Forecast:
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The Relaxation Times

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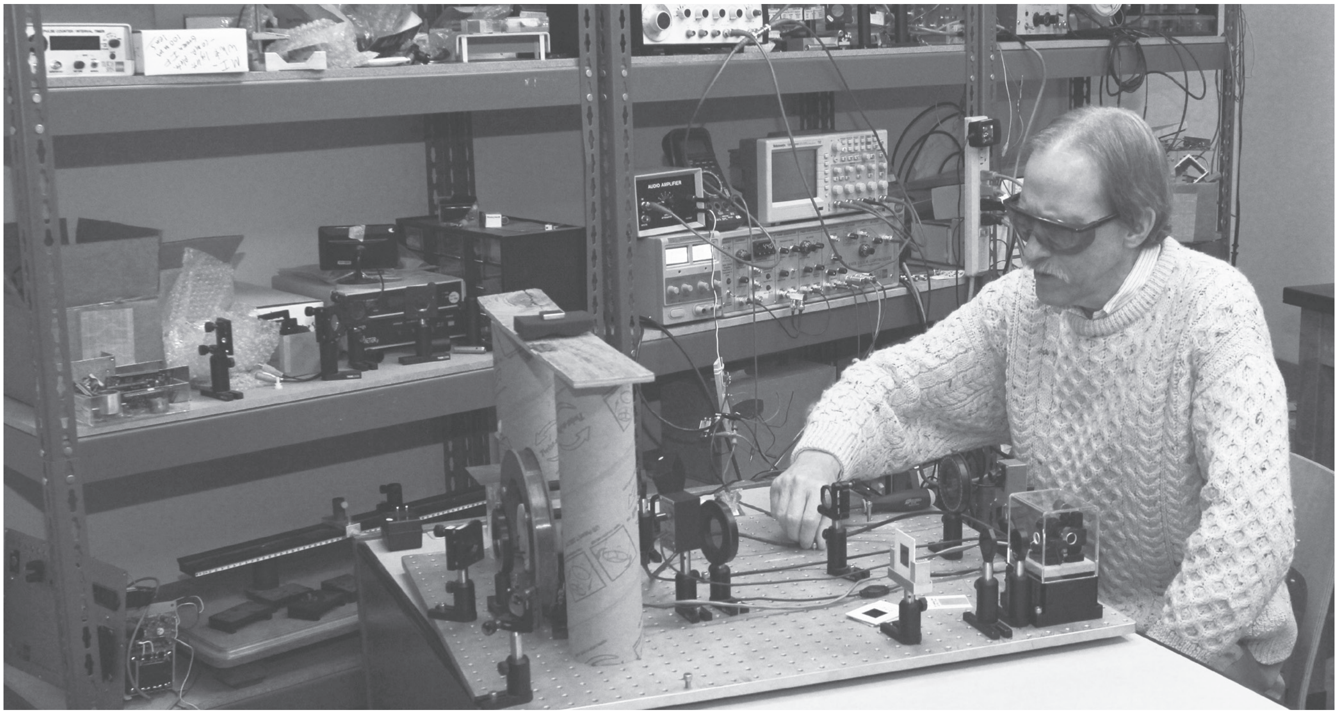
New Experiments with Diode Laser Spectroscopy



TeachSpin's 'Diode Laser Spectroscopy' system includes the full suite of tools your students need to investigate

- Resonant Absorption of light by atoms,
- Resonance Fluorescence of atoms,
- Saturated Absorption (for Doppler-free spectroscopy),
- and even Resonant Faraday Rotation,

all of these making use of tunable, narrow-band laser light of wavelength near 780 nm, interacting with ground-state rubidium atoms inside a vapor cell.

But now you can add a new experiment to that list,

Nonlinear Faraday Rotation

requiring *no more equipment* than is already included in our 'package'. This investigation displays physics connected to glamorous topics of current research interest, including

- Atomic Magnetometry using this nonlinear Faraday rotation,
- Coherent Population Trapping, as used in 'chip-scale atomic clocks',
- Electromagnetically-Induced Transparency, and
- 'Dark States' and adiabatic population transfer.

In this newsletter, we can answer two main questions for you:

1) What's 'non-linear' about this kind of Faraday rotation? and
2) Given that Faraday rotation is such a weak effect in solid glass, how is it that Faraday rotation can be detected using a *vapor* sample with a density so much smaller than glass?

