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Large plasma-edge broadened magneto-optic-polar-Kerr-effect-based broadband incoherent detection of terahertz spectral frequencies

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A magneto-optic Kerr effect (MOKE)-based spectroscopic technique is proposed in the terahertz regime. This method relies on very large reflection edge splitting effects, which occur when the cyclotron frequency (CF) is of the same order of magnitude or greater than the plasma frequency. In the event of a very large reflection edge split, the Kerr rotation (KR) no longer occurs at the plasma edge, but instead occurs at $\mathrm{Re}(\varepsilon_+\varepsilon_-)\approx 1$, within the macroscopic framework of the Drude model. This implies that one can control the spectral occurrence of the MOKE resonance, simply by tuning the magnetic field strength. This phenomenon is unheard of for much shorter wavelengths, due to practical limitations on required magnetic field strengths and hence, can only be realized in the THz regime. A 3 T magnet can easily cover the proposed 0.5–5 THz spectral range for an InSb substrate. Our calculations show that in order to achieve good spectral resolution, the InSb substrate needs to be cooled to 77 K. The Kerr rotation obtained at 77 K for a CF of 1 THz is about 6.28°, which can be increased to about 18.35° by coating a thin low refractive index material on the InSb substrate. A well established ellipsometric technique, which uses four incoherent detectors, is proposed, for fast-simultaneous measurement of KR, Kerr ellipticity and reflectivity. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1865345]

Generation, detection, and applications based on the terahertz (THz) part of the electromagnetic spectrum have experienced unprecedented growth in recent years. Among various applications, high resolution THz spectroscopy is a prime investigative tool in areas such as molecular astronomy, chemical spectroscopy, bio-photonics and solid-state device physics.

Roughly, THz spectral detection techniques can be classified into ones based on time-gated antennas,[1] time-gated electro-optic methods[2,3] which employ a Fourier transform technique and incoherent detection techniques, such as dual source interferometer.[4,5] Incoherent bolometric or photoconductive detection mechanisms also have the advantage of being relatively less noisy than electro-optic methods which use a sampling detector.

In this letter we propose an incoherent InSb based reflection-type THz spectral detection technique based on the magneto-optic polar Kerr effect (MOKE). It is analytically shown that a spectrometer built on principles proposed here would have broadband characteristics, ranging from 0.5 to 5 THz, and high temperature tunable resolution. Furthermore, the incident radiation need not be phase coherent either.

MOKE spectroscopy has been used for some time to determine various optical and physical constants.[6] In the THz regime, recently, a reflection-type MOKE based THz polarization technique was used by Shimano *et al.* to measure the diagonal and off-diagonal dielectric-tensor elements.[7] A temperature dependent magneto-optic THz spectrometer based on quantum cascade lasers was more recently proposed by Larrabee *et al.*[8] Cyclotron resonance experiments are typically used to determine effective electron mass and are not particularly useful for spectroscopic measurements due to relatively low spectral resolution.

Here, we propose a conceptually different magneto-optic (MO) spectroscopic technique, realizable only in the THz regime, that exploits large reflection-edge (or plasma-edge) splitting effects caused when the cyclotron resonance frequency (CF) is much larger than the plasma frequency (PF), in the polar Kerr configuration. For much higher optical frequencies the spectral occurrence of MOKE depends on material parameters and not on the strength of the magnetic field. However, we show that this is no longer the case at THz frequencies. Our analytical approach is based on recognizing the key fact that macroscopically, the $\mathrm{Re}(\varepsilon_+\varepsilon_-)\approx 1$[9] resonance condition and not the Fiel and Hass $\mathrm{Re}(\varepsilon_{xx})\approx 1$[10] condition can be used for a qualitative unified description of the Kerr rotation spectra, irrespective of the relative strength of the cyclotron resonance. Practical restrictions on high magnetic fields required for maintaining large CF to PF ratios makes such a technique realizable only in the THz part of the electromagnetic spectrum.

Large signal amplitude and spectral resolution are key features to any spectroscopic technique. The signal intensity depends on the strength of the MOKE signal and hence the magnitude of the spin-orbit split, whereas the spectral resolution depends on the electron mobility. These requirements make InSb an ideal candidate for such a MOKE-based spectral detection technique.

