Suppression of Self-Induced Depolarization of Laser Radiation in Faraday Isolators

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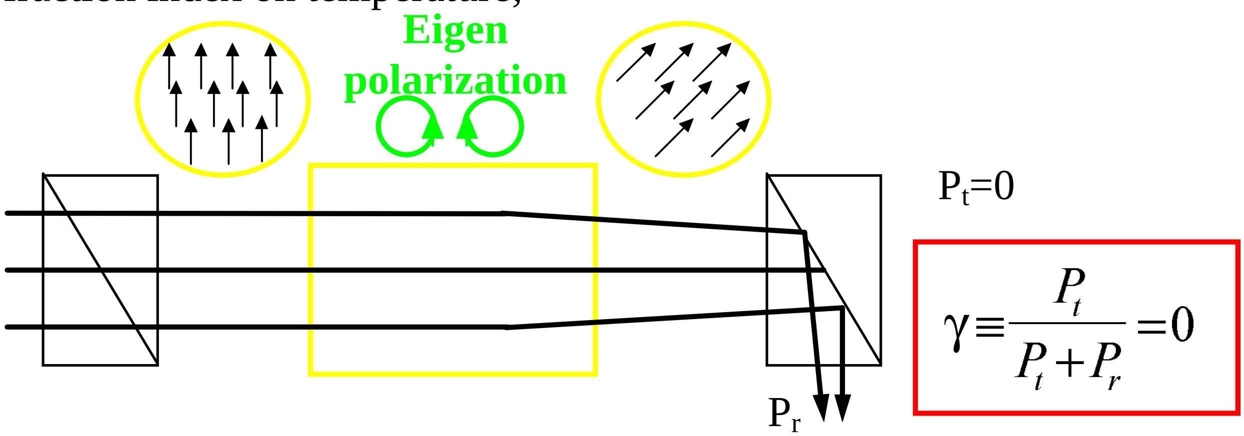
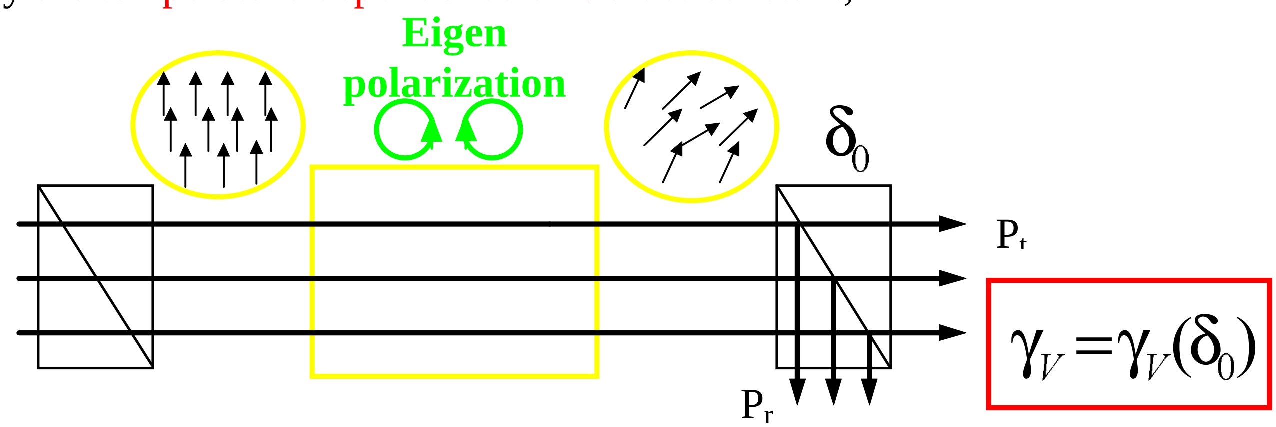
Introduction

The **light absorption in optical elements of Faraday rotators** causes nonuniform cross-section distribution of temperature, which has three physical mechanisms of influence upon laser radiation;

