Enhanced coherent terahertz emission from indium arsenide in the presence of a magnetic field

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We demonstrate enhancement of terahertz (THz) emission from indium arsenide at 170 K in magnetic fields (B) up to 8 T. An order of magnitude increase in visible to terahertz conversion efficiency was observed, with no suggestion of saturation of the TE polarization at higher magnetic fields. Free-space electro-optic sampling measurements confirmed the coherent nature of this radiation over the field range investigated, and gave an insight into the carrier motion subsequent to photoexcitation, which may be responsible for the observed THz power enhancement. © *2000 American Institute of Physics.* [S0003-6951(00)03115-6]

There is currently a great deal of interest in the production of bright, coherent terahertz ($\mathrm{THz} = 10^{12}$ Hz) sources to span the so-called ''terahertz gap'' in the electromagnetic spectrum from 100 GHz to 10 THz. To date, there are no compact solid-state sources of coherent THz radiation within this frequency range, although recent advances in ultrafast pulsed lasers operating in the near infrared and visible have allowed coherent, broadband THz pulses to be produced from semiconductors. There are three widely used methods for generating coherent THz from semiconductors irradiated by such ultrafast pulses: optical rectification,[1] surface-field photocurrent,[2] and lateral photocurrent in antennas.[3] This letter reports magnetic-field enhancement of coherent THz emission due to the surface-field photocurrent effect, which does not saturate with magnetic field. Such enhancement of the visible to THz conversion efficiency is extremely beneficial for potential applications of THz radiation such as imaging.[4] Furthermore, recent studies[5–7] have demonstrated that increased THz powers may be achieved at low magnetic fields, $B = 1.7$ T. In the present letter, we demonstrate different enhancement behavior due to the application of a magnetic field. We show that the conversion efficiency continues to rise with an increasing magnetic field up to $B = 8$ T. In particular, saturation of the enhancement was not observed at these high magnetic fields, suggesting further increases in emission could be obtained with increased magnetic fields. We further demonstrate that the majority of the radiation produced was coherent and, hence, potentially useful in a variety of applications. A mechanism for the enhancement is suggested by the polarization behavior of the THz electric field upon reversal of the magnetic field.

The experimental setup used to generate and detect the coherent THz in a high magnetic field is shown in Fig. 1. A mode-locked Ti:sapphire laser produced 100 fs pulses at a wavelength of 790 nm and a repetition rate of 82 MHz,

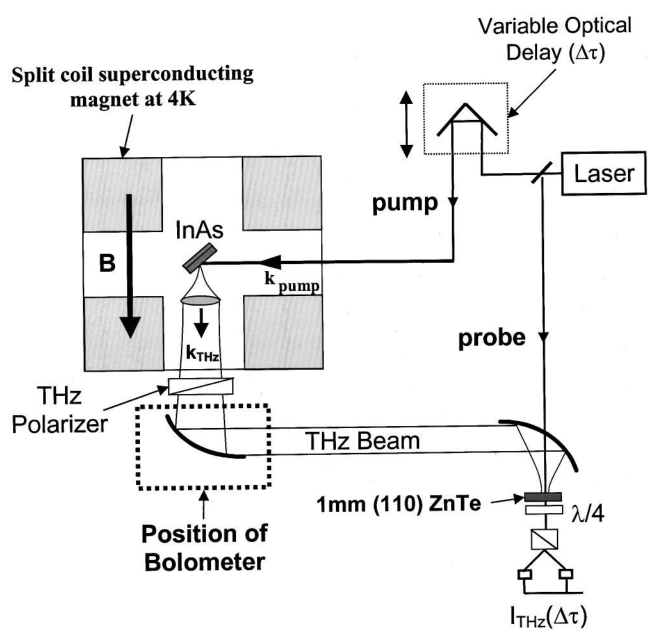

FIG. 1. Experimental arrangement for magnetic-field (B) measurements showing both bolometer and electro-optic sampling techniques. Wave vectors of the visible pump (k_{pump}) and generated THz (k_{THz}) beams are shown, along with the magnetic-field direction relative to the InAs(100) sample. In electro-optic sampling the THz electric field $E_{\mathrm{THz}} \propto (I_1 - I_2)$, where I_1 and I_2 are the currents measured on a balanced diode arrangement.

