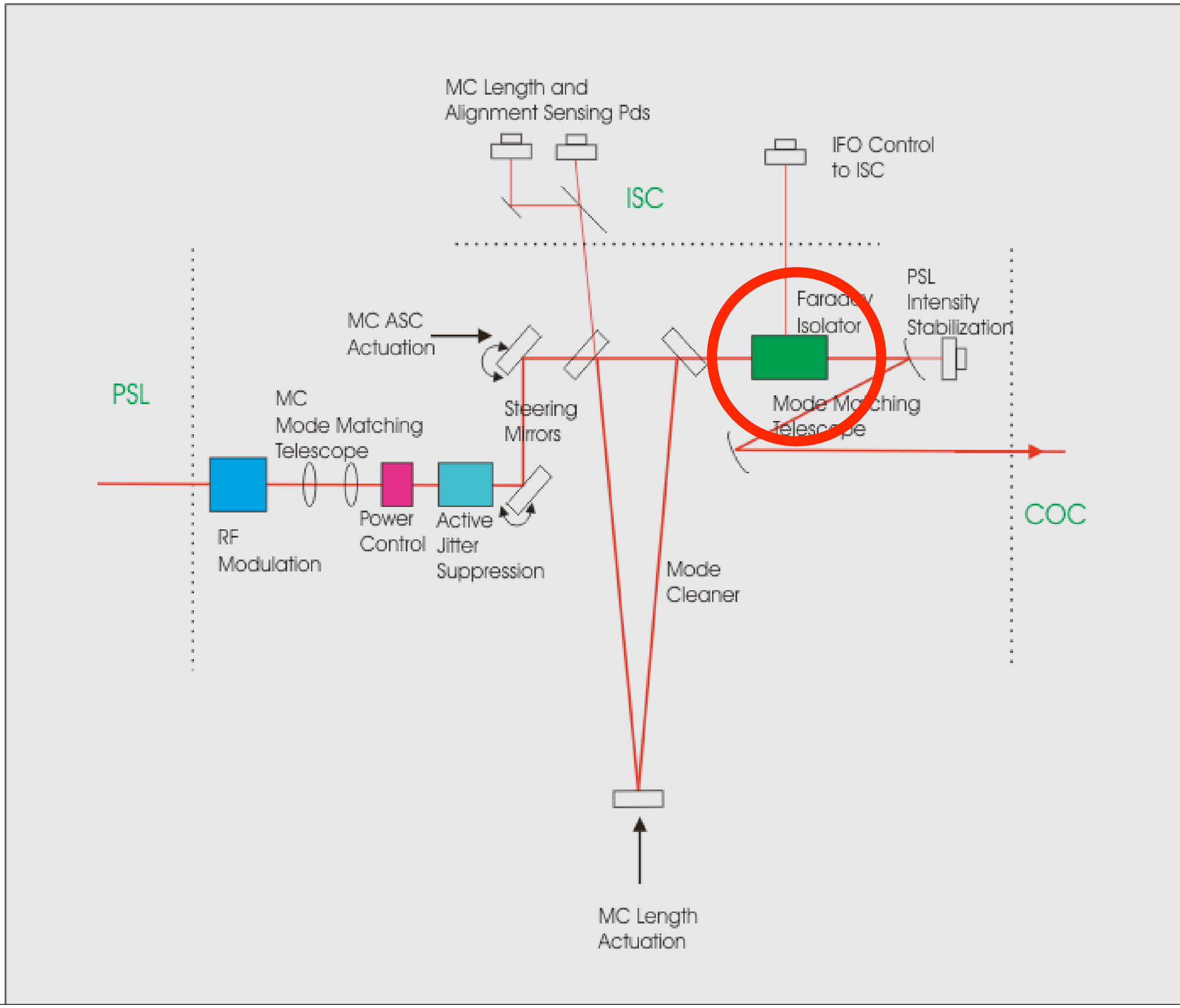
Case Study: Faraday Rotators in LIGO

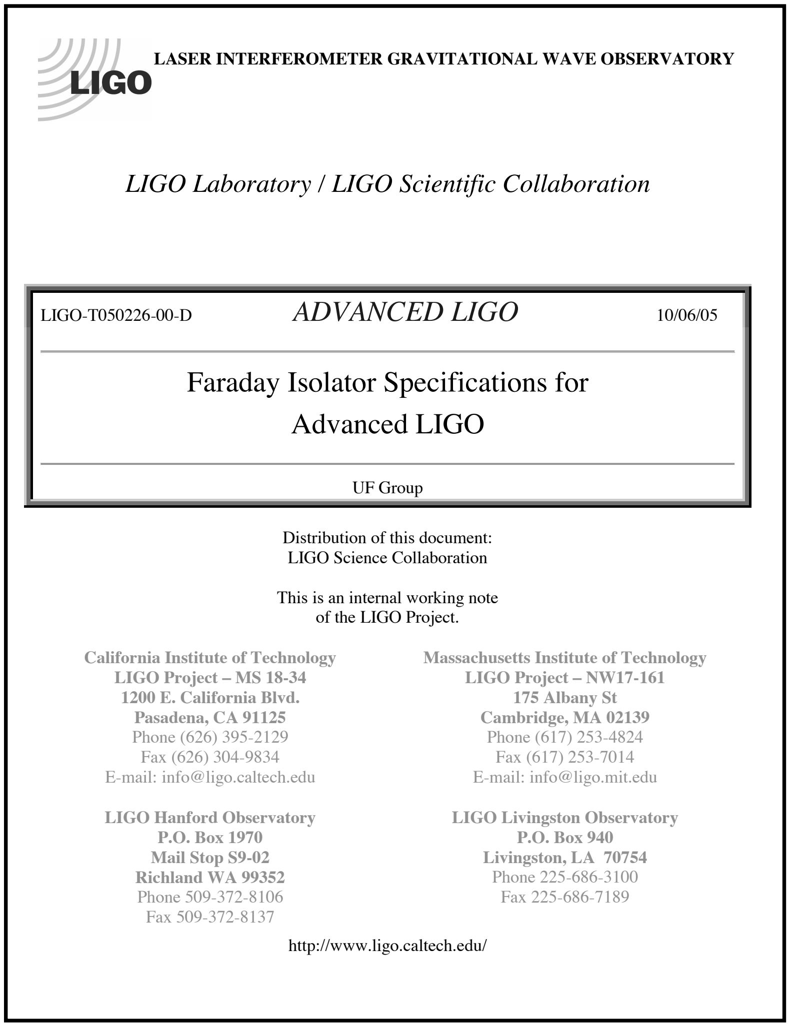
Physics 208, Electro-optics

Peter Beyersdorf

Input Optics Overview



Requirements for LIGO faraday isolator



LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T050226-00-D *ADVANCED LIGO* 10/06/05

Faraday Isolator Specifications for
Advanced LIGO

UF Group

Distribution of this document:
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Optical Requirements

- 0-180 W CW power
- $T_{forward}$>96%
- $T_{backwards}$>80%
- "p" Input polarization
- "p" output polarization
- >38 dB power isolation
- <5% coupling out of TEM_{00} mode
- <100 μrad thermal beamsteering