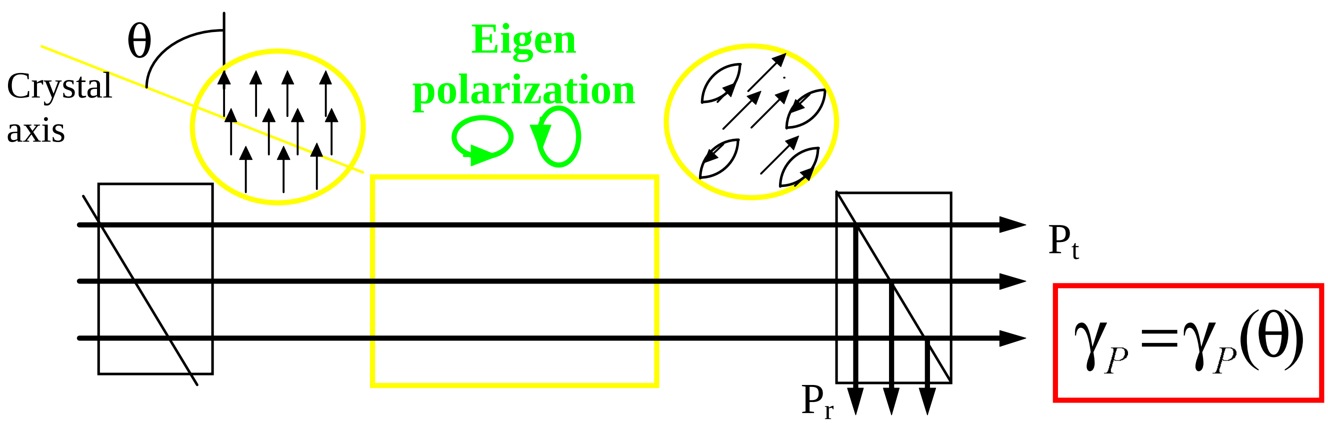
1) wavefront distortions, or thermal lens, caused by the dependence of the refraction index on temperature;



2) nonuniform distribution of the rotation angle of the polarization plane caused by the temperature dependence of Verdet constant;



3) simultaneous appearance of circular (Faraday effect) and linear birefringence as a result of mechanical strains due to temperature gradient (photoelastic effect).



I. Comparison of the influence of the temperature dependence of the Verdet constant and the photoelastic effect

In case of small depolarization, i.e. $\gamma \ll 1$

$$\gamma = \gamma_V(\delta_0) + \gamma_P(\theta)$$

Thus, the depolarization is a sum of two terms representing two physical mechanisms that give rise to the depolarization.

$$\gamma_P^{\min} = \left[\frac{L\alpha P_0 Q}{\lambda\kappa}\right]^2 \cdot \frac{A_1}{\pi^2} \qquad \gamma_V^{\min} = \left[\frac{\alpha P_0}{16\cdot\kappa}\cdot\frac{1}{V}\frac{dV}{dT}\right]^2 \cdot A_3$$

Here indexes «min» indicate values of γ_p and γ_V obtained at optimum values of θ and δ_0, respectively, and

P_0 - laser power
L - length of optical element
α - absorption
κ - thermoconductivity
Q - thermo-optic constant
V - Verdet constant

$$A_1 = \int_0^\infty \left(1/y - \exp(-y)/y - 1\right)^2 \exp(-y)dy \cong 0.137$$

$$A_3 = \int_0^\infty f^2(y)\exp(-y)dy - \left[\int_0^\infty f(y)\exp(-y)dy\right]^2 \cong 0{,}268, \quad f(y) = \int_0^y \frac{1-\exp(-z)}{z}dz$$

