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Faraday rotation imaging microscope with microsecond pulse magnet

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ABSTRACT

We have fabricated a high-performance Faraday rotation (FR) imaging microscope that uses a microsecond pulse magnet comprising an insulated gated bipolar transistor and a 2 μF capacitor. Our microscope produced images with greater stability and sensitivity than those of previous microscopes that used millisecond pulse magnet; these improvements are likely due to high repetition rate and negligible Joule heating effects. The mechanical vibrations in the magnet coil caused by the pulsed current were significantly reduced. The present FR microscope constructed an averaged image from 1000 FR images within 10 min under 1.7 T. Applications of the FR microscope to discriminating three benzene derivatives in micro-capillaries and oscillation-free imaging of spherical polystyrene and polymethyl methacrylate microparticles demonstrated its high performance.

1. Introduction

Faraday rotation (FR) is an optical gyration phenomenon observable in every material under a magnetic field; it results from a linearly polarized light passing through a sample parallel to an external magnetic field [1]. The most remarkable advantage of FR as an analytical technique is that it can be observed in no-absorption wavelength regions. We investigated the FR of paramagnetic and diamagnetic liquids; the magnetic moment and electron configuration of paramagnetic lanthanide(III) ions strongly correlated with FR transition probability [2] and the aromatic property of diamagnetic molecules enhanced FR transition probability [3]. Hence, FR can evaluate these properties by non-invasive wavelength light. We demonstrated that the line form of the FR wavelength dispersion of FR in diamagnetic liquids allowed us to estimate the resonance wavelength of the $\pi \rightarrow \pi^*$ transition in the UV region using the FR dispersion in visible region [3].

FR in diamagnetic or paramagnetic substances is generally too weak to be detected using a normal electromagnet of a few hundreds mT. Lock-in techniques have often been utilized to improve measurement sensitivity [4–6]. Alternatively, high magnetic fields can measure the FR of weak magnetic material, because the FR angle, θ_F, is proportional to the magnetic field, B:

$$\theta_F = VlB \tag{1}$$

where l is the optical path length and V is the Verdet constant, a characteristic value of the sample compound. A pulse magnet is one of the most effective ways to obtain a high magnetic field using relatively simple and conventional instruments [7,8]. Pulsed magnetic fields can be generated by a capacitor discharging in an LCR circuit; the pulse duration depends mainly on the capacitance. Matsuda et al. constructed a portable pulse magnet that could generate 30 T with a 1.2 mF capacitance condenser bank and a small coil with an air core several millimeters in diameter. It was easily brought to a synchrotron radiation facility and used to conduct measurements under strong magnetic field that included X-ray diffraction, X-ray magnetic circular dichroism, and others [9–12]. Mackay et al. fabricated a tiny single turn coil, 150 μm in diameter, that generated ~50 T, 50 ns pulses for which a special technique was required to synchronize with the optical measurements [13]. We have utilized pulse magnets with millisecond duration to measure FR dispersions and to acquire FR images [14,15]. The millisecond pulse magnet has enabled us to observe clear FR images even in weak magnetic materials in transparent wavelength regions by generating a magnetic field up to 2 T, because it was easy to acquire a reference light intensity in the absence of magnetic field. By using commercial 2 mF or 4 mF capacitor banks, a 10 T pulsed magnetic field with 0.5–1 ms full width half maximum pulses could be generated in a small home-made solenoidal coil. By easily attaching the coil to an optical microscopic system, we developed an FR imaging microscope as a new mode of optical microscope.

Micrometer-sized particles are common in nature, for instance cells, cell composites, DNA, environmental colloid particles, soil particles, clay crystals, and so on. These particles comprise many

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small ions and molecules, but each has a characteristic function as a whole. Therefore, characterizing a single microparticle elucidates its function in real systems. This characterization requires nondestructive and noninvasive measurement of the properties of an individual microparticle. FR imaging is a promising technique to assess the character of individual microparticles. However, quantitative FR imaging of micrometer-sized samples, like biological cells, requires technical improvement. Assuming that the thickness and Verdet constant of a typical diamagnetic microparticle are 20 μm and 20 rad T^{-1} m^{-1}, respectively, Eq. (1) predicts the FR angle observed under a 2 T magnetic field to be 0.8 mrad. However, the noise in an FR image averaged 100 times was ~1 mrad, larger than the expected FR angle. The easiest way to reduce the noise is to increase the number of measurements. However, quantitatively measuring such small gyrations requires averaging more than 1500 images, as discussed in the Supplementary materials (SM), which would take ~10 h to acquire an FR image given our previous setup, with its 0.5 Hz repetition rate. The condition of a living cell would change over such a long measurement time.

