Magneto-Optical Characterization of ZnSe Bandgap

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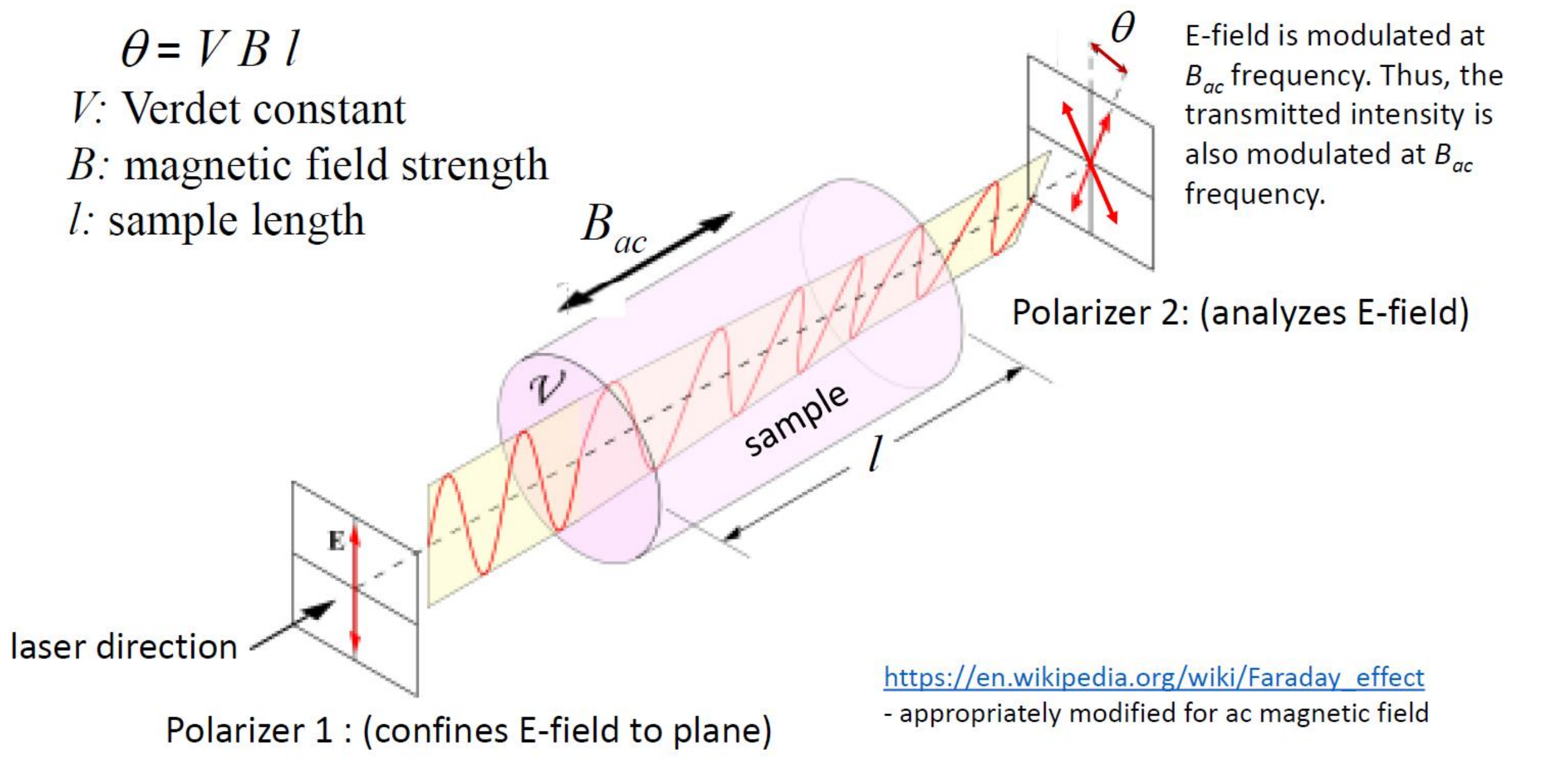
Abstract

The Verdet constant of ZnSe was experimentally determined in the visible to infrared wavelength range corresponding to 480 -980 nm. In addition to the values obtained utilizing phase sensitive detection and an ac magnetic field, we have also analyzed and compared all other known data. This work is intended to characterize the dispersion of the Verdet constant and extract the energy bandgap from existing theories. The values tend to agree with newer theories assuming a quasiparticle and/or quantum dot (nanoparticle structure), which assume a smaller crystalline size and stronger energy confinement than the older the models.