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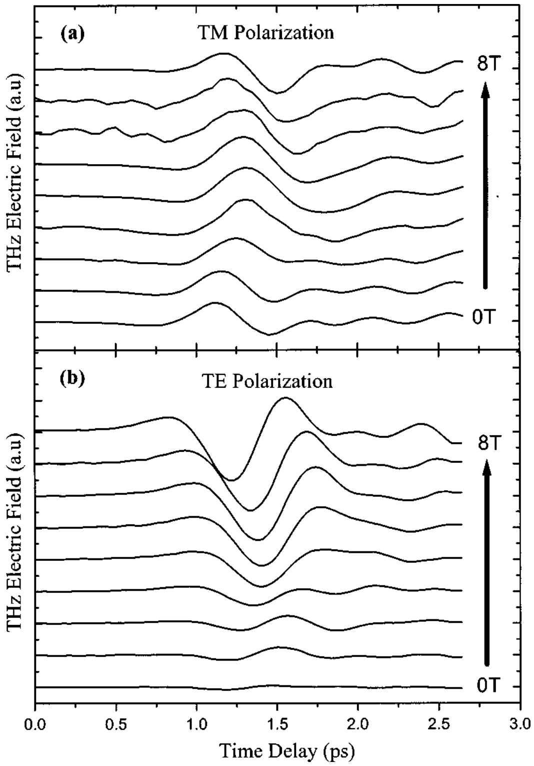

FIG. 2. THz electric fields E_{THz} measured using electro-optic sampling as a function of delay time for both (a) TM and (b) TE THz polarizations at magnetic fields B between 0 and 8 T, shown with increments of $B=1$ T. The traces have been offset for clarity.

yielding 0.8 W average power and pulse energies in the nJ range. The beam was split into a pump and probe beam with an average pump power of 140 mW at the entrance to the cryostat window. This beam was focused to a diameter of approximately 1 mm, giving an optical intensity at the sample surface of $14.3\ W/cm^2$(pulse fluence$=176\ nJ/cm^2$). The sample was a nominally undoped, bulk (100) InAs wafer with a residual n-type carrier concentration of $3.0\times 10^{16}\ cm^{-3}$. It was placed in the cryostat with optical access through a split coil magnet capable of achieving fields from $B=-8$ T to $B=8$ T. The normal to the sample surface was at 45° both to the applied magnetic field and also the wave vector k_{pump} of the incident pump beam. Thus, in this reflection geometry, the magnetic field was orthogonal to k_{pump} but parallel to the wave vector of the generated THz radiation k_{THz}, as shown in Fig. 1. The sample temperature was maintained at 170 K.

Two methods were employed for the detection of this emitted THz radiation. First, free-space electro-optic sampling (EOS) allowed the coherent portion of the emitted THz radiation to be measured. This detection method relied on the ac Pockels effect within a 1-mm-thick (110) ZnTe crystal,[8] allowing the THz electric field to be measured directly in the time domain. The THz power spectrum was obtained by Fourier transforming the time-domain data, with the THz bandwidth extending from 0.5 to 2.7 THz, as determined by EOS. This bandwidth is in part constrained by the thickness of the detector crystal,[9] and prevented highly accurate measurement of enhancement at frequencies outside this range.

