Lecture 30:

Femtosecond Laser Irradiation and Acousto-optic Effects

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For New Functionality in Glass

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Femto second laser irradiation effects in glass

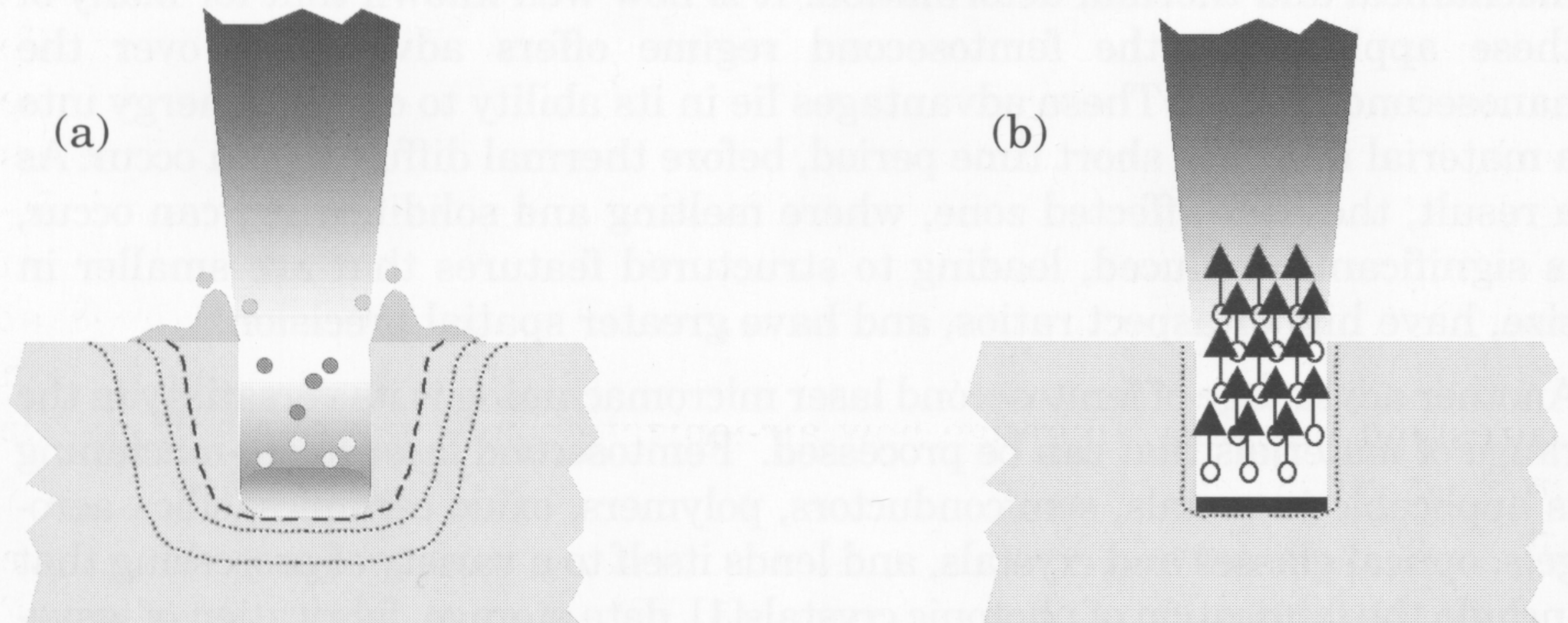
Femto second (fs) laser pulses can be used to produce structural changes in transparent glasses, including soda-lime silicate, lead silicate and ChG's.

Fs laser ablation, or laser micro-machining, has become important in micro-optics, micro-electronics and other fields.

The advantages of the fs over the nanosecond (ns) regime are mostly the ability to deposit energy over a very short period of time, without thermal diffusion, reducing the size of the heat affected zone, where melting and solidification can occur.

Fs laser machining can be applied to metals, semiconductors, polymers, oxide ceramics, gels and optical glasses, enabling the fabrication of photonic crystals, waveguides, gratings, couplers and data storage.

