Short Papers

DC and Microwave-Biased Photoconductive Response in CdS Crystals

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Abstract—DC and microwave-biased measurements of the photoresponse spectrum of sulfur-sensitized CdS single crystals were made in a *K*-band (22-GHz) reflection bridge. The experimental arrangement was such that both dc and microwave measurements could be performed at different temperatures without changing the rest of the sample's environment. For the microwave measurements, the response spectra were narrower and shifted toward shorter wavelengths than for the dc measurements.

Introduction

In recent years, several investigators studied the properties of photoconductors using microwave techniques [1]–[8].

The object of this investigation is to study the interaction of microwave radiation with a photon-induced solid-state plasma. In particular, two problems are of main interest: 1) to characterize the solid-state properties of photoconductors at high frequencies, i.e. to develop a "microwave photoconductivity" model; and 2) to study the propagation of microwaves through this solid-state plasma, whose vital characteristics are controlled by the optical input, i.e., by the light.

In this short paper we present 1) a somewhat different technique for microwave-biased photoconductivity studies performed at 22 GHz, and 2) several results showing differences in the behavior of microwave and dc-biased photoconductors.

Experimental Considerations

If optical radiation of the appropriate wavelength is incident on a photoconductive material, some of the photons will be absorbed. The free carriers that are generated change the sample's conductivity. If a microwave field is allowed to interact with such a material, the increased conductivity will cause an increase in the microwave absorption in the material, which can be detected as a change in transmitted microwave power and used to study the material's properties. The design of the experiment pursued three main objectives: 1) straightforward mathematical analysis of the microwave absorption as a function of sample conductivity, 2) uniform illumination of the sample, and 3) the ability to perform dc- and microwave-biased experiments with minimal change in the sample's environment.

The photoconductive crystal was placed against a microwave short in the sample arm of a reflection bridge. With the sample dark the bridge is balanced and the reference attenuator and short readings noted. When the light source is turned on the bridge is rebalanced and the attenuator and short readings, a function of the optical input to the sample, are recorded. In addition, the bridge is calibrated using a technique developed by Champlin *et al.* [9]. From these data, the complex reflection coefficient and subsequently the conductivity can be calculated very accurately using a computer search routine.

A special microwave elbow and sample holder were constructed. The microwave elbow consists of a stainless-steel block that contains a 90° waveguide bend with a small hole in the outside wall, as shown in Fig. 1. This hole runs through about $\frac{3}{4}$ in of metal, so it acts like a circular waveguide below cutoff. No microwave leakage has been detected from this hole, through which the optical input is coupled to microwave system. A quartz plate and neoprene O ring over the top of the hole provide a vacuum seal. The advantages of this design are that it allows efficient optical coupling to the guide, it introduces a minimum of disruption of the microwave fields, and it maintains a tight vacuum in the guide.

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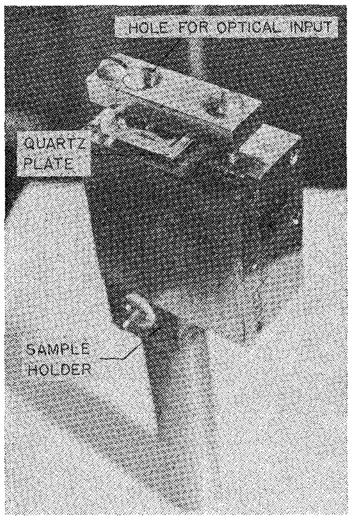

Fig. 1. Microwave elbow.

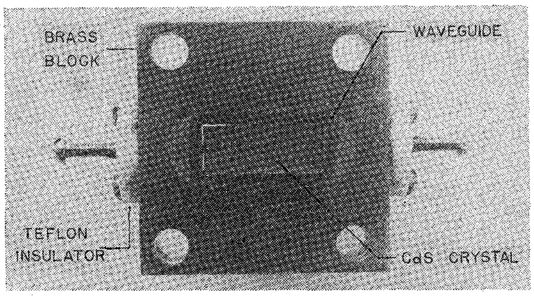

Fig. 2. Sample holder.