For polar semiconductor materials such as InSb, the dielectric tensor is symmetric about the optic axis in the absence of a magnetic field and hence can be treated as a scalar. In case of the polar Kerr effect, the application of a magnetic field in the z direction breaks the time reversal symmetry in the dielectric tensor. The tensor elements can then be expressed in terms of its dispersive and absorptive components. The real component of the diagonal tensor elements represents the ordinary optical absorption and the imaginary com-

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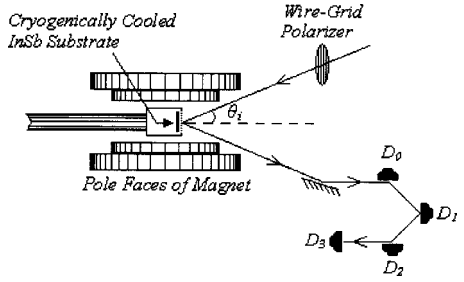

FIG. 1. Proposed THz MOKE-spectroscopic setup using four noncoherent linear detectors.

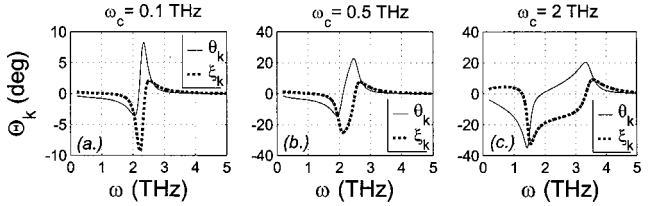

FIG. 2. Room temperature (300 K) plasma-edge broadening effects due to increasing magnetic field shown in Kerr rotation and Kerr ellipticity spectra at (a) ω_c=0.1 THz, (b) ω_c=0.5 THz, and (c) ω_c=2 THz.

ponent of the off-diagonal elements represents the MO absorption, which is proportional to the difference in absorption between left and right circularly polarized light. Therefore the eigenvalues of the dielectric function tensor can be expressed in terms of the complex index of refraction as $\tilde{n}_{\pm}^2=\varepsilon_{xx}\pm i\varepsilon_{xy}=\varepsilon_{\pm}$. The "+" and "−" signs, respectively, represent right circularly polarized and left circularly polarized modes of wave propagation. Since the magnetization is perpendicular to the surface and parallel to the direction of light propagation, the Kerr rotation (KR) can be expressed as the phase difference between the two circularly polarized eigen modes,[11] $\theta_k=-(\Delta_+-\Delta_-)/2$, The phase, $\Delta_{\pm}$, is related to the complex Fresnel's reflection coefficients, $r_{\pm}$, via $e^{i\Delta_{\pm}}=r_{\pm}/|r_{\pm}|$. For a semi-infinite substrate $r_{\pm}=(1-\tilde{n}_{\pm})/(1+\tilde{n}_{\pm})$.

Nonzero components of the dielectric tensor can be described using the free particle Drude model, where random thermal motion of the free carriers is altered into cyclotron orbits in a plane perpendicular to the applied magnetic field. Thus, the application of a magnetic field also splits the plasma reflection edge into two, the spectral separation between which increases linearly[11,12] with increasing magnetic field. In a polar semiconductor material such as InSb, the MO effects would be altered when lattice vibrational modes are added. The changes are largest in the vicinity of the optical phonon frequencies. The dielectric tensor in the polar-Kerr configuration is given by

$$\varepsilon_{\pm}=\varepsilon_{\infty}\left(1-\frac{\omega_p^2}{\omega(\omega\pm\omega_c-i\gamma)}+\frac{\omega_L^2-\omega_T^2}{(\omega_T^2-\omega^2+i\Gamma\omega)}\right), \qquad (1)$$

where, $\omega_p=(4\pi Ne^2/m_{\text{eff}}\varepsilon_0)^{1/2}$ is the plasma frequency, $\omega_c=He/m_{\text{eff}}c$ is the cyclotron frequency; ε_{∞} is the background dielectric constant, ω_L is the longitudinal phonon frequency, ω_T is the transverse phonon frequency, Γ is the phonon damping constant, H is the magnetic field, c is the speed of light, e is the charge of an electron, m_{eff} is the effective mass, N is the charge concentration, $\gamma=1/\tau$ is the optical damping constant, and τ is the carrier relaxation time. The carrier relaxation time is related to the electron mobility, μ, via $\tau=\mu\cdot m_{\text{eff}}/e$.

