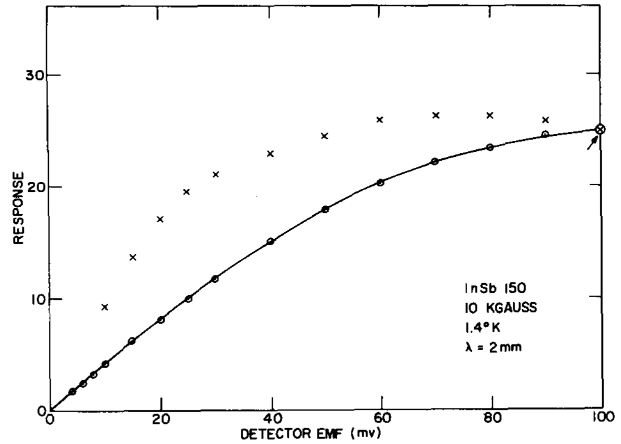

Fig. 2. Relative response of an InSb detector as a function of detector emf. The solid line is the observed response curve; the circles and crosses are values calculated from the current-voltage curve using a photoconductor model and a bolometer model respectively. The arrow indicates the point at which the calculated values were normalized to the observed curve. The sample is equipped with both current and voltage contacts. The magnetic field direction is perpendicular to the sample current direction and parallel to the direction of the incident radiation. The electron concentration and mobility of this InSb sample at 78°K are 6.8×10^{13} cm^{-3} and 7.1×10^5 cm^2/V-sec respectively. The intensity of the incident radiation was low enough so that it produced less than a 2% change in the sample current.

points calculated using the bolometer model is poor while the fit of the points using the photoconductor model is very good. This result is typical of those taken at magnetic fields above 10 kG at 1.4°K and of those taken at magnetic fields above 15 kG at 4.2°K. At small magnetic fields it was found that the theoretical values for both equations were the same and were in agreement with the observed response curve. The two equations yield the same result when $\partial R/\partial V^2$ is independent of V.

It may be concluded that in the high-magnetic-field region the usual bolometer effect does not explain the response of the InSb detectors. It may also be concluded that either the direct photo-ionization mechanism is operative or the ionization-by-hot-electrons process is operative and that the ratio $G_S/(G_T + G_B)$ is constant with detector emf in either case. If the indirect process is operative, then the time constant for excitation of the neutral impurities by the hot electrons must be smaller than the time constant with which the energy distribution of the electron atmosphere is equilibrated.

In order to decide between the direct and indirect mechanisms, it would be of interest to determine the absorptivity of InSb as a function of wavelength for high magnetic fields.

I am indebted to R. Kaplan for the use of his microwave apparatus, to E. Swiggard for most of the InSb samples, to R. F. Wallis for valuable discussions, and to E. H. Putley for preprints and personal communications on this subject.

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[1] This work was performed under Project Defender, sponsored by the Advanced Research Projects Agency, Department of Defense, via the U.S. Office of Naval Research.

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PARAMETRIC FREQUENCY CONVERSION OF COHERENT LIGHT BY THE ELECTRO-OPTIC EFFECT IN KDP[1]

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(nonlinear optics; lasers; interferometry; E/T)

(Received 31 August 1964; in final form 17 September 1964)

We report an experiment in which interaction between an optical wave at frequency f_0 and a microwave signal at f_m was used to generate a coherent optical beam at $f_0 + f_m$. The interaction was provided by *lossless* electro-optic modulation of the dielectric constant *within* a laser resonator and can thus be viewed as a demonstration of parametric[3–5] interaction at optical frequencies.