To be able to make a valid comparison of the dc and microwave results, a special sample holder was designed so that both dc and microwave measurements could be performed with a minimum of change in the sample's environment. As shown in Fig. 2, a piece of waveguide is embedded in a brass block. Brass screws in Teflon insulators pass through the sidewall of the guide and make pressure contact with indium electrodes deposited on the crystal ends. The crystal is cut to leave a 2-mil air space at the ends, so the electrodes do not short out on the guide. For microwave measurements the brass screws are replaced by Teflon ones, and the plug acts like a circular guide below cutoff.

A 0.875-in-square copper bar was machined to provide a microwave short and cold finger. When the elbow, sample holder, and short are assembled, 0.015-in indium wire is used between mating metal surfaces, and GE 7031 adhesive varnish is coated on the Teflon insulators. As a result, the whole assembly maintains a tight vacuum down to 77 K.

Due to the intrinsic low conductivity of the photoconductor, the microwave absorption is small and one has to work with very small signals. To overcome this difficulty, a superheterodyne microwave receiver is employed.

The sensitivity of this receiver is better than −94 dBm, and the response has been found to be linear. A 1-kHz square-wave modulated local oscillator (LO) delivers power to a balanced waveguide mixer containing Sylvania IN23CMR low-noise diodes. In this balanced mixer arrangement, LO AM noise is cancelled out.

The 60-MHz IF system provides a gain of 85 dB with a bandwidth of 600 kHz. The recovered audio signal, i.e., the 1-kHz square-wave modulation of the LO, is amplified by a PAR 113 low-noise preampli-