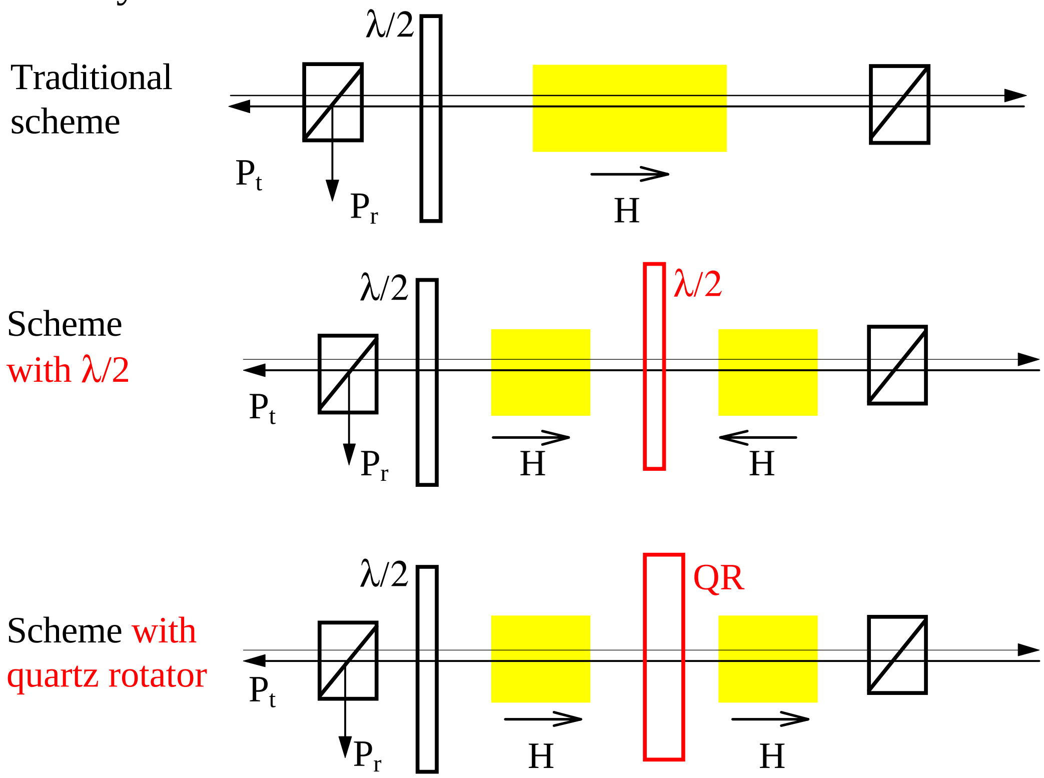
$$\frac{\gamma_V^{\min}}{\gamma_P^{\min}} = 2\cdot\left[\frac{\pi}{16}\cdot\frac{\frac{1}{V}\frac{dV}{dT}}{Q}\cdot\frac{\lambda}{L}\right]^2 \le 0.01$$

Thus, the influence of the temperature dependence of the Verdet constant on depolarization is much lower than that of the photoelastic effect.

Investigation of the ways of compensating depolarization caused by photoelastic effect is therefore more promising. In our discussion to follow we shall neglect the temperature dependence of the Verdet constant.

II. Novel schemes of Faraday isolators

The idea of compensating depolarization consists in using two 22.5° rotators and a reciprocal optical element between them instead of one 45° Faraday rotator. The basic idea of compensating depolarization consists in using two 22.5° rotators and a reciprocal optical element between them instead of one 45° Faraday rotator.



$$\gamma_{0,L,R} \equiv \frac{P_t}{P_t + P_r}$$

Jonse matrices for all optical elements determine the isolation ratio.

$$F = \sin\frac{\delta}{2} \cdot \begin{pmatrix} ctg\frac{\delta}{2} - i\frac{\delta_l}{\delta}\cos 2\Psi & -\frac{\delta_c}{\delta} - i\frac{\delta_l}{\delta}\sin 2\Psi \\ \frac{\delta_c}{\delta} - i\frac{\delta_l}{\delta}\sin 2\Psi & ctg\frac{\delta}{2} + i\frac{\delta_l}{\delta}\cos 2\Psi \end{pmatrix} \qquad \delta^2 = \delta_l^2 + \delta_c^2$$

$$R(\beta_R) = \begin{pmatrix} \cos\beta_R & \sin\beta_R \\ -\sin\beta_R & \cos\beta_R \end{pmatrix} \qquad L(\beta_L) = \begin{pmatrix} \cos 2\beta_L & \sin 2\beta_L \\ \sin 2\beta_L & -\cos 2\beta_L \end{pmatrix}$$