1. Introduction

The Faraday Effect, named for physicist Michael Faraday, is a magneto-optical phenomenon characterizing the rotation of the plane of polarization of light – a form of optical activity due to Zeeman splitting.



https://en.wikipedia.org/wiki/Faraday_effect
- appropriately modified for ac magnetic field

Figure 1. A longitudinal AC magnetic field in the sample induces optical activity in the polarized collinear laser beam. The electric field (polarization direction) of the laser light is modulated at the same frequency as the applied magnetic field. Hence, the intensity of the light after polarizer 2 is modulated at the same frequency.

The angle of rotation, θ is dependent on the strength of the magnetic field (i.e. the magnetic flux density), B, the length, l of the sample, and the Verdet constant, V according to

$$\theta = V B l$$

The Verdet constant, which is also dependent of wavelength (and to a lesser extent on temperature) somewhat like the refractive index (i.e. dispersion), characterizes the Faraday effect in a transparent material.

2. Experimental Method (Theory I)

Lock-in amplifiers (LIAs) record an input signal as RMS volts. It can be shown that the rotation, in radians, induced by a modulating magnetic field, follows from the relations[1,2,3]

$$\theta = \frac{1}{2}\sin^{-1}\left(\frac{V_{AC}}{V_{DC}}\right) \sim \frac{V_{AC}}{2V_{DC}}$$

that are valid for the small rotations occurring in the apparatus shown in Figure 3. The Verdet constant is extracted using measured quantities defined by a measured AC voltage signal, V_{AC}, a measured DC voltage signal, V_{DC} ; both of these utilizing a lock-in amplifier. The magnetic flux density B, which is a function of the supplied current, I is obtained from the solenoid calibration (Fig. 2)

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2. Experimental Method (cont.)

