Subpicosecond Faraday Effect in $Cd_{1-x}Mn_xTe$ and Its Application in Magneto-Optical Sampling

Introduction

Recent technological developments in electronics and optoelectronics have opened prospects for novel devices and digital circuits operating in the subpicosecond temporal regime.[1–5] As the operating speed of modern electrical devices increases, the problem of how to properly characterize them becomes progressively more difficult. Independent measurements of the voltage and the current transients are needed in order to get the full picture of the electromagnetic field distribution in the device or circuit under test and to be able to obtain the complex, frequency-dependent impedance characteristics of the tested element. Information on the voltage transient in the subpicosecond time range, corresponding to the device's THz operation rate, can be obtained using an electro-optical sampling (EOS) technique, based on a nonlinear optical crystal ($LiTaO_3$ in most cases) as the EO sensor.[6] Freeman[7,8] has recently developed a magneto-optical sampling (MOS) technique that is capable of directly measuring magnetic-field transients and, therefore, together with EOS, allows for the complete characterization of ultrafast devices and circuits. These previous realizations of MOS have been limited, however, to Tb-doped EuS[7] or garnet[8] crystals as the MO medium and could probe current pulses with experimentally demonstrated temporal resolution of the order of 10 ps at best. Part of the problem was that the implemented MO materials exhibited ferrimagnetic ordering,[9] leading to slow magnetization relaxation.

This article presents time-resolved studies of the Faraday effect in a diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ single crystal with $x > 0.5$, maintained at cryogenic (10 K) temperature. The $Cd_{0.38}Mn_{0.62}Te$ crystal has been implemented as the ultrafast MO transducer, allowing ultrafast current transients to be characterized with subpicosecond time resolution. Our MOS technique should also be applicable for accurate, time-resolved measurements of transient magnetic-field variations in modern spintronic devices.[10]

Faraday Effect and Magneto-Optical Sampling

The $Cd_{1-x}Mn_xTe$ crystals are very suitable materials for MO applications, in general, and for MOS, in particular, since, especially at low temperatures, they exhibit very high Faraday rotation under externally applied magnetic fields.[11,12] Alignment of Mn spins in $Cd_{1-x}Mn_xTe$ due to the applied magnetic field leads to a large Zeeman splitting of the excitonic energy levels[13] through the strong *sp–d* exchange interaction between the Mn spins and carriers. In turn, this mechanism induces a magnetic-field–dependent birefringence in both optical circular polarization directions, ultimately resulting in the polarization rotation angle θ_F given by[9]

$$\theta_F = \frac{\omega}{2c}\left(n_+ - n_-\right)L = VBL, \tag{1}$$

where ω is the light angular frequency, $n_+(n_-)$ are the right (left) components of the index of refraction of the circularly polarized light within the MO material, L is the optical beam magnetic-field B interaction length, and c is the speed of light. Equation (1) also shows that θ_F can be expressed as the product of the experimentally defined materials constant, so-called Verdet constant V, times B and L. In the time domain, it is predicted that the Mn ion spin–spin interaction time decreases exponentially with increasing x and reaches the subpicosecond range for $x > 0.5$.[14]

Figure 99.77 presents a schematic of our MOS experimental setup. The source of current pulses in our technique was a photoconductive LT-GaAs freestanding photoswitch capable of generating ~0.5-ps-wide electrical pulses.[15] The switch was integrated into a Ti/Au coplanar strip line (CSL) with 10-μm-wide metal strips with 10-μm separation, deposited on a transparent MgO substrate. The CSL was biased and could be shorted at one end in order to perform low-frequency V measurements. A 0.5-mm-thick, optically polished platelet cut from a $Cd_{0.38}Mn_{0.62}Te$ single crystal was placed on top of the CSL and acted as the MO transducer. Our $Cd_{1-x}Mn_xTe$ crystals were grown using a modified Bridgeman method. The synthesized material of proper stoichiometry in the form of a polycrystalline powder was used as the source material for the final crystal growth. The quality of our crystals was verified through extensive x-ray diffraction measurements.[16] The entire arrangement presented in Fig. 99.77 was placed inside a temperature-controlled optical helium cryostat, and the measurements were taken at 10 K.

