor,[2] that the imaging process can be interrupted by recording the interference pattern between light coming from the object and from a reference beam. Usually the interference pattern is recorded in a light-sensitive medium, which is subsequently developed and fixed. This hologram is a true record of the three-dimensional object.

We have been investigating an interesting analogue of this effect, the temporary hologram, which occurs in nonlinear materials. Using strong laser beams for the object and reference beams and a material whose complex index of refraction is a function of the light intensity, we have found that a hologram exists in the material so long as the incident beams are present, and that this hologram

can be used to form an image. The temporary hologram (Fig. 1) was produced in a thin layer of the saturable dye cryptocyanine, using beams from a 100 nsec pulse of a ruby laser with power density of 50 MW/cm$^2$. This relatively low power density can be used on many materials without danger of physical damage.

A combination of nonlinear image-processing operations, including temporary holograms, read-out of a second-order image, and color shift of the image, can in principle yield a "holoscope," a true three-dimensional microscope operating in real time. It was pointed out by D. Gabor[2] that when a hologram is optically enlarged by a factor $M$ and the read-out wavelength is also scaled up by the same factor, a true three-dimensional enlargement of the object by a factor $M$ results. Such a feat is not possible in ordinary optics, as was shown by J. C. Maxwell,[3] since the longitudinal magnification equals the square of the transverse magnification. This effect prevents microscopes from obtaining a magnification of an object in its totality.

Two factors reduce the attractiveness of the holographic enlargement method as suggested by Gabor: first, the precision required in the enlargement of the hologram print, and second, the catastrophic necessity for wavelength scaling proportional to the magnification. Precision enlargement can be avoided, only at the cost of some distortion. The aberrations that occur when the original hologram is read out at $M$ times the original wavelength, by a beam whose divergence differs from that of the taking beam, has been treated by several authors.[4,5] We find that the second problem can be solved by nonlinear effects in a variety of ways, all with the common feature that the nonlinear effect converts the long read-out wavelength back to a shorter one.

We have shown experimentally (Fig. 2) and theoretically that the second-order image from a very thick hologram, when read out by a wavelength half that used in making the hologram, faithfully reproduces the object except for contrast enhancement. An enlargement, faithful except for contrast, can in principle be achieved through application of the above idea in three steps. 1) Illuminate a thin hologram of an object made with wavelength $\lambda$ with a beam having the proper divergence and wavelength $2\lambda$. 2) Use this read-out light to make a second hologram at $2\lambda$ in a thick recording material which has a large second-order nonlinearity (for example, photographic emulsion with large gamma). 3) Illuminate the second hologram with wavelength $\lambda$. Then the second-order image is a true enlargement, and at the original wavelength $\lambda$. Since second-order images are easily produced in most materials used in holography and do not require high-power pulsed lasers, the method is quite straightforward. A disadvantage is the need to repeat the steps many times to obtain large magnification.

Instead of illuminating the second-order image in a thick hologram with wavelength $\lambda$ to give the color shift, one can place a thick frequency-doubling material in the object beam. We have demonstrated this technique by making a hologram in green light, playing it out truly enlarged with a pulsed neodymium laser at 1.06 $\mu$, and converting the infrared image back into a green image using a lithium niobate crystal in the image beam. The need to match the refractive indices at the two frequencies limits the angle of incidence to a cone of five degrees half-

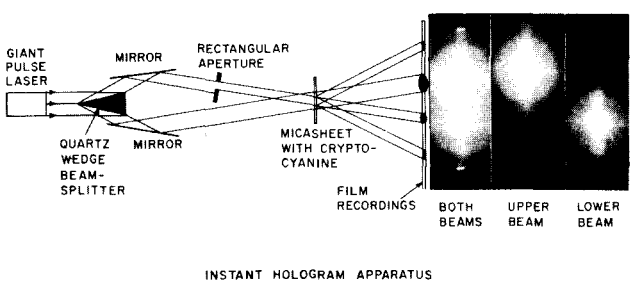


**Fig. 1. Transitory hologram apparatus.**

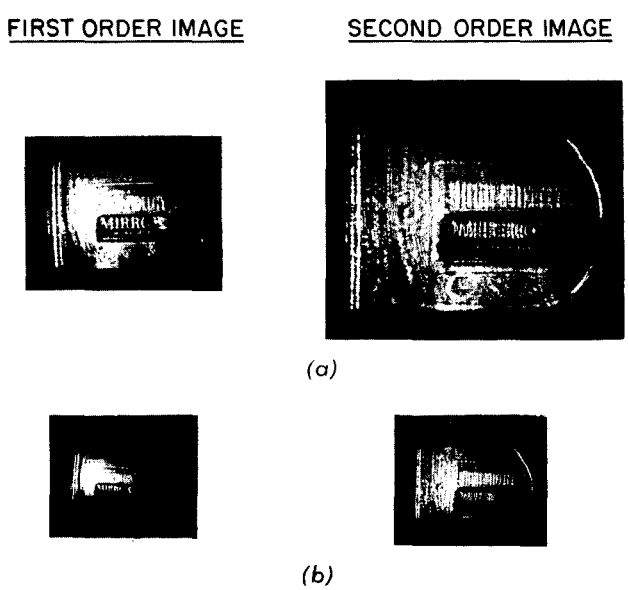


**Fig. 2. (*a*) First- and second-order reconstruction from a 12-$\mu$-thick photographic hologram made at 6328 Å and reconstructed at 6328 Å. (*b*). Same as (*a*) except that reconstruction was made at 3324 Å. Note the rather poor quality of the second-order image, due to the fact that the emulsion was not thick enough to give high resolution.**