The fs laser ablation, in general, starts with electronic excitation via multi-photon absorption, leading to the formation of a plasma at the glass surface, after which energy is transferred to the glass network by bond breaking and material expansion, as depicted below, without the glass having time to melt and resolidify. Therefore, fs laser micromachining is an attractive technique for the fabrication of fine surface structures in transparent materials.



Schematic illustrating the difference between conventional (**a**) and femtosecond (**b**) micromachining.

(Adapted from: M. Richardson et al., *Glass and the photonics revolution*, Glass Sci. Technol., 2002)

Deep hole drilling

Laser ablation has been investigated in two silicate glasses: (1) a soda-lime glass (bandgap ~ 5 eV) and (2) a lead silicate glass (bandgap ~ 2.5 eV), using three different techniques; a fs laser @ 845 nm , a ns laser @ 845 nm and a ns laser @ 1064 nm.

Results

It was found that the penetration depth was larger for the lead silicate than the soda-lime glass for any of the three different ablation regimes, due to the higher electronic density of the lead-containing glass. Also, with fs drilling, there is a greater penetration depth with smaller energy per pulse.

The occurrence of air ionization, in ambient air machining, has also an effect on the achieved ablation rate.

Grating fabrication in thin ChG films

A Ti:sapphire laser was used to fabricate gratings on a 1.7 μm thick As_2S_3 thin film, the laser having a 40 nm spectral bandwidth (FWHM) centered at 800 nm, at a repetition rate of 27 MHz, with ~ 50 fs pulses and 20 nJ per pulse. In (a), the intensity was kept below the ablation threshold, generating a phase (volume) grating; in (b), intensities above the ablation threshold produced a relief grating, with grooves ~ 2 μm deep. The grating period was ~ 20 μm.