$\delta_l = \delta_l(r,\varphi,Q,\xi_a,\vartheta)$ - phase delay of linear eigen polarization

$\Psi = \Psi(r,\varphi,\xi_a,\vartheta)$ - direction of linear eigen polarization

δ_c - phase delay of circular eigen polarization

β_R - angle of rotation of quartz rotator

$$\xi_a = \frac{2p_{44}}{p_{11} - p_{12}}$$

β_R - the inclination angle of the $\lambda/2$ plate optical axis

III. Comparison of the novel and traditional schemes
(case of small depolarization, i.e. $\gamma \ll 1$)

The depolarization ratio $\gamma_{0,L,R}$ can be minimized by

1) **varying the angle $\beta_{L,R}$** i.e., rotating the $\lambda/2$ plate or changing the thickness of quartz rotator

$$\beta_{optL} = \pi/8 + N\pi/2 \qquad \beta_{optR} = 3\pi/8 + N\pi$$

2) **varying the angle θ**, i.e., rotating the crystal around beam axis

$$\theta_{opt\,0} = -\pi/8 \qquad \theta_{optL} = \frac{\pi}{16} + \frac{1}{4}\arcsin\left[\frac{a}{b}\cdot\frac{\xi_a^4 - 1}{(1-\xi_a^2)^2}\right] \qquad \theta_{optR} \text{ - any angle}$$

The minimal values of the depolarization ratio $\gamma_{min0,L,R} = \gamma_{0,L,R}(\theta_{opt}, \beta_{opt})$ are

$$\gamma_{\min 0} \cong 0.014\,p^2 \,,$$

$$\gamma_{\min L} \cong 0.846 \cdot 10^{-4}\,\xi_a^2 p^4$$

$$\gamma_{\min R} \cong 0.4 \cdot 10^{-5}\left(1 + \frac{2}{3}\xi_a^2 + \xi_a^4\right)p^4$$

$$p = \frac{L}{\lambda}\frac{\alpha Q}{\kappa}P_0$$

Parameter p characterizes the force of the photoelastic effect.

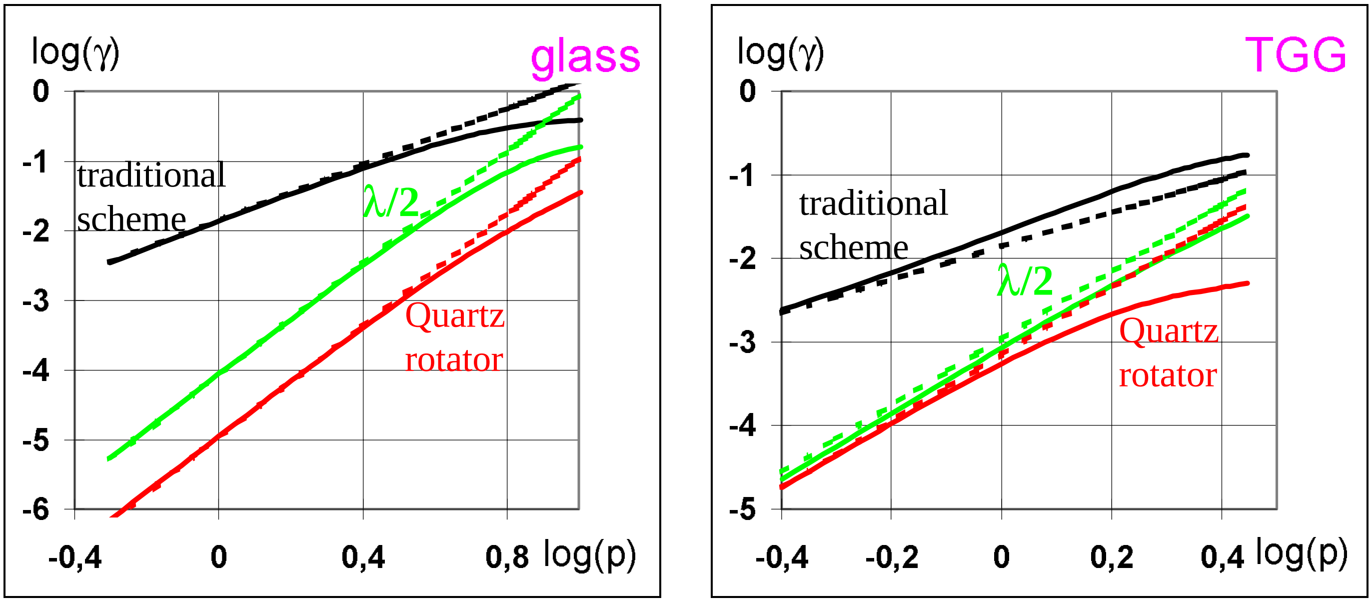
$\xi_a = 1$ for glass $\qquad \xi_a = 3.6$ for TGG