The theory[6] predicts that dielectric modulation of a laser oscillating at f_0, in the form of

$$\epsilon(\bar{r},t) = \epsilon_0 + \epsilon(\bar{r}) \cos (\omega_m t + \phi) \tag{1}$$

should cause a buildup of energy at $f_0 + f_m$, in the appropriate resonator mode, according to:

$$c_{(f_0+f_m)} = c_{(f_0)} J_1(kt) \exp \left\{ j \left[(\omega_0 + \omega_m) t + \phi + \frac{\pi}{2} \right] \right\} , \tag{2}$$

where J_1 is the Bessel function of the first kind of order unity. The parameter k characterizes the strength of the parametric interaction between the resonator modes and is given by

$$k = \frac{\omega_0}{2\epsilon_0} \int_v \epsilon(\bar{r})\, \bar{E}_0(\bar{r}) \cdot \bar{E}_1(\bar{r})\, dv , \tag{3}$$

where $\bar{E}_0(\bar{r})$ and $\bar{E}_1(\bar{r})$ are the electric field vector functions of the modes at f_0 and $f_0 + f_m$, respectively.

The parametric interaction was achieved by applying a microwave electric field at 8.9 Gc to a KDP(KH_2PO_4) crystal placed within the laser resonator as shown in Fig. 1. The 6328-Å(He-Ne) light propagation was directed along the crystal Y' direction with the optical electric field along the X' direction, so that the application of an electric field along Z (optical axis) causes a modulation $\delta\epsilon = \epsilon(\bar{r}) = n^2\Gamma_{63}E_z$ without effecting the polarization of the light beam.[7]

The 4-mm-long KDP crystal was placed in a capacitively loaded cavity resonant at 8.9 Gc with a Q of 200. Excessive heating limited the maximum cw power input to 250 mW.

To detect the presence of the parametrically generated energy at $f_0 + f_m$, we replaced one of the end reflectors of the laser with a tunable Fabry-Perot etalon whose transmission pass-bands occur at 16-Gc intervals. The length of the etalon was adjusted so that one of the pass-bands occurred exactly at $f_0 + f_m$, while the main oscillation at f_0 took place in the region of maximum reflectance (>98%) approximately half-way between the pass-bands. This made available as external output most of the converted energy at $f_0 + f_m$ without quenching the oscillation at f_0. Another consequence of using an etalon mirror was that, because of the very high transmission (~1) at $f_0 + f_m$, the parametric interaction was limited to a single pass through the resonator. This obviated the necessity of having $f_0 + f_m$ correspond to a free resonance and made the choice of f_m arbitrary. The amplitude of the signal at $f_0 + f_m$ is given by (2) with $t = L/c$, where L is the resonator length.

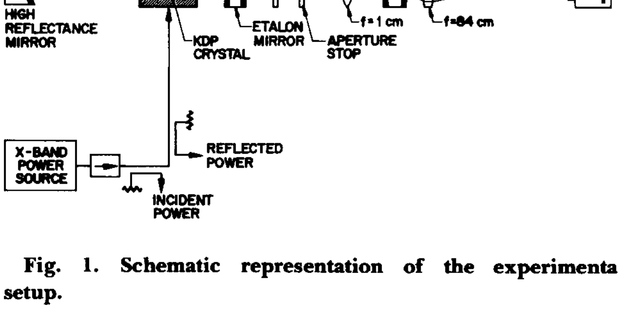

Fig. 1. Schematic representation of the experimental setup.

Spectral analysis of the output light beam was performed with a second Fabry-Perot etalon. The fringe pattern resulting from the nonmodulated beam is shown in Fig. 2(*a*), which was photographed in the focal plane of a long focus (84-cm) lens following the analyzing etalon. The application of the microwave signal resulted in the appearance of a new set of circles displaced by 8.9 Gc. These are shown in Fig. 2(*b*). Either up or down conversion could be obtained by tuning of the mirror etalon.

An estimate, based on Eq. (3) and a microwave power input of 250 mW, yields ~0.15% for the fraction of output power at $f_0 + f_m$. With some obvious improvements, to be discussed separately, this situation can be greatly improved.

A number of discussions with H. V. Hance and W. R. Ramsay contributed to this work. We are also indebted to Spectra-Physics for the generous loan of a high-gain laser which made this experiment possible.

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[1] This work was supported by the Lockheed Independent Research Program.

[2] Permanent address: California Institute of Technology, Pasadena, California.