It is widely accepted that, macroscopically, MOKE occurs at the plasma edge or in the vicinity of $\text{Re}(\varepsilon_{xx})=1$.[10] However, in Ref. 9, we have shown that this is not so in the event of a large reflection edge split (which occurs when CF and PF have similar orders of magnitude). Instead a more general condition is proposed where a pronounced enhancement in the MOKE spectrum is expected in regions where $\text{Re}(\varepsilon_+\varepsilon_-)\approx 1$, and not necessarily in the vicinity of plasma resonance of free charge carriers. (It must also be emphasized that the commonly used approximate expression for the complex Kerr effect, $\theta_k-i\xi_k=\varepsilon_{xy}/[(1-\varepsilon_{xx})\sqrt{\varepsilon_{xx}}]$, cannot be used to calculate the MOKE spectra if the reflection edge splitting effect is large.)

In Ref. 12 we derived the following expression for the CF satisfies the "$\text{Re}(\varepsilon_+\varepsilon_-)\approx 1$" resonance condition for any given optical frequency and other material parameters:

$$\omega_c=\left(\frac{\omega_p^4}{\omega^2(2\zeta-\varepsilon_{\infty}^{-2}-1)}-\frac{2\omega_p^2(1+\zeta)}{2\zeta-\varepsilon_{\infty}^{-2}-1}+\omega^2\right)^{1/2}, \qquad (2)$$

where

$$\zeta=\frac{(\omega_L^2-\omega_T^2)(\omega_T^2-\omega^2)}{(\omega_T^2-\omega^2)^2+\Gamma^2\omega^2}.$$

Equation (2) forms the basis of our magneto-optic spectroscopic technique. Notice that when $\omega_p \ll \omega$ (or if $\omega_p \ll \omega_c$[9,12]), then

$$\omega_c \approx \omega. \qquad (3)$$

This implies that large Kerr rotation effect will be observed when the incident optical frequency matches the cyclotron resonance frequency. Practically, to determine the wavelength of an unknown incident THz beam one would have to merely sweep the strength of the magnetic field and note the field strength that induces the maximum Kerr rotation.

The PF≪CF condition can be implemented by dropping the sample temperatures down and thereby reducing the number of free charge carriers. This also increases the mobility, which increases the spectral resolution and also aids in enhancing the Kerr rotation.

The temperature dependent carrier concentrations were calculated using $N=\Delta N/2+\sqrt{\Delta N^2+N_i^2}$ cm^{-3} where, ΔN is the difference in extrinsic donor and acceptor carrier concentration in cm^{-3}. For our calculations we have used $\Delta N=10^{14}$ cm^{-3}. N_i is the intrinic carrier concentration given by $N_i=\sqrt{N_C N_V}\exp(-E_g/2K_BT)$ cm^{-3}, where, K_B is the Boltzmann constant, T is the temperature, E_g is the band gap energy, N_V and N_C are valence band and conduction band electron concentrations, respectively. For InSb we have used $N_C=8\times 10^{12}T^{3/2}$ cm^{-3} and $N_V=1.4\times 10^{15}T^{3/2}$ cm^{-3}.[13] These values yield an intrinsic carrier concentration of $\sim 2\times 10^{16}$ at 300 K.

The temperature dependent electron mobility for InSb was calculated using the empirical formula $\mu=7.7\times 10^4(T/300)^{-3/2}$ $\text{cm}^2/V\,s$[13] and the temperature dependent effective mass can be determined using Kane's formula

$$\frac{1}{m_{\text{eff}}}=\frac{1}{m}+\frac{2P^2}{3\hbar^2}\left(\frac{2}{E_g}+\frac{1}{E_g+\Delta}\right), \qquad (4)$$

where, m is the free electron mass. The momentum matrix element, P^2, and the spin orbit splitting energy Δ are taken to

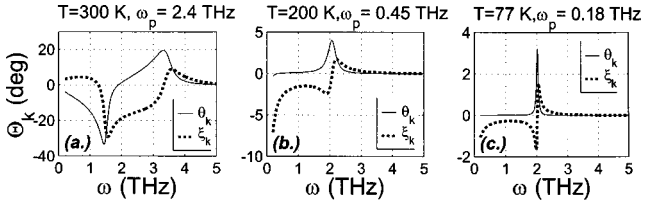

FIG. 3. Further plasma-edge broadening due to lowering of temperatures shown in Kerr rotation and Kerr ellipticity spectra at (a) $T=300$ K, (b) $T=200$ K, (c) $T=77$ K at $\omega_c=2$ THz. Note the sharp positive-edge MOKE resonance at $T=77$ K.