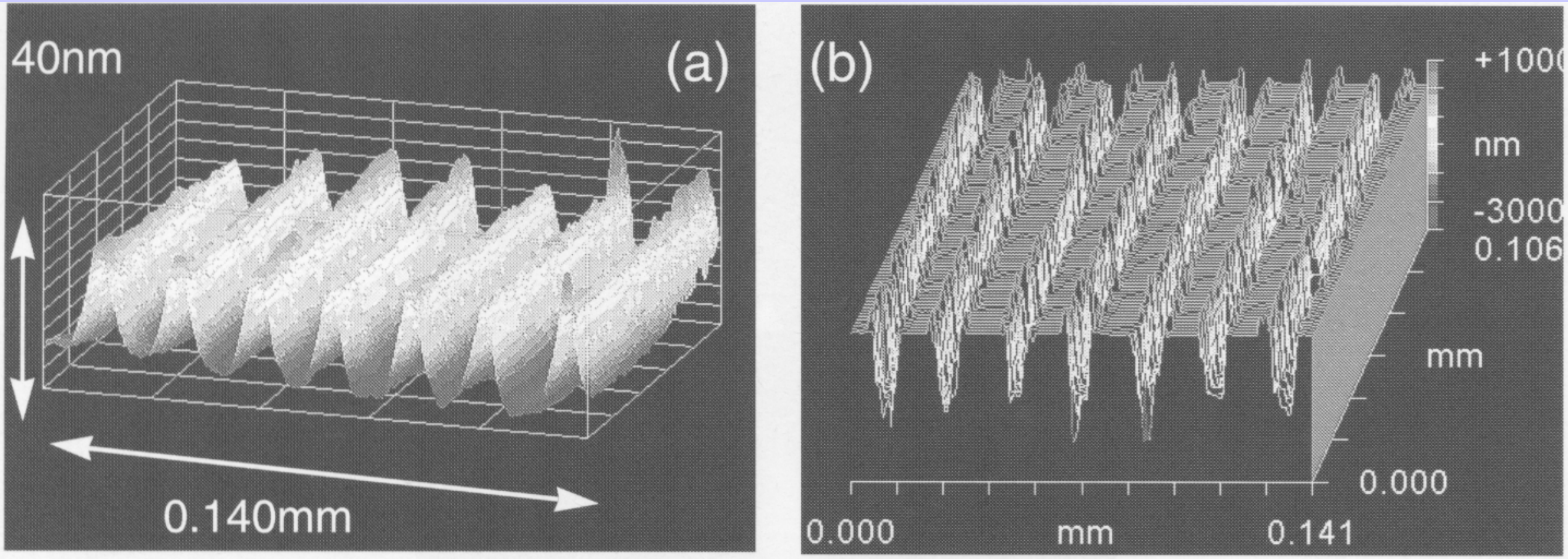


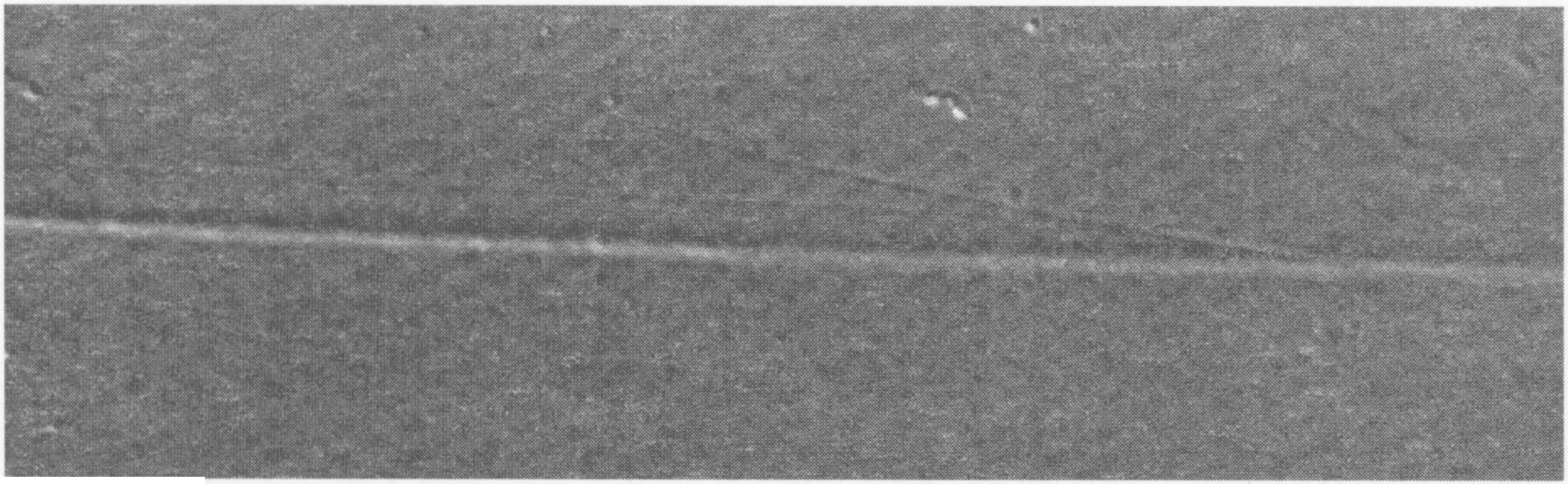
Figure 7 Surface profile of (**a**) the phase and (**b**) relief grating on the As_2S_3 film produced with sub-50 fs laser pulses from the extended cavity Ti:Sapphire oscillator.

(Adapted from: M. Richardson et al., in, *Glass and the photonics revolution*, Glass Sci. Technol., 2002)

Waveguide fabrication

Previous Raman spectroscopy studies have linked bulk glass structural changes and PS, showing that non-linear absorption-induced changes were linked to local bonding changes in As_2S_3. Following this approach, channel waveguides over 1 cm in length and ~ 10 μm in diameter were fabricated in As_2S_3 thin films, by direct writing, using the 27 MHz, 20 nJ, 100 fs Ti:sapphire laser pulses.