The formulas for $\gamma_{min0,L,R}$ are justified at any ξ_a including $\xi_a = 1$, i.e., for glass magnetooptical media in which the depolarization ratio does not depend on θ.

IV. Comparison of the novel and traditional schemes

(case of large depolarization, i.e. $\gamma \approx 1$)

At a given ξ_a the depolarization ratio of a Faraday isolator, like in the case of the weak linear birefringence, is completely determined by parameter p.



Dashed lines show the formulas for small depolarization.

<u>Approximate</u> estimations show that

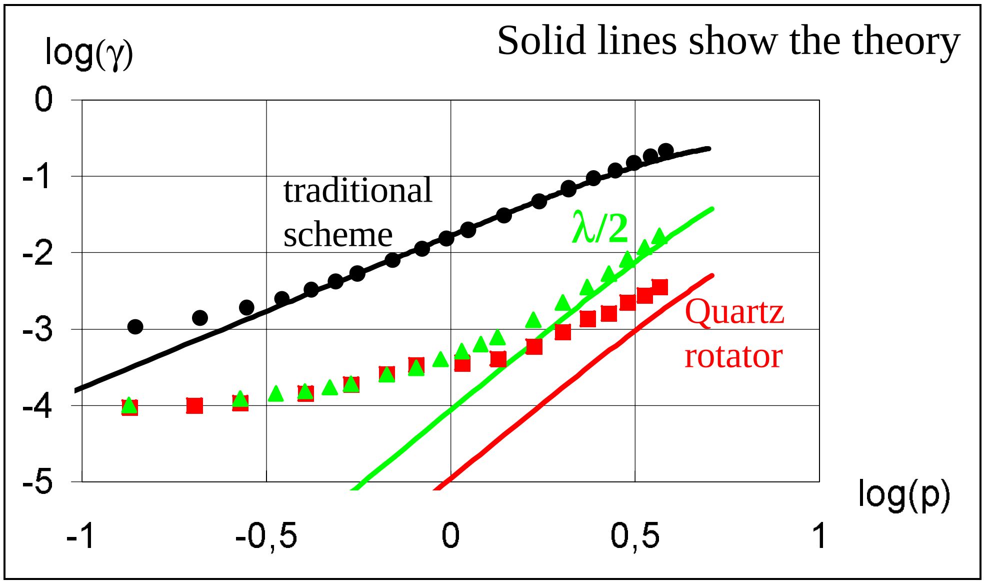
for TGG p=1 at power P_0=2.5kW
(Q=7×10^{-7}/K, κ=7W/Km , L/λ=2×10^4, α=2×10^{-3} cm^{-1}).

for glass p=1 at power P_0=250W
(Q≅5×10^{-7}/K, κ=0.5W/Km, L/λ=4×10^4, α=2×10^{-3} cm^{-1}).