First question, then – what's 'non-linear' Faraday rotation? You might recall that Faraday rotation is the systematic rotation of the plane of polarization of light, while it's propagating through a sample, parallel to a uniform and static magnetic field B. The simplest theory predicts a rotation-of-polarization angle $\Delta\varphi = V B L$, where L is the distance of propagation, and V is the 'Verdet constant' of the material for the light used. But 'non-linear Faraday rotation' doesn't refer to $\Delta\varphi$'s dependence on B; instead, it's a kind of Faraday rotation where the rotation $\Delta\varphi$ depends on the *intensity* of the light involved. So it's an *optical* non-linearity we're in search of here – and happily, our diode-laser light is easily bright enough to give non-linear response in our atomic transition.

Second question – if even for a sample of specially-chosen solid glass (of mass density > 10^3 kg/m^3) we get only a paltry few degrees of Faraday rotation (say, for $L = 0.1$ m of glass in a field of $B = 30$ mT), how is it that we can hope to detect *any* Faraday rotation using a vapor-phase sample, of a shorter length, in a smaller field? Our sealed rubidium cell, even heated to 45°C to give a vapor pressure of 3×10^{-6} Torr, contains Rb atoms in a very dilute sample indeed – the Rb mass density is only about 10^{-8} kg/m^3! That's more than 11 orders of magnitude less dense than glass. But it's the *resonant* interaction of light with the atoms that makes even ordinary Faraday rotation in atomic vapors so readily detectable – it's called the Macaluso-Corbino effect after its discoverers. (See Am. J. Phys. **64**, 724 (1996) for the theory.)

The optical layout required is simplicity itself:

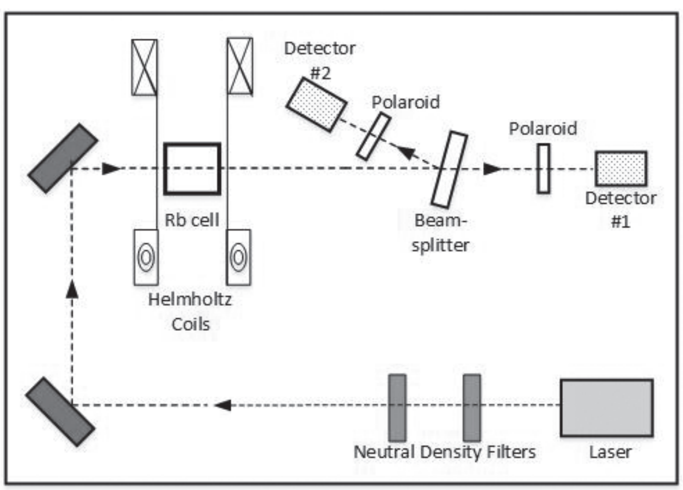


Fig. 1: A typical optical-table layout for the study of nonlinear Faraday rotation.

[You can find a detailed guide to this experiment at the top of our Diode Laser Spectroscopy page at www.teachspin.com]

The diode-laser output is linearly and vertically polarized at the source; we attenuate it with two neutral-density filters, and send it through the vapor cell. We have that vapor cell centered inside the set of Helmholtz coils that come with our set-up; a dc current of ±3 A will give a field B of about ±10 mT. We send the emerging light beam into a beam-splitter, and in each of the two resulting beams we put a Polaroid (with its 'pass' orientation inclined at +45° and -45° respectively from the vertical) and a photo-detector, thus creating a 'balanced polarimeter'. The *difference* of the intensity signals from the two photodetectors is easily formed, using the electronics built into our diode-laser controller, and it gives as output a real-time electronic signal that is proportional to $\sin(2\Delta\varphi)$. If we display this polarization-rotation signal, as a function of electrically-scanned laser frequency, for a few fixed values of magnetic-field B, we get this plot:

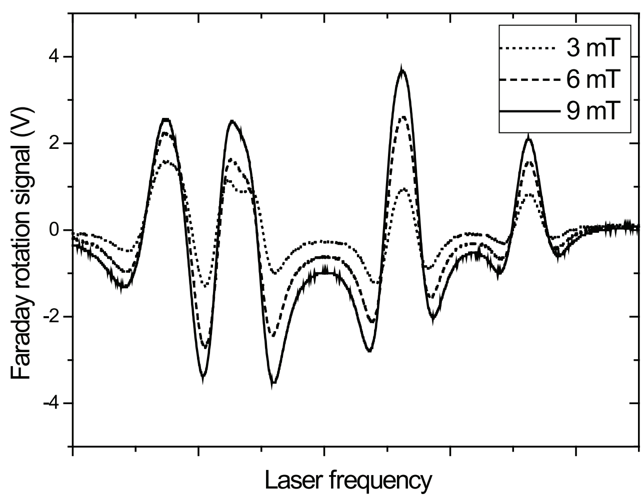


Fig. 2: Scan over about 10 GHz of optical frequency covering the Rb D2 transitions, showing resonant Faraday rotation at fields 3, 6, and 9 mT.

The plot displays four resonances, rather than just one, because there are two isotopes of rubidium, and each has its ground state split into two by the hyperfine interaction. At the center of any of these resonances, the Faraday rotation depends, apparently linearly, on the magnetic-field strength. So we can make a different kind of plot – here's the same Faraday-rotation signal, but now plotted as a function of magnetic field, for a laser frequency *fixed* at the center of one of the resonances.

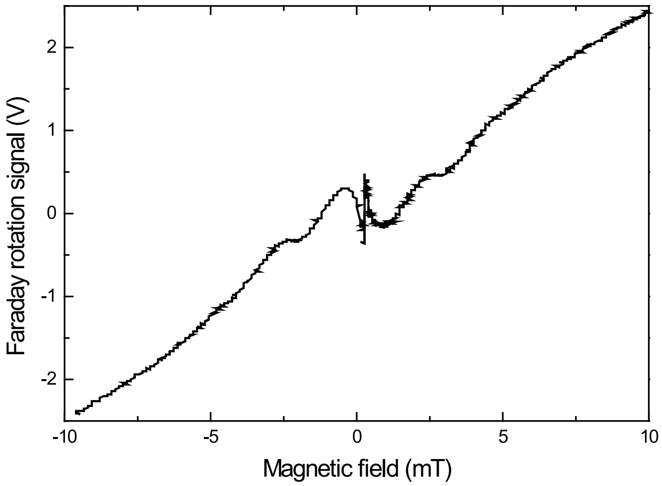


Fig. 3: For laser light fixed at one (of the four) Rb resonances, Faraday rotation signal as a function of magnetic field. Horizontal scale covers ±10 mT; vertical scale corresponds to about ±40° of Faraday rotation.

You can see the generally linear dependence on magnetic field, but you can also see some deviations that occur near $B = 0$. So making an electronic scan over a smaller range of Helmholtz-coil currents, we can get another real-time plot, still of Faraday rotation vs. field:

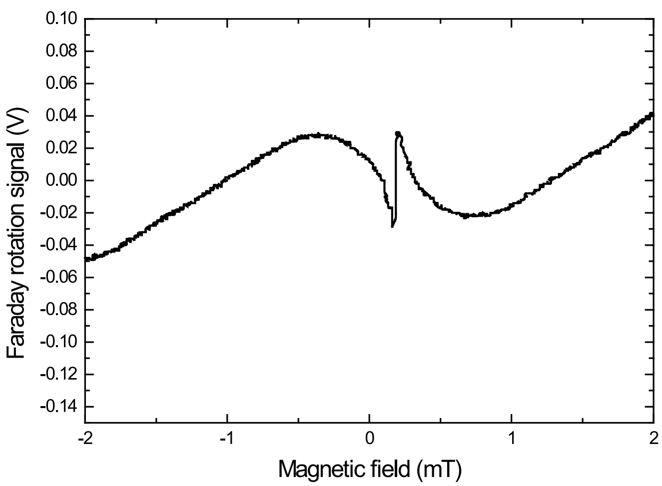


Fig. 4: Faraday rotation signal as a function of magnetic field, on a smaller horizontal scale of ±2 mT.

Something very curious happens right near zero field – atop the overall linear dependence on B, we now see there are two dispersive-shaped features, and the 'inner' or narrower one of the two displays a vastly greater slope than the overall linear dependence shown in Fig. 3. [There are *other* unexpected features visible right in that raw data – do you see some breaks in the linear trends, away from $B = 0$? Would these occur for all four resonances? Does their presence depend on optical intensity? Could you imagine a senior project, or an undergraduate research project, in this sort of investigation?]