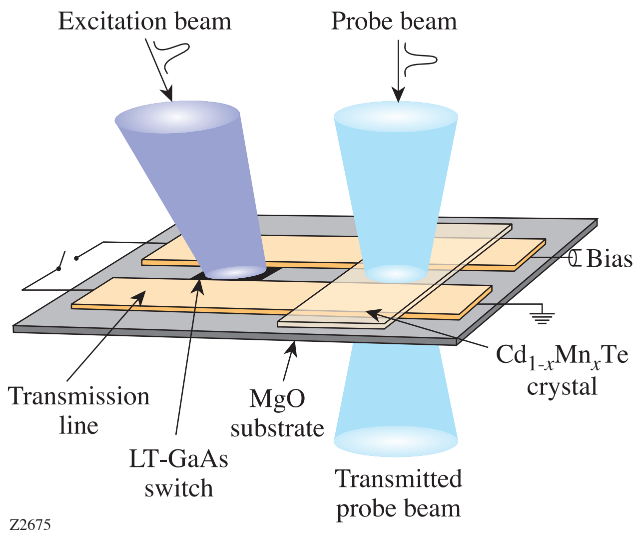

Figure 99.77
Schematic of the MOS setup, including the LT-GaAs freestanding photoswitch as an electrical pulse generator and the $Cd_{1-x}Mn_xTe$ crystal as an MO transducer. Both the switch and the transducer are integrated into a CSL fabricated on a transparent MgO substrate.

For our time-resolved Faraday rotation experiments, the LT-GaAs switch was excited by ~800-nm-wavelength, 100-fs-duration, 76-MHz-repetition-rate laser pulses generated by a commercial Ti:sapphire laser, while ~200-fs-wide probe pulses were generated by an optical parametric oscillator (OPO) with internal frequency doubling and their wavelengths covered the range from 570 nm to 615 nm. A 7:3 beam splitter was used to direct 70% of the optical energy to OPO; the remaining 30% was modulated by an acousto-optical modulator at 90 KHz and delivered to our LT-GaAs freestanding switch.[17] The linearly polarized femtosecond probe pulses from OPO traveled through the MO crystal between the metal CSL electrodes, about 300 μm away from the photoswitch. The CSL was connected to a bias source that charged the LT-GaAs switch. The polarizer and photodetector (not shown in Fig. 99.77) detected the polarization rotation of the transmitted probe light, which was displayed on a computer as a function of the excitation-probe delay time. The implemented two-color-beam approach allowed us to tune the probe-beam wavelength to reach the $Cd_{1-x}Mn_xTe$ maximum Faraday rotation, while, at the same time, exciting the LT-GaAs switch with the near-infrared (just above the bandgap) radiation. We could also maintain the excitation-probe synchronization needed for the sampling technique. Both the excitation and probe beams were focused to spots with an ~10-μm diameter.

Experimental Results and Conclusions

At the first phase of our measurements, we measured the spectral characteristics of our $Cd_{0.38}Mn_{0.62}Te$ crystal response and determined the static MO effect. A 3-KHz sinusoidal voltage was applied to one end of the CSL with no light excitation on the LT-GaAs switch, so its resistance remained of the order of 1 MΩ and its presence in the circuit could be neglected. When the other end of the line was shorted (see Fig. 99.77), a 3-KHz current signal was induced in the CSL and the polarization rotation of the probe beam, passing through the $Cd_{0.38}Mn_{0.62}Te$ crystal and between the CSL lines, was observed because of the Faraday effect. In the opposite situation, i.e., when the left end of the CSL was opened, no polarization rotation of the probe beam was observed, excluding any possibility of the EO effect in our MO crystal. Open circles in Fig. 99.78 show the results of the above measurements in a form of the V dependence on the probe-beam wavelength. We observe a broad local maximum centered at 593 nm, which corresponds to the earlier measured position of the exciton resonance in $Cd_{0.38}Mn_{0.62}Te$, although the significant (~6-nm) spectral width of our femtosecond probe

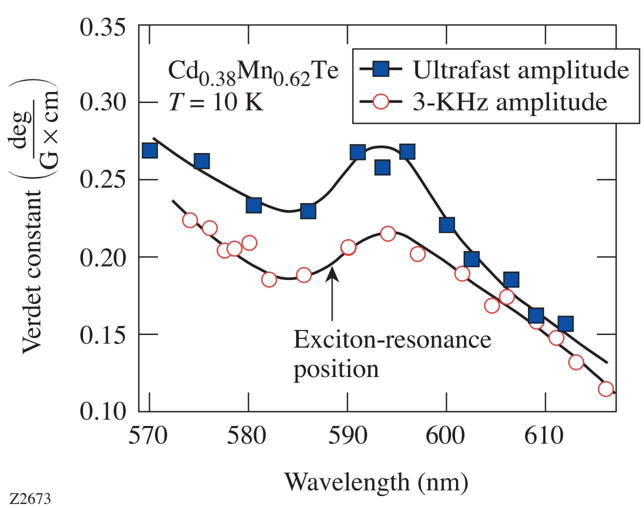

Figure 99.78
Spectral dependences of the transient (solid squares) and static (open circles) Verdet constant for a $Cd_{0.38}Mn_{0.62}Te$ single crystal measured using subpicosecond current pulses generated by the LT-GaAs switch and 3-KHz ac excitation. Both measurements were performed at 10 K in the tunability range of our OPO. The arrow shows the position of the exciton resonance. Solid lines are guides to the eye.

pulses did not allow us to resolve the resonance structure in detail. The V value obtained at the 593-nm wavelength compares favorably to other MO materials reported in literature.[9] Finally, one can also notice the increase of V at the bandgap edge below 580 nm. Faraday rotation experiments are not practical in this range due to the strong light absorption; however, one could try to implement the Kerr-effect–type measurements. We will discuss the MOS technique based on the Kerr effect in a separate publication.