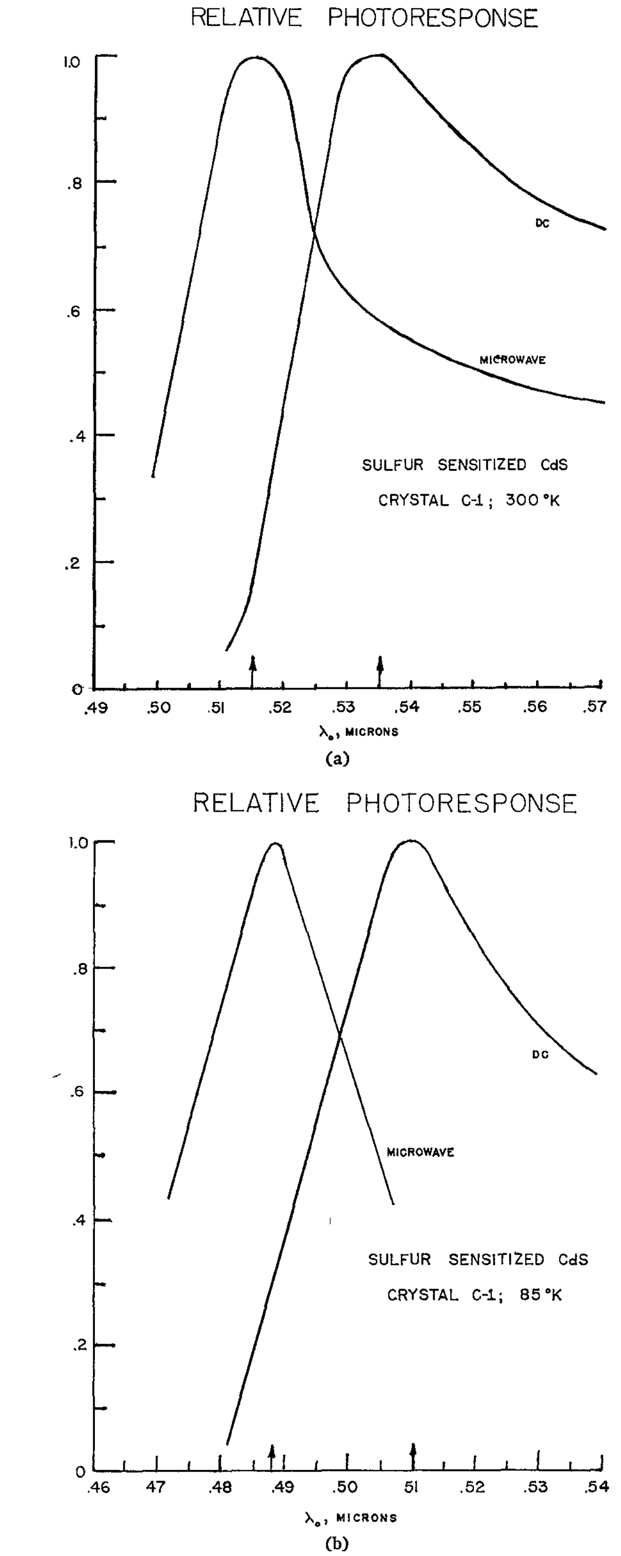

Fig. 3. (a) DC versus microwave response at 300 K for crystal C-1. (b) DC versus microwave response at 85 K for crystal C-1.

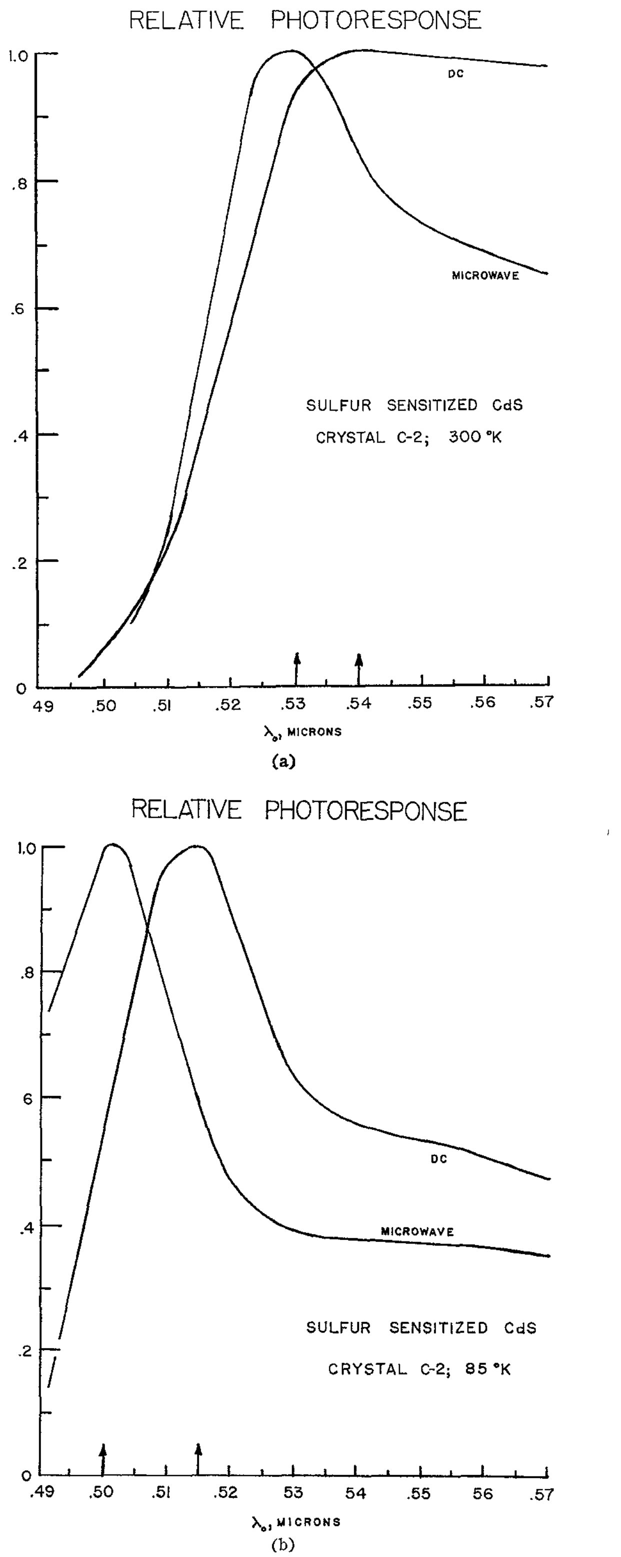

Fig. 4. (a) DC versus microwave response at 300 K for crystal C-2. (b) DC versus microwave response at 85 K for crystal C-2.