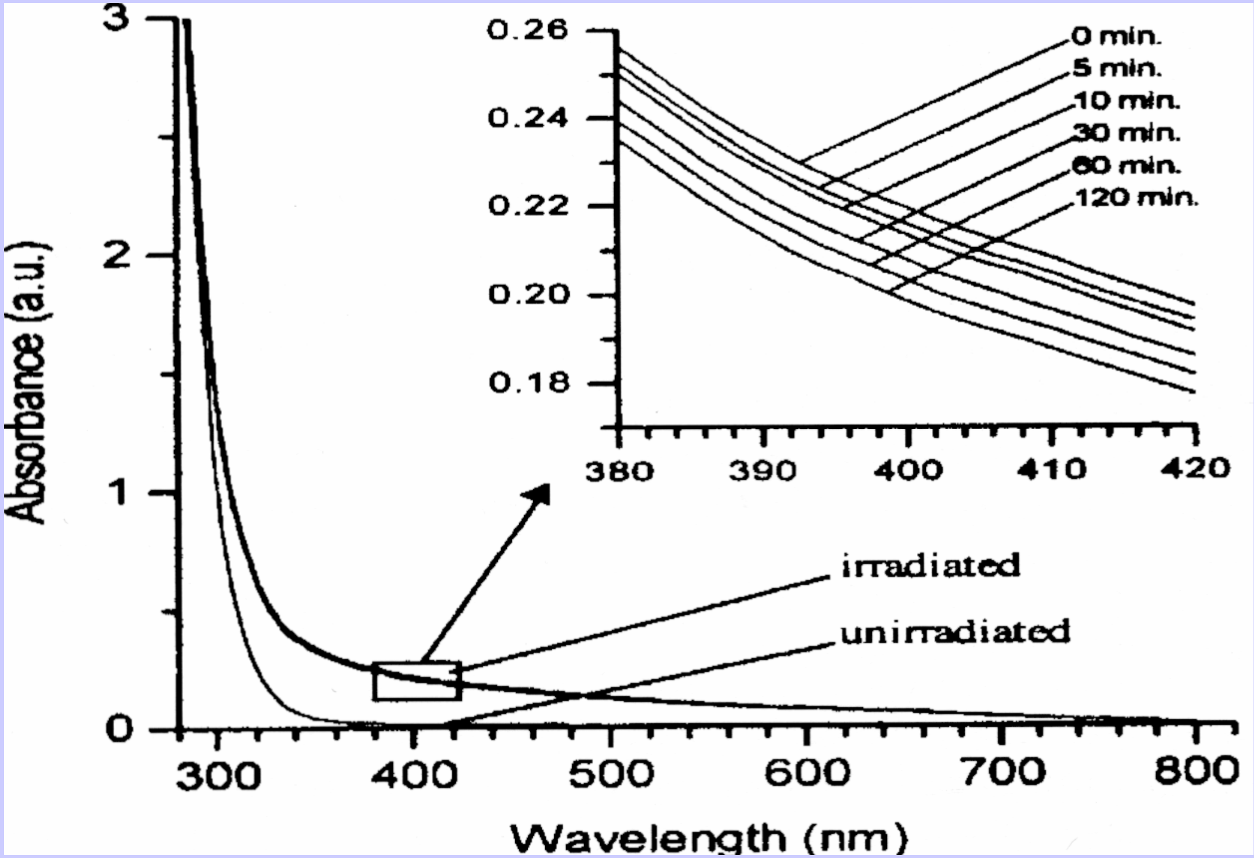
Non-linear material processing with near IR fs laser pulses will be of significant interest to optical communications systems.



Waveguide fabricated with 27 MHz, 20 nJ Ti:Sapphire laser pulses

(Adapted from: M. Richardson et al., in, *Glass and the photonics revolution*, 2002)

This figure shows the absorption spectra of Schott glass BK-7 before and after 120 fs laser irradiation @ 800 nm. Although the glass showed no absorption @ 800 nm, the short wavelength absorption increased significantly after irradiation. This laser-induced darkening could be assigned to color center formation due to trapping of electrons and holes, generated by multi-photon absorption, near glass defects.



Absorption spectra of K9 glass irradiated by the fs laser (800 nm, 120 fs) and the attenuation process after irradiation.