Taking into account these estimations and graph, it is evident that the novel schemes allow construction of Faraday isolators with isolation ratio of 30 dB (γ=10^{-3}) for average laser power at kW (glass) and multikW (TGG) level.

V. Experimental investigation of novel schemes

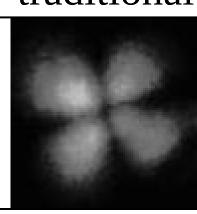
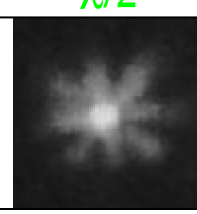
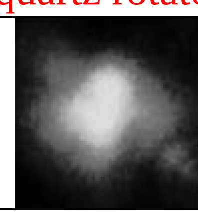
- **λ=532nm**
- **CW Nd:YAG laser**
- **power up to 5.5 W**
- **2 mm diameter Gaussian beam.**
- **magneto-optical glass**
- **absorption α(532nm)=0.05cm^{-1}**



The disagreement between the predictions and experiment at low power is due to the residual, power independent depolarization in magneto-optical elements.

At high powers, however, when the depolarization ratio is mainly determined by self-induced effects, experimental data are in good agreement with theoretical predictions for all three schemes

The good agreement of the experiment with theoretical analysis, which assumes only photoelastic-induced depolarization, confirms the theoretical prediction that the photoelastic limits the isolation ratio at high average power. Analysis of the transverse structure of the depolarized radiation also confirms this result:

	traditional	λ/2	quartz rotator
Images of the spatial profiles of the depolarized beams			
Theoretical prediction of period of the dependence of the local depolarization ratio on the polar angle	90^0	**45^0**	**No** angular dependence

VI. Conclusions

The theoretical and experimental investigation of a traditional scheme of a Faraday isolator and two novel schemes with a $\lambda/2$ plate and with a quartz allows us to draw the following general conclusions.

- The depolarization ratio is a sum of two terms which represent two effects: the change in the angle of rotation due to the temperature dependence of the Verdet constant and, more efficient, the birefringence due to the photoelastic effect of thermal strains.
- At optimal values of β and θ the depolarization ratio (and, consequently, the isolation ratio) is determined by parameters p and ξ_a in all three schemes.
- Parameter p characterizes the degree of influence of the photoelastic effect on the depolarization ratio. To decrease the depolarization ratio, the parameter p must be decreased. Parameter ξ_a may assume two values of much practical interest: $\xi_a = 3.6$ for TGG crystal and $\xi_a = 1$ for all types of glass.
- The depolarization ratio in the both novel schemes is considerably lower than in the traditional scheme at any value of parameter p.
- For Faraday isolators with glass optical elements the novel scheme with a rotator is most optimal at any p. When TGG is used, the both novel schemes have approximately equal depolarization ratios at small p; when p is large, the scheme with a rotator ensures a significantly lower depolarization ratio.
- The data obtained confirm the possibility of creating a Faraday isolator with isolation ratio of 30 dB for laser radiation with average power of several kilowatt.

Scheme	β_{opt}	θ_{opt}	γ_{min} **at** $p<p_m$ **(accuracy 5%)**		p_m		γ_{min} **at high*** p	
		TGG	glass	TGG	glass	TGG	glass, p=2	TGG, p=6
traditional	–	$-\pi/8$	$1.4\times10^{-2}p^2$	$1.4\times10^{-2}p^2$	1.7	0.1	0.29	0.11
with half-wave plate	$\pi/8$	$\cong$0.275 0.90	$0.85\times10^{-4}p^4$	$1.1\times10^{-3}p^4$	2.5	1.0	0.060	0.010
with reciprocal rotator	$3\pi/8$	$\pi/16$	$1.07\times10^{-5}p^4$	$0.71\times10^{-3}p^4$	2.5	0.5	0.0084	0.0034

*) These values of p approximately correspond to power of laser radiation 1.5kW for glass and 5kW for TGG.