In the microsecond magnet, the following restricted the repetition rate and the spatial resolution of the FR image measurement: (A) Joule heat generation in the coil, (B) the charging time of the capacitor, and (C) mechanical displacement of the coil due to Maxwell stress, which results from interaction between the current in the coil and the generated magnetic field. (A) and (B) limited the ability to improve the signal to noise ratio of FR measurements by increasing the number of images averaged over. The highest repetition rate of our previous magnet was limited to 0.5 Hz due to the charging time (1.5 s) and the time required to cool the coil. Furthermore, (C) limited the objective magnification in the microscope. The FR imaging microscope of the previous work utilized a Xe flash lamp incident light source with 3 μs in full width at half maximum. The flashes and the pulsed magnetic field were synchronized to obtain the image under the magnetic field. The pulsed magnetic field of 0.5 ms was much longer than the light flash (see SM). The longer pulse current in the coil caused greater heat generation and mechanical displacement, so a shorter magnetic field pulse with would be preferable in the FR imaging microscope. Ghosh et al. proposed a novel detection technique for FR, in which they observed the difference in deflection between right and left circular polarized light [16]. In this work, they fabricated a pulse magnet with 100 μs pulses to examine the polarity of the obtained signal. They used a 20 μF capacitor in the pulse magnet and an insulated gate bipolar transistor (IGBT) as a switching device, because IGBT can switch between an insulated off-state and a conductive on-state within 1 μs. In the present study, we have increased the repetition rate of the FR measurement by using a microsecond pulse magnet. We report that the FR imaging microscope with a microsecond magnet suppressed Joule heating and mechanical oscillation and increased the repetition rate, greatly improving signal to noise and accuracy from our previous FR microscope design. In order to determine the capabilities of the present FR imaging microscope, we examined FR images of three different benzene derivatives in micro-capillaries and a spherical micro-particles of polystyrene and polymethyl methacrylate.

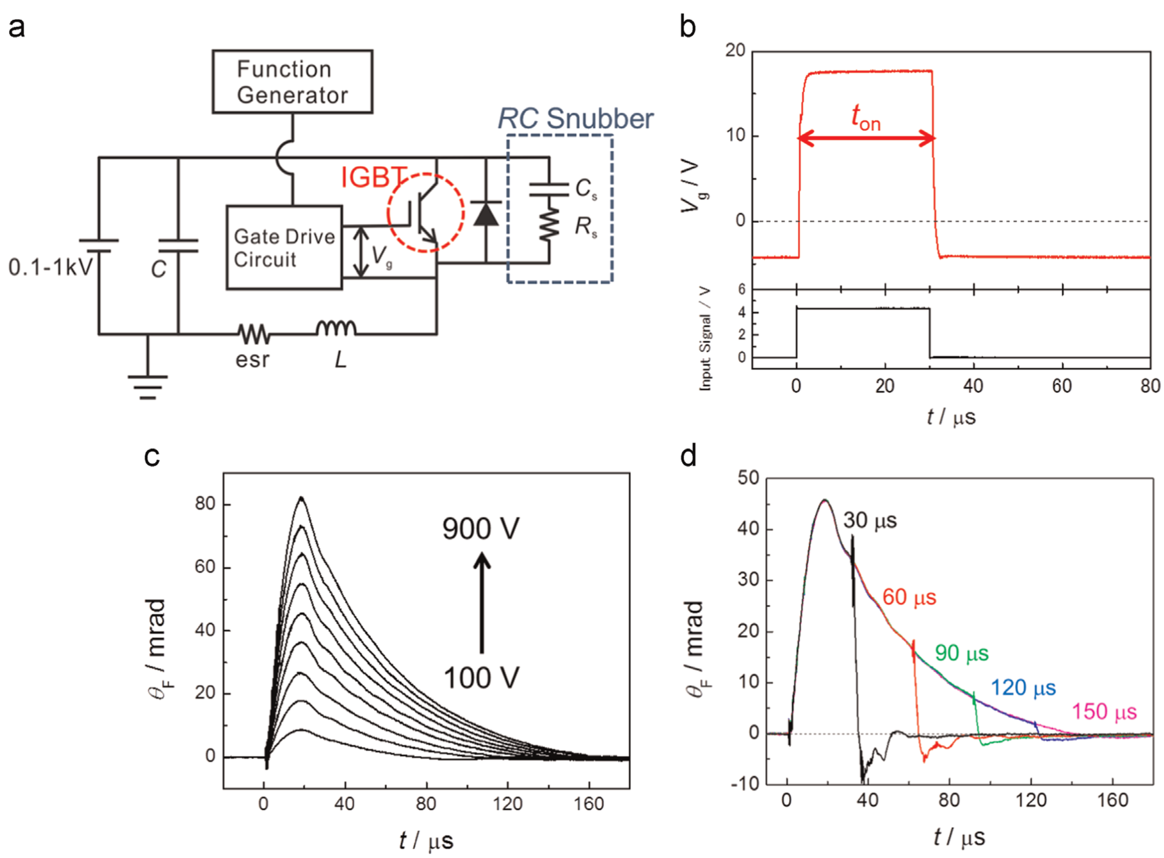

Fig. 1. (a) The electrical circuit for generating the microsecond pulsed magnetic field. ESR: equivalent series resistance; IGBT: insulated gate bipolar transistor. An RC snubber protects the IGBT from a surge pulse in the main circuit when the IGBT turns off: $C_s = 0.1$ μF, $R_s = 33$ Ω. (b) The time course of the gate drive voltage between the gate and the emitter of the IGBT (bottom) and a signal input from the function generator (top); t_{on} indicates the time the IGBT stays in the on-state. (c) Dependence on the charging voltage of the waveform of the FR in 5 mm thick water and a 180 μs applied gate drive voltage. Voltage was varied from 100 V to 900 V at 100 V intervals. (d) Variation of the waveform with t_{on}.