fier. The signal is then fed to a PAR 121 lock-in amplifier, and finally recorded by a Honeywell chart recorder.

The sensitivity of the receiver requires the use of an electronic micrometer for positioning the short to balance the bridge. A Tropel PZM electronic micrometer was substituted for the normal micrometer head on a microwave precision moving short. The resolution of the overall system is better than 5×10^{-3} deg in phase and 1×10^{-5} dB in attenuation.

Results

The dc and microwave photoconductive spectral response on two sulfur-sensitized CdS crystals was measured using the above-described apparatus. The $4.2\times4.3\times10.7$-mm CdS crystals obtained from the Clevite Corporation were shaped to fill a K-band rectangular waveguide for three-quarters of a microwave wavelength. Crystals 1 and 2 had a dark conductivity of 10^{-7} and 3×10^{-4} $(\Omega\cdot\text{cm})^{-1}$, respectively; their conductivity under green illumination was about two orders of magnitude higher. The optical signal was provided by a Bausch and Lomb 500-mm monochromator that was adjusted for a bandwidth of 60 Å. The photon flux density was monitored at the output of the monochromator to maintain a constant (i.e., independent from λ_0) light intensity. The photoconductive spectral measurements were performed at 85 and 300-K temperatures. The experimental results are shown in Figs. 3 and 4. We plotted the dc response (σ_{dc}) and microwave response ($\sigma_{\mu\text{wave}}$) in relative units with the peak of the response normalized to 1.

The results indicate that 1) the microwave response is sharper than its dc counterpart, and 2) the microwave peak response is shifted to shorter wavelengths compared to the dc peak by about 100–200 Å, depending on the crystal and the temperature. It may be noted that the change in the dc response with temperature is expected and reasonably well understood.

The measurements were reproducible over a long period of time (6 months) and were independent of the direction in which the optical wavelength was changed (i.e., from short to long wavelengths or vice versa). Corresponding dc and microwave measurements were always made at identical light intensities. The response spectra obtained for several different intensities of light and microwave fields (150–500 V/m) were found to be the same.

Discussion

The most probable cause for the observed shift of the photoconductive response peak is the inhomogeneity of the solid-state plasma.

The spectral distribution of photoconductivity for the dc case was first explained by DeVore [10], who solved the continuity equation for the spatial distribution of the electron density given below:

$$n(x, \lambda_0) = Ae^{-x/L_D} + Be^{x/L_D} + Ce^{-\alpha x} \qquad (1)$$

where

- L_D $=\sqrt{1/D\tau}$ = characteristic diffusion length;
- D diffusion constant;
- τ carrier lifetime;
- α $=\alpha(\lambda_0)$ = optical absorption coefficient, a function of the wavelength λ_0.

A, B, and C are constants determined by the parameters D, τ, α, and S, the surface recombination velocity. In the dc measurement the applied electric field is uniform across the crystal and the photoconductive response is proportional to the average of the electron density:

$$\text{dc photoconductive response } \alpha \frac{1}{l}\int_0^l n(x, \lambda_0)\, dx$$

where l is the length of the crystal. The dc measurement is insensitive to the local variations of the electron density.

The microwave bridge produces standing waves and the field is nonuniform across the crystal. The response will be related to the product of the inhomogeneous electron density and the inhomogeneous electric field. Mathematically, one has to substitute (1) into the wave equation, solve for the propagation constant, and subsequently for the reflection efficient. Initial results of our calculation, which will be published shortly, show excellent agreement with the experiment.

