F is lowest. The TSEE intensity here is lower than the intensity of the x-rayed area that was not exposed to laser light, suggesting that light-stimulated release of trapped electrons exceeded retrapping during the duration of the laser pulse. This may be expressed by \( \beta n_e (N - n) = P F n_s \), where \( N \) is the density of the traps associated with the 120°C peak of Fig. 1, \( n \) is the density of trapped electrons, \( n_e \) is that of free electrons, and \( \beta \) is the retrapping coefficient. \( P \) is the absorption cross section for 1.06- \( \mu \)m photons. By absorbing a photon, electrons are released from the traps \( N \) and reach the conduction band.

At intermediate light fluxes (region II in Fig. 4), the TSEE intensity is much higher than the intensity of the original x-rayed area, indicating that additional electrons had been trapped during the laser pulse. Now we have \( \beta n_e (N - n) > P F n_s \), which is of course possible only if the generation of photocarriers from donors increases faster with \( F \) than the release of trapped carriers does. A nonlinear dependence of photocconductivity on the light flux is well known in other materials, e.g., ruby. \( ^5 \)

At the peak laser flux in the center (region III, Fig. 4), new processes occur. The concentration \( n_e \) of photocarriers becomes large enough, at laser power densities around the surface-damage threshold, that they are able to absorb large amounts of light energy, which is either quickly deposited to the lattice in the form of a "phonon shock wave" or which heats up the conduction electrons sufficiently to ionize filled traps by inelastic scattering. \( ^5 \) In any case, traps that were filled up to this time are now completely emptied. Our experiments indicate that the threshold laser flux required for the occurrence of the dark center spot is only a fraction (typically \( \frac{1}{2} \)) of the laser surface-damage threshold.

The appearance of a dark center spot in the TSEE image is, therefore, an indication that the peak laser power density is approaching the surface-damage threshold.

The experiments described above suggest that the TSEE-imaging technique be applied to nondestructive testing of optical surfaces with respect to their susceptibility to laser damage.

The contribution of R. Hall to the construction and operation of the apparatus and stimulating discussions with Dr. P. N. Keating are gratefully acknowledged.

\[ 1 \]
\[ 2 \]
\[ 3 \]
\[ 4 \]

Peak Voltage of the Pyroelectric Response to Short Infrared Laser Pulses

A. Shaulov* and M. Simhony

The Racah Institute of Physics, The Hebrew University, Jerusalem, Israel

(Received 16 September 1971)

The peak voltage of the response in a pyroelectric sample to IR signals much shorter than the thermal and electronic time constants of the sample is shown to be proportional to the energy absorbed per signal, and independent of load resistance and signal repetition frequency, as long as temperature is far enough from the Curie point. These results were checked experimentally in triglycine sulphate and strontium-barium niobate.

Consider a pyroelectric (PE) sample with thermal and electronic time constants \( \tau_T = C_T / G_T \) and \( \tau_e = R C_e \), \( C_T \) being the thermal capacitance of the sample, \( G_T \) is its thermal conductivity to ambient, \( R \) and \( C \) are the resistance and capacitance of sample and circuitry at preamplifier input. The sample temperature is far enough from the Curie point, so that all these values remain constant under small changes of temperature and voltage. Let a train of short IR signals of duration \( T_1 \ll \tau_T \), \( \tau_e \) and intervals \( T \gg T_1 \), be absorbed uniformly in the sample. If \( T \) does not exceed \( \tau_T \), the mean sample temperature \( T \) may be rising, but after a certain number of pulses a steady state is achieved in which \( T \) remains constant. Due to absorption of energy \( E_p \) per signal, at the beginning of each period the sample temperature will rise suddenly by \( E_p / C_e \) above the level at the ends of the periods. This will cause an abrupt rise of the PE voltage from its level at the ends of the periods by a peak value \( V_0 \).

\[ V_0 = E_p C_e / AC_e. \]  

Here \( \varepsilon = \lambda / \varepsilon_c \) is a material constant, \( \lambda = d\rho / dT \) being the PE coefficient, with \( P_c \) as the spontaneous polarizaton vector, \( \varepsilon \) is the permittivity, and \( c \) is the volume specific heat of the material. \( A \) is the electroded area, and \( C_e \) is the capacitance of the sample.