The second method of detection used a calibrated silicon composite bolometer, which was placed immediately after

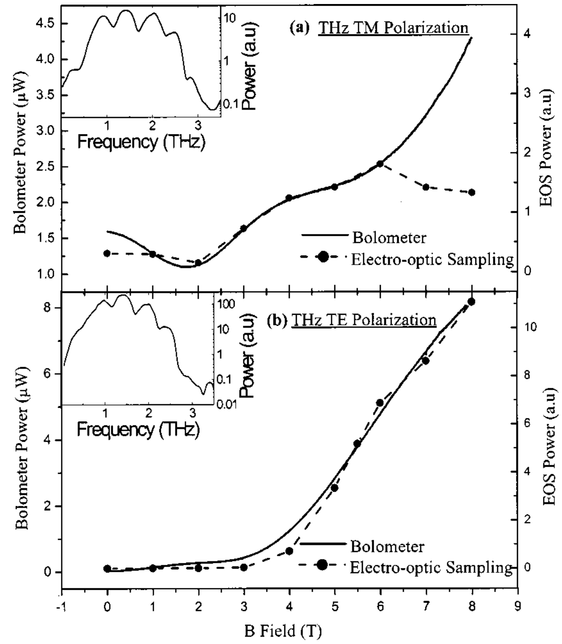

FIG. 3. Comparison of absolute powers measured by the bolometer and numerically calculated from EOS frequency-domain spectra for both the (a) TM and (b) TE polarizations. The insets show typical power spectra at $B=8$ T.

the cryostat, allowing efficient collection of the emitted THz radiation. The bolometer measured both coherent and incoherent contributions to the THz power. In both detection schemes, a polarizer allowed selection of either the transverse electric (TE) or transverse magnetic (TM) THz polarization with a 10% transmission loss. Losses by other elements in the THz beam path were determined using a far-infrared Fourier transform spectrometer and contributed 50% loss at a frequency of 1 THz. In addition, 19% of the visible pump beam was also attenuated by the cryostat windows (Spectrosil B), before incidence on the sample. A total scaling factor of 2.75 on was used to correct the measured THz power.

For the surface-field photocurrent effect, THz radiation is generated when the electron–hole pairs, created by the visible pump beam, are accelerated by the surface electric field ($\mathbf{E}_{surf}$). The resulting transient photocurrent j, proportional to charge acceleration, radiates at THz frequencies,[2] with the THz electric field $\mathbf{E}_{THz}\propto\partial\mathbf{j}/\partial\mathbf{t}\propto\mathbf{E}_{surf}$. For the surface-field photocurrent effect alone, the polarization of E_{THz} is transverse magnetic due to the dipole nature of the radiation arising from the induced surface photocurrent $\mathbf{j}$, which was parallel to the surface normal for the experimental arrangement utilized. Application of a magnetic field results in a Lorentz force acting on the photoexcited carriers, therefore giving $\partial\mathbf{j}/\partial\mathbf{t}\propto(\mathbf{E}_{surf}+\boldsymbol{v}\times\boldsymbol{B})$; within this simple model, a nonzero TE component is expected to arise in the presence of a nonzero magnetic field, given the geometry in Fig. 1.

EOS measurements demonstrated that the coherent emission at $B=0$ T was indeed highly TM polarized (with electric fields $E_{TM}/E_{TE}>500$, limited by the extinction of the Fourier infrared (FIR) polarizers). Using the FIR polarizer, the TE and TM components of the coherent THz emission were characterized independently as a function of magnetic field (Fig. 2). On the application of a magnetic field a TE

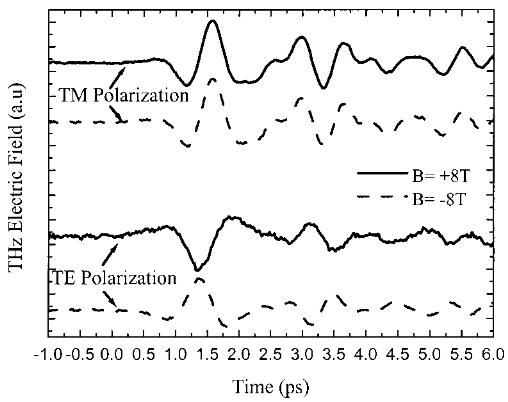

FIG. 4. EOS THz electric field E_{Thz} for TM and TE polarizations with the magnetic field at $B=+8$ T and $B=-8$ T, traces offset for clarity. Note the 180° phase change evident in the TE polarization for reverse-field directions, while the phase is maintained for both positive and negative magnetic fields in the TM polarization.

component was observed, consistent with the simple Lorentz model. As shown, the emission was enhanced and remained coherent for both polarizations.