(Adapted from: F. Gan, in, *Glass and the photonics revolution*, Glass sci. Technol., 2002)

Acousto-optic Effects

Acousto-optical glasses

Periodic variations in the refractive index of a transparent medium by ultrasonic waves act as a diffraction grating for light. This principle can be used for the fabrication of acousto-optic modulators (smaller than electric light modulators), for example using tellurite, or other optical glasses.

When light is Bragg-reflected by a diffraction grating created by ultrasonic waves, the deflection angle, θ and the intensity of the diffracted light, I are given by:

$$\sin\theta = K / k$$

$$I = I_o \sin^2 (A\, M_e\, P / \lambda^2)^{1/2}$$

where K and k are the wavenumbers of the ultrasonic and laser light waves, respectively, A is a factor determined by the shape of the ultrasonic beam, P is the ultrasonic power, λ is the laser wavelength and M_e is a “figure of merit” of the glass. Therefore, the direction and the intensity of the diffracted light are determined by the frequency (or wavenumber) and power of the utrasonic waves.

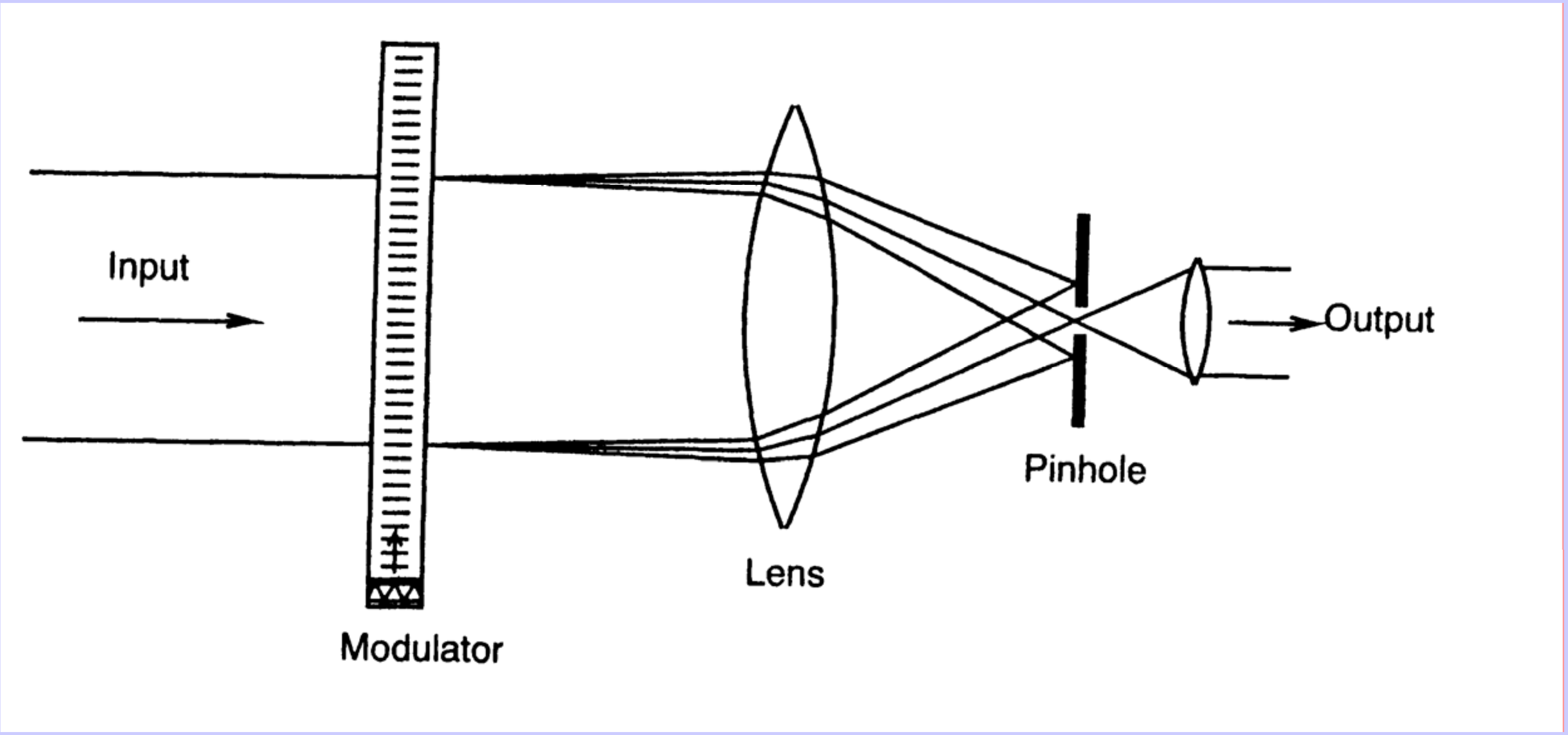
A candidate acousto-optic material must thus satisfy the following requirements:

- high figure of merit
- low ultrasonic absorption
- broad light transmission (transparency) region

The previous equation showed that the intensity of the diffracted light depends on the fugure of merit, which in turn is given by the following equation:

$$M_e = n^6\, p^2 / \rho\, v^3$$

where n is the refractive index, p is the photoelastic constant, ρ is the density and v is the velocity of sound in the glass. Tellurite glasses tend to have high figures of merit, because of their high refractive index and low sound velocity.



An analog acousto-optic modulator

(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice Hall, 1998)

Magneto-optical glasses

The magneto-optical effect in glass, the Faraday rotation, is widely used in optical isolators and magnetic field sensors. In the former case, linearly polarized laser light incident on the input side of the optical isolator has its plane of polarization rotated 45^o by a magneto-optical glass placed in a magnetic field; if the same laser light is reflected by the target and returns, it again passes through the magneto-optical glass, so its plane of polarization is rotated a further 45^o and becomes perpendicular to the polarization of the incident light, such that it cannot pass through.

The relationship between the rotation angle of the polarization plane, θ and the magnetic field intensity, H, is given by:

$$\theta = V\ H\ l$$

where l is the path length and V is the proportionality constant, the Verdet constant, specific of the particular glass.

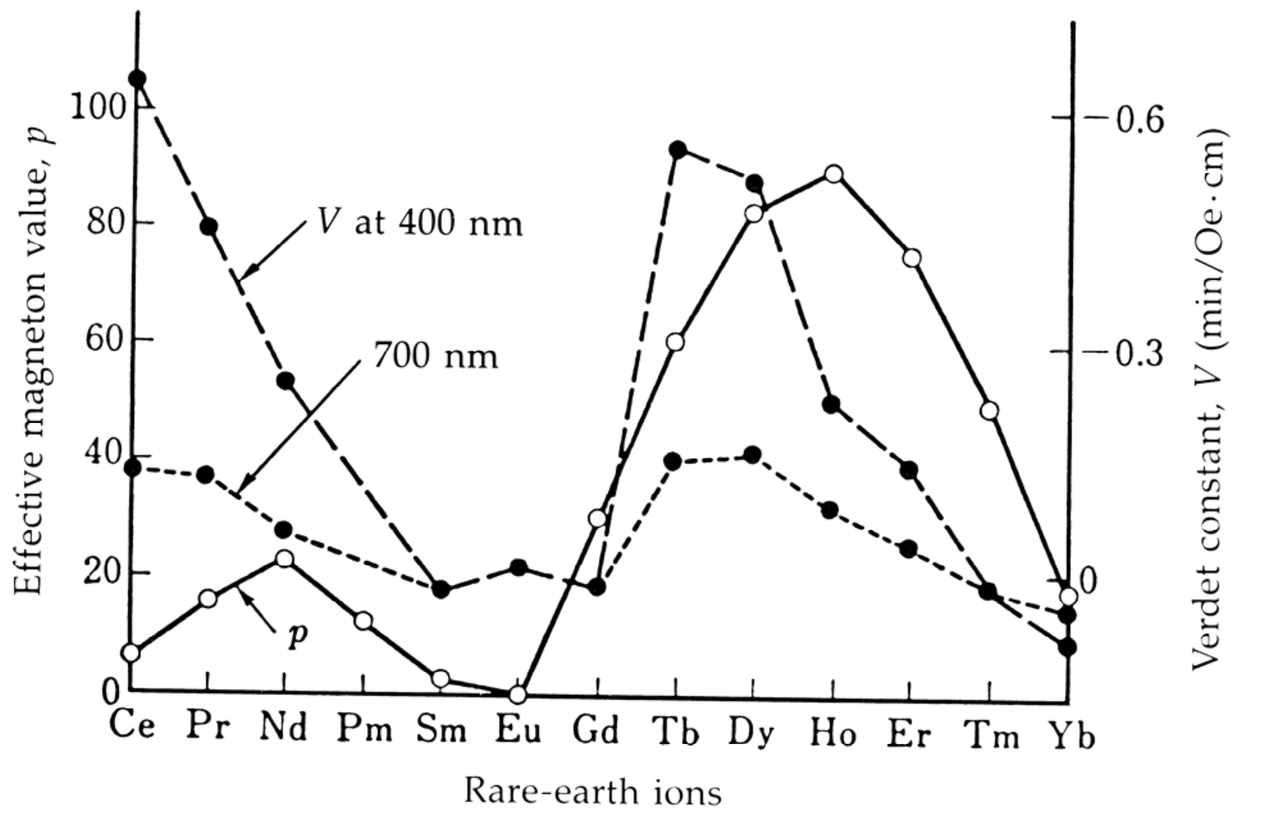
Most network former and modifier ions in glass will give rise to *diamagnetic* rotation, whereas rare-earth and transition metal ions will give rise to *paramagnetic* rotation.