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Wave Propagation in Multilayered Drifted Solid-State Plasmas

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***Abstract*—The problem of the propagation of transverse magnetoplasma waves in drifted, stratified, media consisting of periodically distributed homogeneous slabs of solid-state plasmas is investigated. The action of the drifting carriers is to introduce an asymmetry into the propagation characteristics while the influence of the periodic structure introduces space harmonics. A detailed assessment of the possibility of a synchronous space-harmonic interaction for on-axis waves, which leads to wave amplification, has been performed. It is found that, contrary to the results of some prior work in the field, the gain that occurred could not be attributed directly to the periodic structure.**

I. Introduction

Over the last few years some considerable interest has developed in the propagation of electromagnetic waves in stratified media [1]–[4]. If the stratified medium is periodic and an electric field is applied to the system, there arises an attractive possibility of utilizing space harmonics to promote wave amplification (solid-state analog of the traveling-wave tube). The space harmonics provide the possibility of a synchronous interaction, in which gain occurs at low plasma velocities. A theoretical estimate, by Wisseman, of a single slab of plasma, supporting on-axis helicons under the influence of an electric and magnetic field [5], claims to reveal the possibility of helicon amplification due to the Fabry–Perot geometry. The purpose of this short paper is to determine, precisely, whether the presence of space harmonics arising from a drifted (presence of an external electric field) periodic structure will promote on-axis helicon amplification or not.

In this short paper, then, the type of electromagnetic wave transmission made possible by immersing the system in a uniform external magnetic field $\boldsymbol{B}_0$ that is parallel or has a component parallel to the direction of propagation [6], [7] is considered. The modes of propagation turn out to be circularly polarized magnetoplasma waves of which the now classical helicon is a special case. One of the special advantages of such a configuration is that the band edges are sensitive to the magnetic field.

II. Properties of the Layers

The propagation of an electromagnetic wave through an infinite periodic structure, along a direction that is parallel to a constant external magnetic field $(0, 0, B_0)$, is examined. This structure is made up of alternate homogeneous slabs of solid-state plasma of uniform thickness. The whole system is generated by repetition, along the direction of wave propagation, of a unit cell consisting of two such slabs of different thickness and containing different carrier densities. The whole system is immersed in a constant external electric field $\boldsymbol{E} = (0, 0, E)$.

If a layer contains α types of free carriers possessing a scalar mass m_α and a charge q_α, then the external electric field will impart drift velocities $\boldsymbol{V}_\alpha = (0, 0, V_\alpha)$ to them. The linearized equation of motion of the carriers then is

$$m_\alpha \left\{ \frac{\partial \boldsymbol{v}_\alpha}{\partial t} + V_\alpha \cdot \frac{\partial \boldsymbol{v}_\alpha}{\partial z} + \nu_\alpha \boldsymbol{v}_\alpha \right\} = q_\alpha (\boldsymbol{e} + \boldsymbol{V}_\alpha \times \boldsymbol{b} + \boldsymbol{v}_\alpha \times \boldsymbol{B}_0) \qquad (1)$$

where $\boldsymbol{v}_\alpha$ is the ac particle velocity, $\boldsymbol{V}_\alpha$ is the dc drift velocity, ν_α is a constant phenomenological collision frequency, and $\boldsymbol{e}$ and $\boldsymbol{b}$ are, respectively, the electric and magnetic fields associated with the passage of the electromagnetic wave.

Assuming the field variables in each inhomogeneous layer to possess a temporal variation of $e^{-i\omega t}$, Maxwell's equations become

$$\text{curl}\, \boldsymbol{e} = i\omega \boldsymbol{b} \qquad (2)$$

$$\text{curl}\, \boldsymbol{b} = \mu_0 \sum_\alpha n_\alpha q_\alpha \boldsymbol{v}_\alpha - i \frac{\omega}{c^2} \epsilon_L \boldsymbol{e} \qquad (3)$$

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