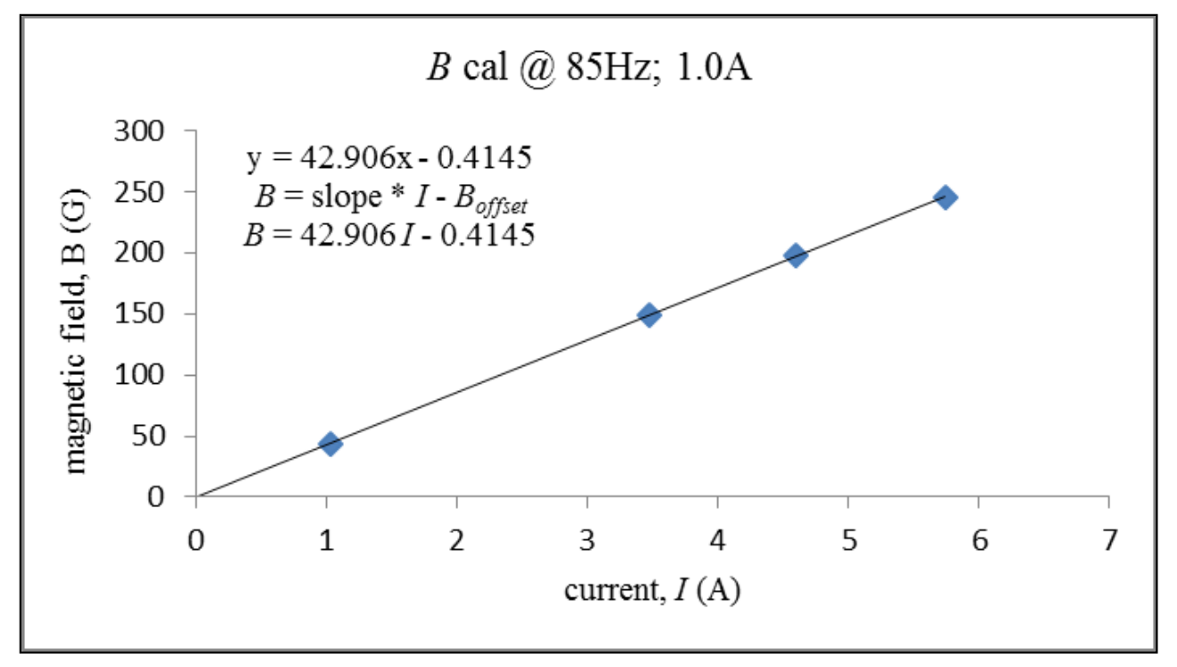

Figure 2. Calibration of the solenoid

V_{DC}: constant photodiode signal (auxiliary input of the LIA)

V_{AC}: referenced modulated signal (the PSD input of the LIA)

Bl :solenoid calibration (Figure 2 - left); B is applied along the sample length, l

After calibrating the solenoid (Figure 2), the magnetic field strength is determined as a function of the monitored current, I supplied to the solenoid. The Verdet constant of the sample follows from $V = \theta / Bl$