Diamagnetic glasses usually have small and positive Verdet constants, almost independent of temperature, whereas paramagnetic ions have large and negative Verdet constants, generally inversely proportional to the temperature.

The origin of the Faraday effect (discovered by M. Faraday in 1830, in PbO-containing flint optical glasses) lies in the difference between the refractive indices for right- and left-circularly polarized light, i.e. n^+ and n^-, under an applied longitudinal magnetic field. Plane polarized light can be thought of as a superposition of two contra-rotating circularly polarized lights. In the presence of a magnetic field, these two light beams propagate through the glass with different velocities, corresponding to the two refractive indices, n^+ and n^-, so the resultant plane of recombined polarization (of the reconstituted linearly polarized light) will be rotated of an angle θ with respect to the original plane. θ is defined as positive (diamagnetic rotation), when it is clockwise looking along the direction of light propagation, for a magnetic field in the same direction.

Diamagnetic glasses containing Tl^+, Pb^{2+}, Bi^{3+} or Te^{4+} ions usually have a high (positive) Verdet constant. Paramagnetic glasses with Ce^{3+}, Tb^{3+}, Dy^{3+} or Eu^{2+} usually show an even higher (but negative) Verdet constant.

This figure shows Verdet constants of phosphate glasses containing rare-earth ions.



Effective magneton values and Verdet constants of phosphate glasses containing rare earths.

(Adapted from: *Optical glass*, T.S. Izumitani, Amer. Inst. Physics / Hoya Corp., 1986)

Various characteristics of Faraday rotation glasses.

	Diamagnetic glass	Paramagnetic glasses	
	SF 6	FR 4 (Hoya)	FR 5 (Hoya)
Verdet constant (min/Oe·cm)			
0.633 μm	0.093	−0.104	−0.268
1.06 μm	0.028	−0.035	−0.082
Absorption coefficient			
α (1.06 μm)	0.0065	0.0054	0.0085
n_d	1.8052	1.5718	1.6862
ν_d	25.4	56.8	53.2
n (1.064)	—	1.556	1.678
n_2 (10^{-13} esu)	9.9	1.8	2.5
Performance indices			
V/α	4.3	6.5	9.6
$V(n/n_2)$	0.005	0.030	0.055

(Adapted from: *Optical glass,* T.S. Izumitani, Amer. Inst. Phys. / Hoya Corp., 1986)

Among the optical glasses, SF (heavy flint) glasses have large (positive) Verdet constants and are particularly useful for the visible / near IR range, since they have a large optical dispersion, due to the presence of Pb^{2+} ions.