Verdet Constant of Common Materials

Table 4.5. Values of the Verdet Constant at $\lambda = 5893$ Å

Substance	T (°C)	V (deg/G · mm)
Water	20	2.18×10^{-5}
Fluorite		1.5×10^{-6}
Diamond		2.0×10^{-5}
Glass (crown)	18	2.68×10^{-5}
Glass (flint)		5.28×10^{-5}
Carbon disulfide (CS_2)	20	7.05×10^{-5}
Phosphorus	33	2.21×10^{-4}
Sodium chloride		6.0×10^{-5}

Periodic Table of the Elements

Substances with paramagnetic ions (such as Terbium) have the largest Verdet constants. Maximum paramagnetism comes from lanthanide and actinide ions with maximum number of singly filled f shells

Mateial Properties of TGG

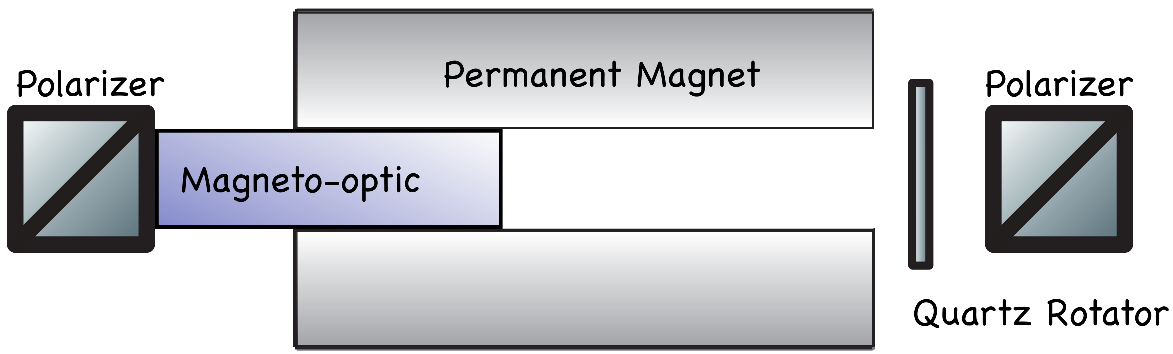
Terbium Gallium Garnet - TGG ($Tb_3Ga_5O_{12}$)