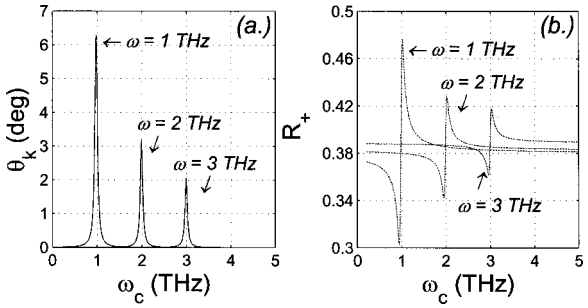

FIG. 4. (a) Kerr rotation, (b) reflectivity shown as a function of ω_c (proportional to magnetic field) for $\omega=1$, 2, and 3 THz at $T=77$ K.

be temperature independent. Their chosen respective values are 20 and 1 eV for InSb. The above calculations require the temperature dependent band gap energy, which for InSb is given by $E_g=0.24-(6\times10^{-4}\ T^2)/(500+T)$ eV.

The proposed spectroscopic technique has the configuration of any standard Kerr rotation measurement experiment as shown in Fig. 1. The incoming unknown, incoherent THz radiation is incident on a wire-grid polarizer, which is then incident on the InSb substrate placed in a polar configuration between pole faces of the magnet. The easiest and quickest way to simultaneously detect the Kerr rotation and ellipticity is to use a four detector polarimetric technique proposed by Azzam.[14] The four required detectors should be linear and could either be bolometers or photoconductive devices. Four proportional electric signals that depend on the incident light intensity and the 4×4 instrument matrix[14] are produced. This enables one to simultaneously measure all four components of Stokes vector (which is the most complete description of polarized light). Apart from being fast and extremely accurate in making polarimetric measurements, this method eliminates the need for additional analyzer optics such as polarizers, quarter-wave retarders, electro-optic modulators (the technology for which is currently not fully mature in the THz regime). However, this method does require the incident radiation to be collimated; in order to reduce measurement errors, this can be achieved for a broad range of frequencies using parabolic reflectors.

We next numerically demonstrate the principle of operation of the proposed magneto-optic spectroscopic technique for a realistic set of parameters. First, in Fig. 2, resonance-broadening effects, at room temperature (300 K) are shown, as the magnetic field strength or CF is increased. Note that the difference between the positive and negative rotation peaks in Fig. 2(c), is approximately equal to the CF; also the magnitude of the KR increases as the field strength is increased. In Fig. 3 we see that as the temperature is decreased the resonance edge split gets broader and sharper. The broadening effect is due to the decrease in PF, which, via N, has a direct dependence on temperature. The increase in sharpness of the MOKE spectra is attributed to the free carrier electron mobility, which has an inverse dependence on temperature, and hence the optical damping constant term is decreased. This effect is crucial, since it dictates the spectral resolution of this spectrometer. Notice that at 77 K, in Fig. 3(c), a sharp Kerr-rotation peak occurs exactly at the cyclotron resonance frequency, as predicted by Eq. (3). This feature is further highlighted in Figs. 4(a) and 4(b), where a one-to-one correspondence is shown between resonances in the KR and reflectivity CF spectra and incoming THz radiation. The maximum KR at 1 THz was $\sim$6.28°. Our calculations show that these resonances are observable and can be exploited up until the vicinity of phonon frequencies ($\sim$5 THz for InSb). Note that by coating a thin low refractive index film on the MO media,[15] the Kerr rotation can be further enhanced. This is achieved by reducing the polarization component of the directly reflected light without influencing the component induced by the KR. At 1 THz it is seen that the KR increases from 6.28° to 18.35° by coating the InSb substrate with a thin film of refractive index =1.5 and film thickness of $\lambda/2$. However, this is accompanied by a proportional decrease in the reflectivity (from 0.303 to 0.048 at 1 THz).

In summary, based on macroscopic effects, we have analytically and numerically demonstrated the principle for a type of a MO THz spectroscopic technique. This method requires that the incoming optical frequency be of the same order of magnitude as the CF (hence realizable only in the THz regime) and that the CF be much greater than the PF. When the above two conditions are simultaneously fulfilled, a one-to-one correspondence can be established between the cyclotron resonance frequency and the MOKE THz spectra, which we propose to exploit for THz spectroscopy. Furthermore, sharp MOKE resonances at low temperatures can provide good spectral resolution. Apart from THz spectroscopy, experimental verification of this phenomenon could have other important technological implications.

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