3. Apparatus

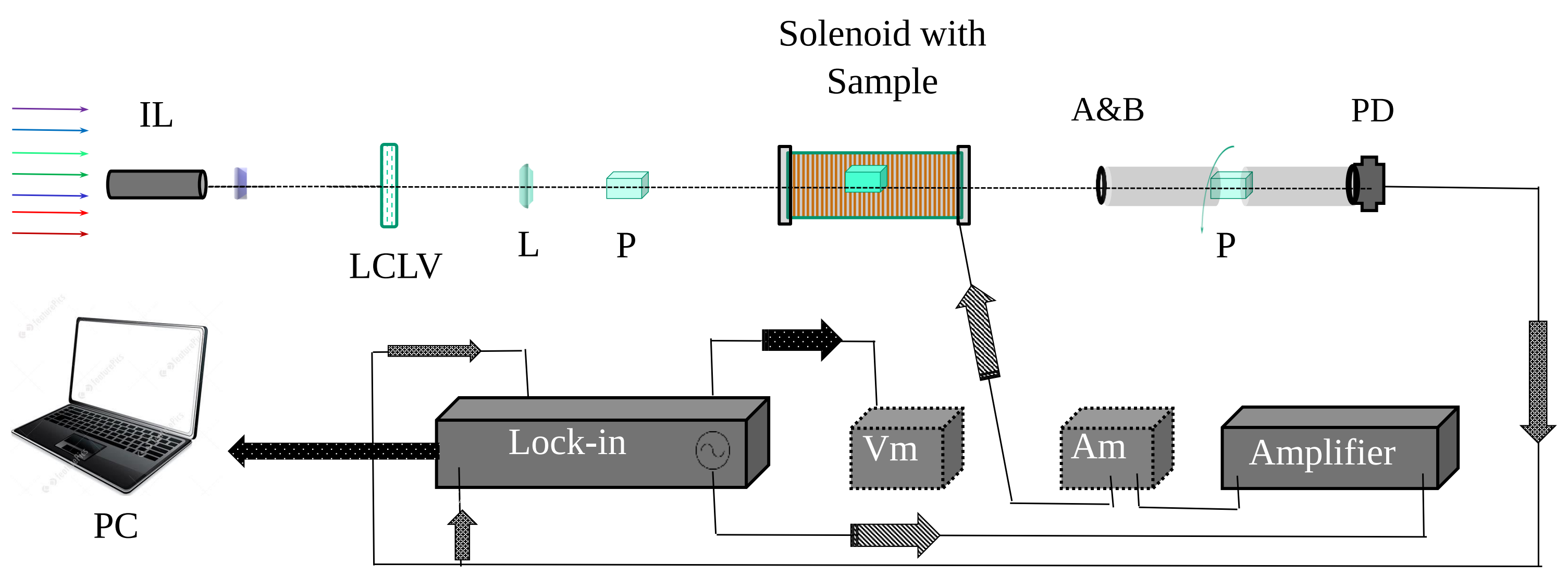

Figure 3. Signal to noise ratios approaching 10^{-5} may be achieved in a well-designed experiment utilizing the SR 830[4] lock-in amplifier. A transimpedance amplified photodetector and a proper V_{DC} setting, associated with laser intensity adjustment, optimizes the signal noise ratios and affords real time signal ratios, V_{AC} / V_{DC} . A collection of eight laser diodes spanning the visible spectrum were employed to determine the dispersion of the Verdet constant, $V(\lambda)$.

4. Data Analysis (Theory II)

Two different theories were used to analyze, via nonlinear curve fitting, the dispersion of the Verdet constant for the ZnSe glass sample:

BHL[5] → $$nV = K\left\{\frac{1}{\xi}\left[(1-\xi)^{-1/2} - (1+\xi)^{-1/2}\right] - 1\right\}$$

KLN[6] → $$nV = K\left\{\frac{1}{\xi}\left[(1-\xi)^{-\frac{1}{2}} - (1+\xi)^{-\frac{1}{2}}\right] - \frac{4}{\xi^2}\left[2 - (1-\xi)^{\frac{1}{2}} - (1+\xi)^{\frac{1}{2}}\right]\right\}$$

A detailed discussion of the theories and significance of the fitting parameters is beyond the scope of this presentation. Nevertheless,

BHL[5] → K, ξ are fitting parameters ($\xi = \lambda_g/\lambda$), n is the refractive index

KLN[6] → K, ξ are fitting parameters ($\xi = \lambda_g/\lambda$), n is the refractive index

Interestingly, an energy gap can be calculated from the fitting parameter, $\xi = \lambda_g/\lambda$ in the BHL and KLN theories according to:

$$E_g = hc/\lambda_g \text{, where } hc = 1240$$

Finally, the refractive index, n is also a dispersive quantity (i.e. depends on l), which we calculate using the Marple equation from https://refractiveindex.info/