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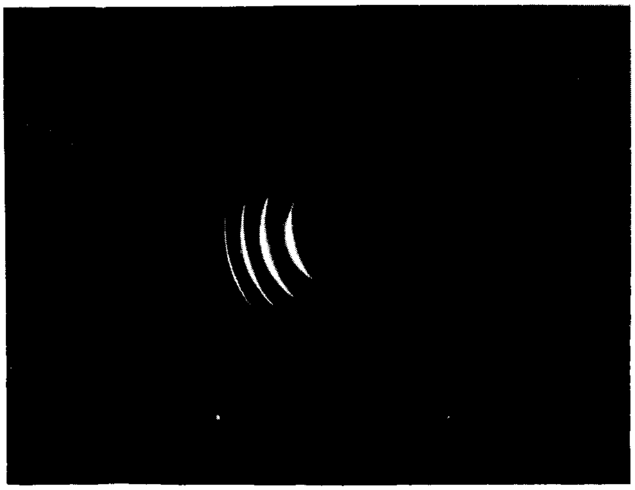

Fig. 2(*a*). The Fabry-Perot fringe system corresponding to nonmodulated oscillation at 6328 Å.

Fig. 2(*b*). The Fabry-Perot fringe system with 250-mW power input at 8.9 Gc. The new intermediate circles indicate the presence of an optical beam shifted by 8.9 Gc.

POST-BREAKDOWN CONDUCTION IN FORWARD-BIASED *P-I-N* SILICON DIODES

(filamentary post-breakdown conduction; E)

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(Received 8 September 1964; in final form 5 October 1964)

Theoretical treatment of double-injection phenomena in high-resistivity semiconductor materials has been most extensively dealt with by Lampert,[1-3] with some important extensions by Ashley.[4,5] The theory predicts a negative-resistance region in the V-I characteristics of *P-I-N* devices, as shown in Fig. 1. If such a device were to be biased in the negative-resistance region instabilities would be observed experimentally. If, however, a circuit with a fairly steep load-line (dotted lines in Fig. 1) were used to trace out the characteristic a hysteresis would be experimentally observed as indicated by the arrows. Both instabilities[5-8] and hysteresis[6,9-11] compatible with this model have been observed.

However, experiments have been reported in which the results cannot be explained on the basis of the model of Fig.1.[6,12,13] The possibility of reabsorption of recombination radiation has been proposed to explain the data on GaAs structures,[14] and the possibility of plasma-like effects in the post-breakdown region of silicon or germanium structures has been noted.[5,6] In the work reported here silicon *P-I-N* diodes have been fabricated in different lengths, and the V-I characteristics observed over a wide range of currents. The pre-breakdown region of these devices has been extensively studied, and reported elsewhere.[15,16] The post-breakdown observations are not compatible with the Lampert-Ashley model, and a modification is proposed which explains these data.

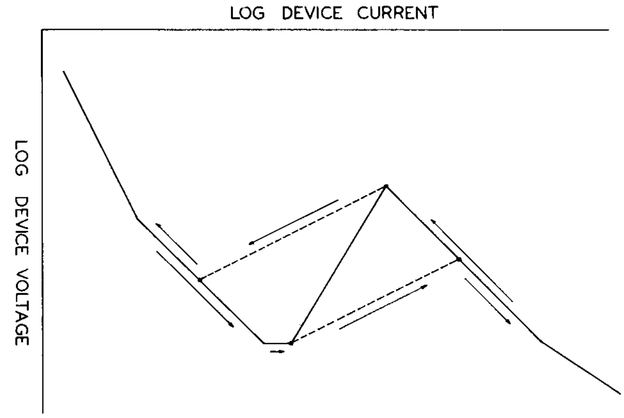

Fig. 1. Theoretical V-I characteristic of Lampert and Ashley (solid lines). At lowest currents the characteristic is ohmic, followed by a region where $J \sim V^2$. After breakdown a negative resistance region is encountered, after which the current again increases with the applied voltage, first as V^2 and finally as V^3.