The relative amount of coherent power was determined from the area under the frequency-domain power spectra between 0.5 and 2.7 THz. Calculating this power for both polarization components allowed a direct comparison with the magnetic-field dependence of the bolometer measurements (Fig. 3). The bolometer measurements show no sign of saturation with increasing field for either polarization. The summation of both polarizations gave a total THz power of 12 μW at $B=8$ T, once the losses in both the cryostat and polarizers were taken into account. As observed in both techniques, the enhancement in the TE polarization rapidly increased above $B=3$ T, with the TM polarization showing a minimum in the emission around $B=2$ T before increasing. The dependence of THz power on the magnetic field was very similar for the EOS and bolometer power measurements, suggesting that a majority of the field-enhanced emission was coherent. However, there was a decrease in EOS intensity in the TM-polarized THz at $B>6$ T, which was not present in the bolometer measurement. This may have been due to the detection bandwidth limitation of the ZnTe crystal; any higher-frequency components generated could only be observed with the bolometer, due to its larger bandwidth (100 GHz–20 THz). Roll off in the THz was not observed in the TE polarization, suggesting that the enhancement for this polarization over the field range was within the bandwidth of the ZnTe. Therefore, these data imply that a further increase in B would yield an even larger enhancement of the coherently generated THz power. The minimum around $B=2$ T for the TM polarization, evident in both measurement techniques, initially suggested absorption due to cyclotron resonance (CR). CR measured in an InAs sample with comparable carrier concentration and mobility showed that at $B=2.25$ T the cyclotron frequency was 2.5 THz. However, due to the large bandwidth of the bolometer, the CR absorption would, therefore, have been evident throughout the magnetic-field range. Analysis of the EOS frequency power spectra at comparable magnetic-field values further confirmed no obvious absorption due to such CR. The origin of the dip in TM power might be suggested by the corresponding rise in the TE polarization, evident at the same field, suggesting that there is a partial transfer in emission from one polarization to the other. This could be explained by consideration of the carrier trajectories being acted upon by the Lorentz force, which are altered once the magnetic field is applied.

The importance of the Lorentz force in modifying the carrier trajectory was also suggested by the effect of reversing the direction of the magnetic field. Upon reversal of the magnetic-field direction, bolometer measurements showed the same trend and power as for the positive field direction. However, further investigation by EOS revealed important differences for the two polarizations, unattainable via the bolometer measurement. As shown in Fig. 4, when the magnetic field was reversed the TM polarization maintained its phase, unlike the TE polarization, which underwent a 180° phase rotation. This may be explained by consideration of a simple Lorentz force model, acting on the carriers after excitation. For a TE polarization, the relevant component of carrier acceleration (and, hence, E_{THz}) flips sign with a corresponding change in sign of B, whereas this is not the case for the TM polarization. This information further suggests that the dramatic enhancement of the TE power upon application of the magnetic field is due to the magnetic-field-induced component of the photocarriers' acceleration in the plane of the sample.

In conclusion, we have observed a magnetic-field-induced enhancement of the visible to THz conversion efficiency associated with the surface-field photocurrent effect in InAs. At a temperature of 170 K and magnetic field of $B=8$ T, a THz power level of 12 μW was detected on a bolometer. We have demonstrated that both orthogonal polarizations of the THz electric field continue to rise with increasing magnetic field up to $B=8$ T, with no sign of a plateau in total THz power. Our EOS results show that the majority of this enhancement is likely to be coherent, and thus useful in EOS-based applications such as THz imaging and spectroscopy. The change in phase observed for the TE polarization suggests a simple Lorentz model of the force acting on the carriers, although the detailed understanding of the mechanism is the subject of further investigation.

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