TABLE I. Definition of the piezo-optical constants.

| Strain tensor | Type of strain | Stress axis $z'$ | $\Delta\epsilon_2$ with respect to $x', y', z'$ | Components $\Delta\epsilon_2$ and $\Delta R/R$ |
|---|---|---|---|---|
| $\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}e/3$ | Hydrostatic | None | $\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}\Delta\epsilon_2$ | $\Delta\epsilon_2=\frac{1}{3}(W_{11}+2W_{12})e$ <br> $\Delta R/R=\frac{1}{3}(Q_{11}+2Q_{12})e$ |
| $\begin{pmatrix}0&1&1\\1&0&1\\1&1&0\end{pmatrix}e_{yz}$ | Trigonal | [111] | $\begin{pmatrix}\Delta\epsilon_2^{\perp}&0&0\\0&\Delta\epsilon_2^{\perp}&0\\0&0&\Delta\epsilon_2^{\parallel}\end{pmatrix}$ | $\Delta\epsilon_2^{\parallel}=-2\Delta\epsilon_2^{\perp}=4W_{44}e_{yz}$ <br> $\Delta R/R^{\parallel}=-2\Delta R/R^{\perp}=4Q_{44}e_{yz}$ |
| $\begin{pmatrix}-\frac{1}{2}&0&0\\0&-\frac{1}{2}&0\\0&0&1\end{pmatrix}e_{zz}$ | Tetragonal | [001] | $\begin{pmatrix}\Delta\epsilon_2^{\perp}&0&0\\0&\Delta\epsilon_2^{\perp}&0\\0&0&\Delta\epsilon_2^{\parallel}\end{pmatrix}$ | $\Delta\epsilon_2^{\parallel}=-2\Delta\epsilon_2^{\perp}=(W_{11}-W_{12})e_{zz}$ <br> $\Delta R/R^{\parallel}=-2\Delta R/R^{\perp}=(Q_{11}-Q_{12})e_{zz}$ |

the strain-induced change of $\epsilon$ at the surface. This condition was always fulfilled in our measurements. The second contribution will be neglected here.

The phase-sensitive detector was locked to the fundamental frequency of the vibration. Thus, only changes of the reflectance proportional to odd powers of strain were detected. Tuning to twice the frequency which should pick up mostly the quadratic effect produced a signal barely above the noise. Thus, only changes linear in the strain components were detected in our measurements.

## EXPERIMENTAL RESULTS

### Symmetry Relations

The optical properties of a solid are determined by the complex second-rank dielectric tensor $\boldsymbol{\varepsilon}$, which reduces to the unit tensor times the complex dielectric constant for cubic crystals, i.e., cubic crystals are optically isotropic. A general strain applied to these crystals destroys the isotropy. Restricting the discussion to changes linear in the strain components, we may write

$$\Delta\epsilon_{ij}=W_{ijmn}e_{mn}. \tag{3}$$

Cu has the point symmetry $O_h$. In this case, Eq. (3) parallels the stress-strain relation ($\Delta\boldsymbol{\varepsilon}$ replaces the stress tensor, $\mathbf{W}$ the stiffness tensor), i.e., the fourth-rank piezo-optical tensor $\mathbf{W}$ has three independent complex elements.[8,9,11] We adopt the matrix notation used for the stress-strain relation (see, e.g., Ref. 24). Table I shows the resulting relations for $\boldsymbol{\varepsilon}_2$, the imaginary part of the dielectric tensor. ($W_{44}$ defined in Ref. 11 is four times that of Table I. Using the corresponding definition of the stiffness constant[24] might help to avoid confusion, which frequently arose at that point in the past.) Selecting special geometries, namely the stress axis, the normal to the reflecting plane, and the polarization of the light parallel to the principal axes of $\Delta\boldsymbol{\varepsilon}$ leads to[8,9,11]

$$\Delta R=(\partial R/\partial\epsilon_1)\Delta\epsilon_1+(\partial R/\partial\epsilon_2)\Delta\epsilon_2, \tag{4}$$

where $\Delta\epsilon_1$ and $\Delta\epsilon_2$ are the appropriate eigenvalues of $\Delta\boldsymbol{\varepsilon}_1$ and $\Delta\boldsymbol{\varepsilon}_2$. Thus we can define quantities $Q_{ij}$ (similar to $W_{ij}$) that describe the relative change of the reflectance. The definition of $Q_{ij}$ is also given in Table I.

### Measurements and Piezo-Optical Constants

Figure 6 contains the measurements of the relative change of the reflectance per strain along the stress axis for three different samples, the stress axes being parallel to [001], [111], and [110], respectively. The surface of the samples was the (1$\bar{1}$0) plane in all cases. For each stress direction, the reflectance for light polarized parallel and perpendicular to the stress axis is given. The independent information contained in

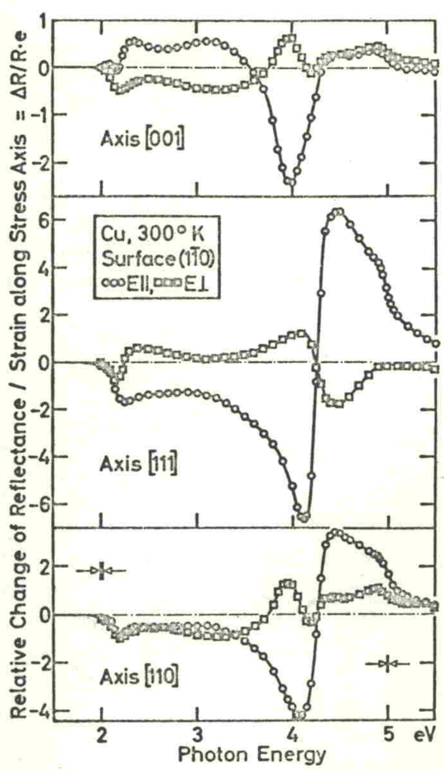


FIG. 6. The relative change of the reflectance per unit strain along the stress axis at room temperature for Cu crystals with the stress axes [001], [111], and [110], and with the reflecting surface (1$\bar{1}$0). The curves are given for light, plane polarized parallel and perpendicular to the stress axes.

[24] C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons, Inc., New York, 1956), 2nd ed., pp. 87, 89, and 91.