ChG's have high dispersion and correspond also to large Verdet constants.

Applications – optical isolators

Optical isolators are very important optical components, which allow the passage of light in only the forward direction, but prevent the passage of light in the backward direction. So these are large unidirectional light gates, which prevent back reflection of light into lasers or optical amplifiers (e.g. in the EDFA's) and reduce signal instability and noise. In the high power controlled laser fusion experiments, for example, where amplified light is directed against a small target, there is the danger that laser materials or optical components will be hit by light back reflected by the target, so they need to be protected against such a possibility, by an optical isolator.

This figure shows a schematic diagram of an optical isolator. A Faraday rotation material (e.g., a glass) is placed between input and output polarizers oriented at 45^o and a magnetic field is applied, which will rotate the plane of polarization of light by 45^o. The polarization of back-reflected light undergoes an additional 45^o rotation and is rejected by the input polarizer. Low absorption at the laser wavelength is also important for the Faraday rotator glass.

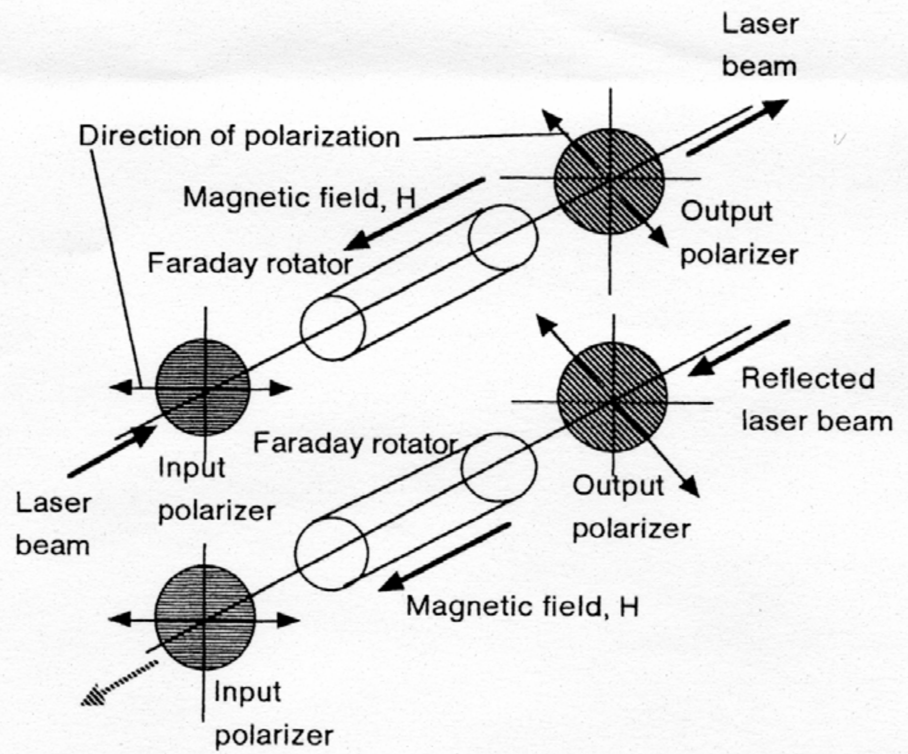


Fig. 5.7. Principle of optical isolator using Faraday effect.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, UK, 2000)

Another application of magneto-optical glasses is as current sensors.

A current sensor consists of a glass fiber coil turning around an electric power cable. Linearly polarized light is emitted by a polarization-maintaining fiber and the plane of polarization of the light transmitted by the fiber will be rotated due to the Faraday effect, generated by the magnetic field associated with the current passing through the cable. The light is divided into two orthogonally polarized beams by an analyzer and the rotation of the polarization angle is then converted into magnetic field and current intensities.

Diamagnetic glasses are usually chosen for this application, because of the superior temperature stability of their Verdet constant. In particular, special flint glasses with no photoelastic effect are usually chosen, in order to prevent polarization disturbance caused by bending of the fiber.