angle about the $c$ axis. The mathematical formalism which describes the image formation in the thick hologram is essentially the same as for the frequency converter.

The different methods of image enlargement can in principle be combined with the temporary hologram to give a practical microscope with true three-dimensional magnification in real time. The development of efficient optically isotropic nonlinear materials, and the proper balancing of the aberrations due to the holograms and lenses, seem to be the major problems, as are nonlinear cross terms.

Important contributions to the analytical part of the work were made by E. G. Ramberg and S. Freeman. A stimulating discussion with H. S. Sommers, Jr. and technical assistance from M. E. Heller are gratefully acknowledged.

[1] H. J. Gerritsen, E. G. Ramberg, and S. Freeman, Modern Optics Symposium, Polytechnic Institute of Brooklyn, Brooklyn, N. Y. (April, 1967), to be published.

[2] D. Gabor, *Proc. Royal Soc.* **A197,** 454 (1949).

[3] J. C. Maxwell, *Scientific Papers,* Vol. I (Cambridge University Press, 1890), p. 271.

[4] R. W. Meier, *J. Opt. Soc. Am.* **55,** 987 (1965).

[5] J. A. Armstrong, *IBM J. of Res. and Dev.* **9,** 171 (1965).

# $Cd_xHg_{1-x}Te$ INFRARED PHOTOVOLTAIC DETECTORS*

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Using departure from stoichiometry for doping, $p$-$n$ junctions were prepared from $Cd_xHg_{1-x}Te$ alloys with $0.15 < x \leq 0.28$, and their current-voltage characteristics were measured at 77°K. The spectral study of these photovoltaic detectors operating at 77°K showed responses from 3 $\mu$ up to 17.5 $\mu$. Detectivity measurements at the wavelengths of maximum response of these detectors yielded values at 77°K between 1 and $5 \times 10^9$ cm-W$^{-1}$-Hz$^{1/2}$ in the range 3 to 14 $\mu$. The speed of these detectors was measured to be <50 nsec, which was also confirmed by the observation of mode beats on the continuous output of a low-power $CO_2$ laser at several frequencies up to 25 MHz.

The $Cd_xHg_{1-x}Te$ alloys are known to be small bandgap semiconductors for definite values of $x$, in the range $0.15 < x < 0.30$.[1] Photoconductivity measurements have shown intrinsic detection at 77°K up to 14 $\mu$.[2] Photoluminescence has been observed in a wide range of wavelengths in the infrared, up to 15 $\mu$ at 12°K.[3] Furthermore, $p$-$n$ junctions have been produced by diffusion of interstitial atoms of mercury in $p$-type $Cd_xHg_{1-x}Te$ single crystals, and they exhibit classical electrical rectification, photovoltage and electroluminescence.[4] All these results suggest that $p$-$n$ junctions, prepared in suitably selected $Cd_xHg_{1-x}Te$ samples, should be promising for infrared optoelectronic components such as photovoltaic detectors, modulators (by Franz-Keldysh effect) and monochromatic emitters.

In this Letter we report the characteristics of such infrared photovoltaic (PV) detectors operating at 77°K prepared from $Cd_xHg_{1-x}Te$ alloys with $0.15 < x \leq 0.28$, which show responses from 3 $\mu$ up to 17.5 $\mu$.

The starting materials[5] were single crystals grown by the Bridgman technique. The ingots were oriented and cut along (110) planes into wafers on which Hall effect and electron-microprobe measurements were made. A hole concentration $p \simeq 10^{17}$ cm$^{-3}$ is found in such crystals. For $x > 0.19$, these crystals selected by the electron-microprobe measurements can be used directly for junction preparation. However, for $x \leq 0.19$, the absolute error of $\Delta x = \pm 0.01$ in composition determination together with the composition gradients generally observed in these materials,[2] led us to supplement the electron-microprobe measurements by the Hall-effect method[6] for selecting the samples. It has been shown[6] that Hall-effect data in the intrinsic regime may yield a simple criterion for distinguishing very small energy gap semiconductors from semimetals. Furthermore, this method is more practical than the electron-microprobe one for testing the bulk homogeneity of the samples. For this purpose the samples were annealed to remove the acceptors, i.e. Hg vacancies, leaving an $n$-type material with 2 to $5 \times 10^{15}$ carriers per cm$^3$. After the Hall-effect measurements, the samples were suitably heat treated to

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