To show that these features have something to do with optical non-linearity, we merely move one of the neutral-density filter from 'upstream' of the vapor cell, to 'downstream' of it. Though we might expect this to give an unchanged size of signals on the photodetectors, in fact this change immerses the Rb atoms in a stronger light field, and the result is that our curious feature near $B = 0$ is enhanced in size in this stronger light. Conversely, these features disappear in the weak-light limit.

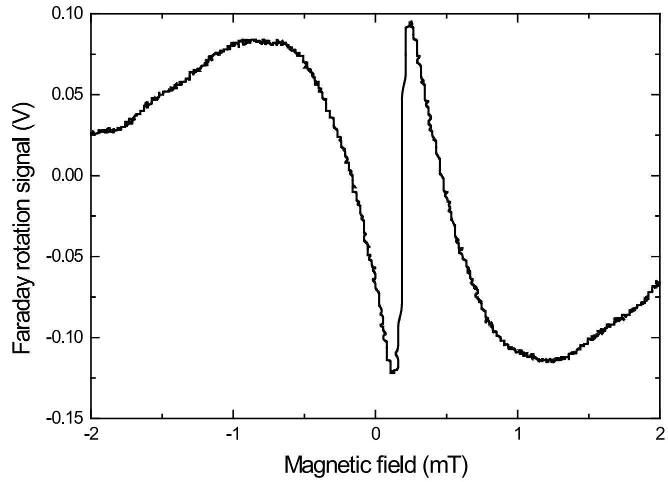


Fig. 5: Faraday rotation signal as a function of magnetic field, on the same horizontal scale of ±2 mT, but now with the Rb atoms in a stronger light field.

The 'peak' and 'valley' in the central dispersive feature shown in Fig. 4 are separated by only 0.033 mT (or 33 μT, 0.33 gauss). The use of a spatially-expanded beam of light can make this feature still narrower – and this starts to require control of the ambient earth's field. Researchers using internally-coated storage cells have gotten features with widths measured in nT, nanoTesla!

The theory of this effect is a complicated exercise in quantum mechanics; it represents one of the many manifestations of 'ground-state coherences', or superpositions of ground-state magnetic sub-levels differing in magnetic quantum number m by 2 units. Such coherences can have very long lifetimes, which accounts for the narrowness of the features in B shown above. (See Am. J. Phys. **67**, 584 (1999) for the theory and illuminating experiments.)

The steep slope of the central region of that dispersive feature illustrates the possibility of magnetometry exploiting this interaction. The data above were taken in single scans of duration 0.1 s, and with no signal-averaging at all, yet the signal-to-noise ratio of the central part of the curve easily allows the real-time detection of field changes of 1 μT or less. Vastly higher sensitivity has been obtained in research investigations – and there is plenty of interest in a device which could detect tiny magnetic-field changes, and operate near room temperature, and might even be miniaturized to the 'chip scale' of an integrated circuit.

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New Experiments with Diode Laser Spectroscopy: Nonlinear Faraday Rotation

Barbara "steps back" – a message from Barbara Wolff-Reichert to members of the TeachSpin community

With Carl Grossman fully on deck as Marketing Director and Abra Greer as his able assistant, my role at TeachSpin will be changing. While they take over the day to day responsibilities, I will continue to be an Undergraduate Laboratory Consultant. That means I will still be involved in special projects and attending conferences to show off the instruments that so consistently intrigue and delight me. You may even hear from me encouraging you to participate in ALPhA Immersions – especially the ones here in Buffalo where a highlight is dinner at the Reichert residence, a special opportunity I cherish for some 'down-time' with people I so much admire.

And, of course, I will be there at the APS March Meeting to co-present the Reichert Award for Excellence in Advanced Laboratory Instruction. I will probably never stop holding my breath as we hand off an award that honors not only the awardee but also the entire community of laboratory educators. This extraordinary group of men and women have put so much time, energy, and personal passion into providing the kind of wide-ranging, hands-on laboratory experience that I believe is crucial to the education of the next generation of physicists.

So, expect to hear from Carl and Abra. They will be checking up on how your TeachSpin apparatus is behaving, making sure you have .pdf versions of the latest materials, and offering information about any new experiments or accessories we have developed to continue challenging and intriguing your students. But do know, I still share your passion and am just as likely to show up cheering when something wonderful happens.