The PE responses have been studied at room temperature on six triglycine sulphate (TGS) and three strontium-barium niobate (SBN) samples, 10-40 mm thick, with major faces perpendicular to the polar axis. \( \lambda \) The IR source was a CO\(_2\) laser (wavelength 10.6 \( \mu \)m) with a power meter. Interchangeable load resistors \( R_L \) were connected parallel to the sample and to a simple FET source-follower circuit. \( \lambda \) \( R_L \) was always much smaller than the resistance of the sample (\( 10^8 \) \( \Omega \)), so that \( R = R_L \). The output voltages were led to a CRO.

The measured values of \( V_0 \) were proportional to \( E_p / A \) in all samples in a wide energy range starting from \( 10^{-11} \) J/cm\(^2\) per pulse, with signal widths of 1 \( \mu \)sec to 4 msec. For low \( f \) and single pulses the linearity could be

PEAK VOLTAGE OF PYROELECTRIC RESPONSE

FIG. 1. Oscillograms of PE voltage response in a TGS sample (A=3.2 mm²) at different signal repetition frequencies.

observed up to 10⁻³ J/cm². In order not to raise T by more than a safe 10 °C above ambient, with f = 300 Hz the range was limited to 10⁻⁴ J/cm² per pulse, and with f = 7.2 kHz to 4 × 10⁻⁶ J/cm² (in TGS; in SBN the energies could be increased by a factor of 2). Values of V₀, calculated from Eq. (1) using ξ = 4600 cm²/C for TGS and 630 cm²/C for SBN and neglecting any temperature

FIG. 2. Oscillograms of PE voltage response to Q-switched laser signals in a TGS sample with different load resistors.

or frequency dependence of the material and sample parameters, were in agreement with the measured values within a factor of 2.

That V₀ remains constant under an almost four-order-of-magnitude change in f is shown by the oscillograms of Fig. 1. Here a TGS sample (F-8) with Rₐ = 10⁹ absorbs from each 100-μsec-wide ir signal an energy of 6 × 10⁻⁷ J. The peak voltage is ~65 mV with 1, 10 as well as with 590 signal/sec. (Note that the conditions T₁ << τₚ and T₁ << T hold.)

The dependence of V₀ on Rₐ is illustrated in Fig. 2. Sample F-8 absorbs here 10⁻⁷ J from each 1-μsec-wide Q-switched laser pulse, while f = 7.2 kHz. V₀ is seen to be ~12 mV for Rₐ = 10⁻⁹ Ω as well as 10⁻⁶ Ω (the same V₀ is obtained even with 10¹¹ Ω). With 10⁻⁶ Ω, V₀ is only slightly decreased (9 mV). However, Rₐ = 10⁹ makes τₚ = 3.2 μsec, which is close to T₁; the short-signal condition does not hold, and V₀ is now smaller by a factor of 7 (and will continue to decrease proportionally to decreasing Rₐ).

Considering the peak-to-peak voltage Vₚₚ one should take into account that in the single-signal or low-f case, if Rₐ makes τₚ approach τₚ, the PE response has a shape as shown in Fig. 3. When τₚ = τₚ the undershoot of the response reaches a maximum which is e⁻²V₀ ~ 0.14 V₀. Thus, except for the low-f case, when an increase in Rₐ may cause an up to 14% increase in Vₚₚ, Vₚₚ = V₀ and does not depend on Rₐ, as long as the short-signal condition holds.

The authors thank Professor A. Many for pointing out that the peak voltage should be independent of load resistance and A. Rosenthal for help in measurements.

---