When the excitation pulses were applied to the LT-GaAs switch, a train of subpicosecond electrical pulses was generated and propagated along the CSL. These electrical pulses induced the transient magnetic-field component in the CSL that coupled to our MO crystal and rotated the polarization of the transmitted probe beam. A 1.1-ps-wide magnetic pulse transient recorded using our MOS system for the probe-beam wavelength of 595 nm (corresponding to the maximum V value in Fig. 99.78) is shown in Fig. 99.79. The pulse rise time, defined as the 0.9-to-0.1-amplitude time difference, was measured to be about 0.6 ps, and the decay time, obtained using exponential fittings, was 1.1 ps. The MOS signal amplitude scan, performed for different probe-beam wavelengths (closed squares in Fig. 99.78), showed that the transient V value followed the low-frequency Verdet constant data. The latter confirms that the transient shown in Fig. 99.79 is due to the MO effect in $Cd_{1-x}Mn_xTe$, based on the ultrafast Mn ion spin–spin interaction.[14] We note, however, that within the exciton resonance range, the transient V values are consistently ~30% larger than the static ones obtained using low-frequency excitation (open circles in Fig. 99.78). From the MOS transient signal-to-noise ratio, we estimated the sensitivity of our system as ~ 0.1 mA at 10 K. This resolution could be obtained after averaging 100 data scans with 0.3-s lock-in amplifier time constant.

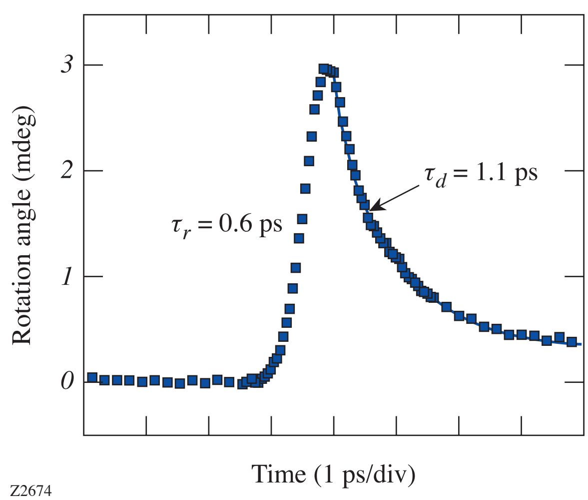

Figure 99.79
Time-resolved Faraday angle rotation as a function of time, measured using our MOS system. The probe-beam wavelength was 595 nm, and the experiment temperature was 10 K. Solid line is an exponential fit to the fall part of the signal.

To confirm the time dynamics of the MO effect in $Cd_{1-x}Mn_xTe$, we substituted the $LiTaO_3$ crystal for our MO crystal and performed the standard EOS testing at 10 K with the same LT-GaAs switch and CSL. The measured EOS response showed some additional oscillatory features due to apparent dielectric loading of the relatively large $LiTaO_3$ crystal, but the recorded MOS and EOS pulses exhibited essentially identical characteristic times. Since the response time of our $LiTaO_3$-based EOS system is 200 fs,[15] we can confirm that the response time of the cryogenic Faraday effect in $Cd_{1-x}Mn_xTe$ with $x > 0.5$ is of the order of a few hundred femtoseconds or less. The latter conclusion is in qualitative agreement with the data discussed in Ref. 14.

We have demonstrated subpicosecond dynamics of the Faraday effect in highly Mn-doped $Cd_{1-x}Mn_xTe$ at low temperatures and have implemented these crystals as MO transducers in the MOS system for time-resolved measurements of magnetic/current transients. The high sensitivity and subpicosecond temporal resolution of our MO sampler makes it practical for characterization of ultrafast current–driven (e.g., superconducting) devices and circuits. The presented sampler should also be very useful for testing the switching dynamics of spintronic logic elements. Finally, the $Cd_{1-x}Mn_xTe$ crystals should find applications as ultrafast MO modulators[18] for electrical-to-optical coupling of superconducting digital circuits.[19]

ACKNOWLEDGMENT

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