5. Results

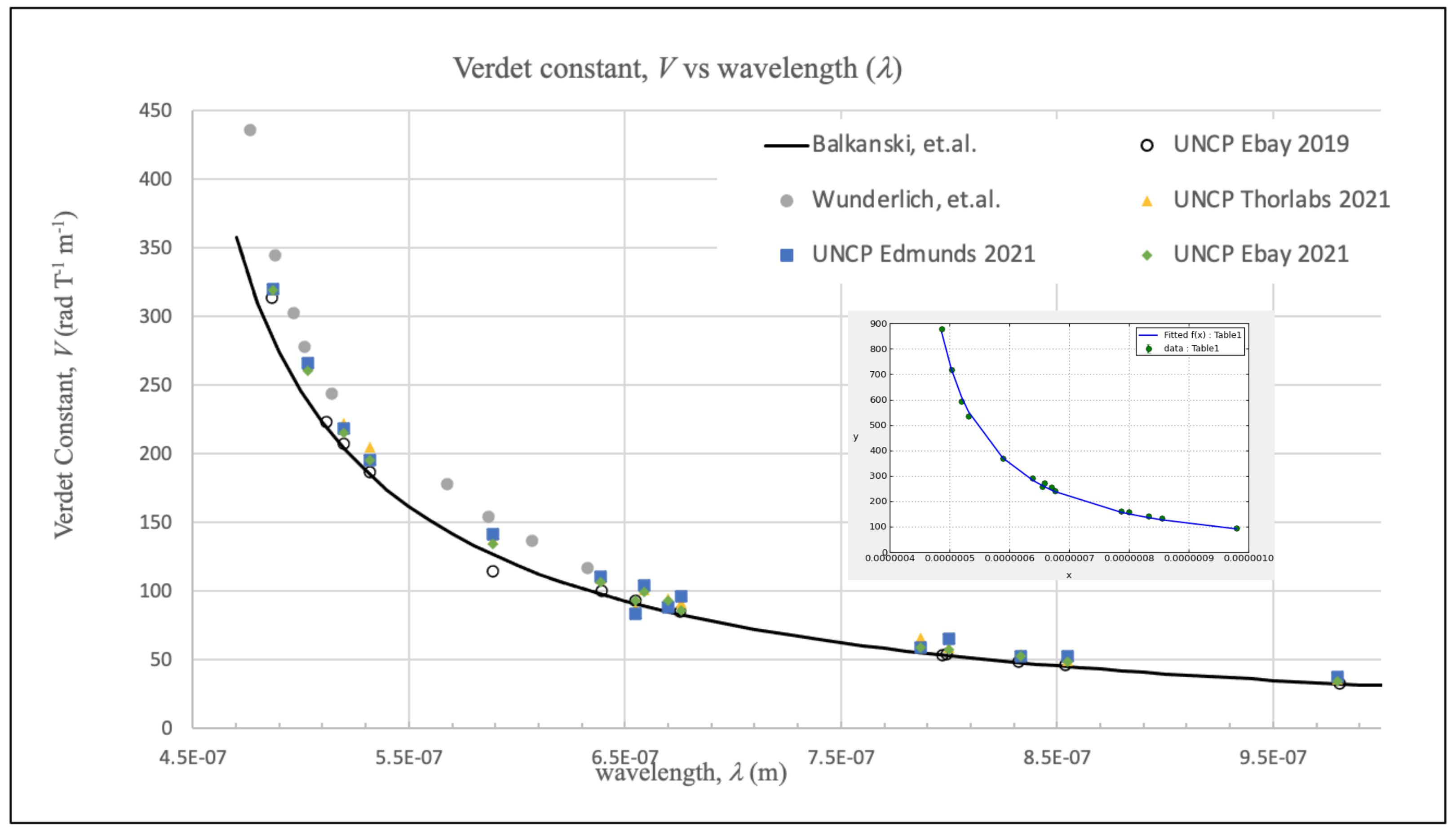

Figure 4. Verdet constant of ZnSe reported from all known published data[7,8], in addition to this work (blue squares, black circles, yellow triangles, and green diamonds). The smooth line represents Balkanski, et. al. data which was reverse engineered from published fitting parameters and the grey circles is data from Wunderlich, et. al. The inset graph represents a BHL fit to the eBay 2021 sample. The bandgap extraction proceudre requires graphing the product of the refractive indices and Verdet constant against the wavelength.

	K_{BHL}	$\lambda_{\mathrm{g,BHL}}$	K_{KLN}	$\lambda_{\mathrm{g,KLN}}$
UNCP eBay	680	420	1441	396
E_g		2.95 eV		3.13 eV
UNCP Thor Labs	723	416	1539	392
E_g		2.98 eV		3.16 eV
UNCP Edmund Optics	707	418	1505	394
E_g		2.97 eV		3.15 eV

Table 1: Fitting parameters resulting from the BHL[5] and KLN[6] theories providing the most comprehensive data set associated with magneto-optic bandgap characterization of ZnSe. The bandgap energy levels are closer to those resulting quasiparticle[9] and nanoparticle[10] theories, rather than those expected of crystalline structures. Essentially, quasiparticle and nanoparticle bandgap levels tend toward a 10% increase, reflecting a reduced crystalline size and stronger valence electron confinement when compared to bandgap energies obtained for quasi-cystalline ZnSe via standard optical measurements (e.g., absorption)

6. Conclusion

Faraday rotation experiments afford valuable exposure to advanced undergraduate and graduate student researchers. The experimental methodology incorporated into this investigation utilizes phase sensitive lock-in regarding the general problem associated with data extraction of signals buried in noise. Summarizing, we have found that the dispersive characteristic of the Faraday rotation in ZnSe can well be described by the effects of direct allowed transitions between a simple valence and conduction band (e.g., BHL and KLN theories). Our measurements, in conjunction with intensive data mining, provides the most comprehensive set of magneto-optical parameters for the dispersion of the Verdet constant, in addition to "magneto-optic based" bandgap energy of ZnSe to date.

Citations

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