Crystal structure	cubic
Lattice constant, Å	12.347
Thermal conductivity, W x cm^{-1} x ¡K^{-1}	0.045
Refractive indexes:	
at 1060 nm	1.954
at 600 nm	1.978
Birefrigence, %	< 0.01
Insertion loss, cm^{-1}	< 0.01
Extinction ratio, dB	>30
Absorption coefficient at 500 - 1200 nm, cm^{-1}	0.0055 - 0.0060
Verdet constant (V), deg x $gauss^{-1}$ x mm^$^{-1}$	
at 1058 nm	1.2 x 10^{-4}
at 633 nm	4.6 x 10^{-4}
Pulse damage threshold, MW/cm^2	>300
Operation temperature range, ¡C	23 ± 5
Orientation of the rod axis	<100> or <111> crystallographic direction (± 15')

Thermal conductivity is an order of magnitude higher than for terbium doped glasses

Verdet constant is twice that of terbium doped glasses

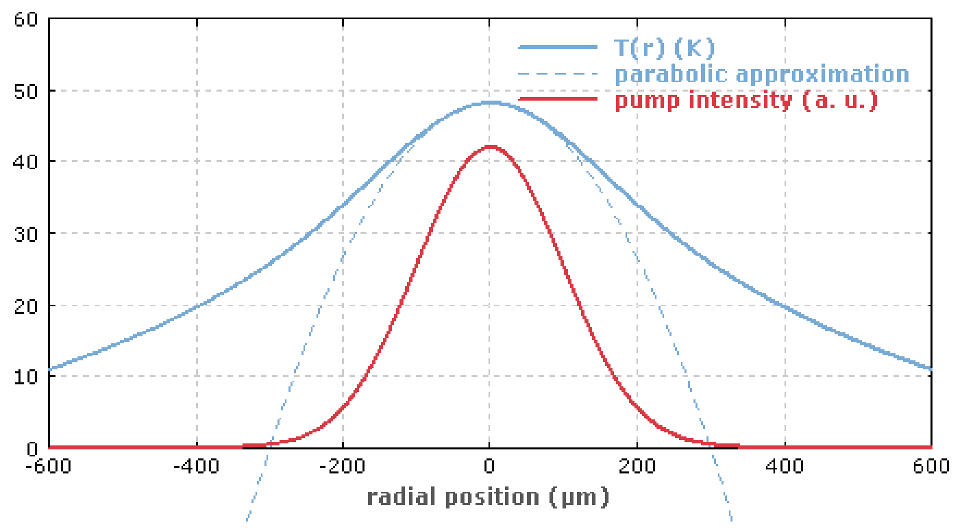
Typical Faraday Isolator Design



- Large permanent magnet surrounds magneto-optic glass or crystal.
- Amount of insertion of magneto-optic material in magnet can be adjusted to compensate change in birefringence asa function of wavelength.
- Quartz rotator restores polarization of forward beam to match the input polarization.
- Polarizers redirect retro-reflected beams

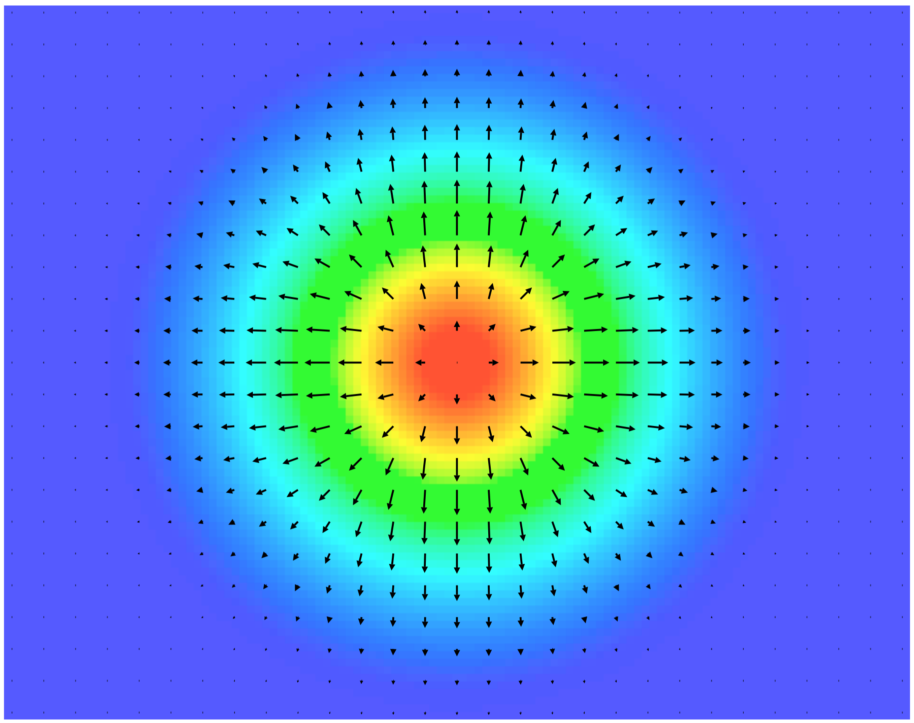
Thermal Lensing

Parabolic radial temperature profile in optic leads to non-uniform thermal expansion producing "thermal lens"

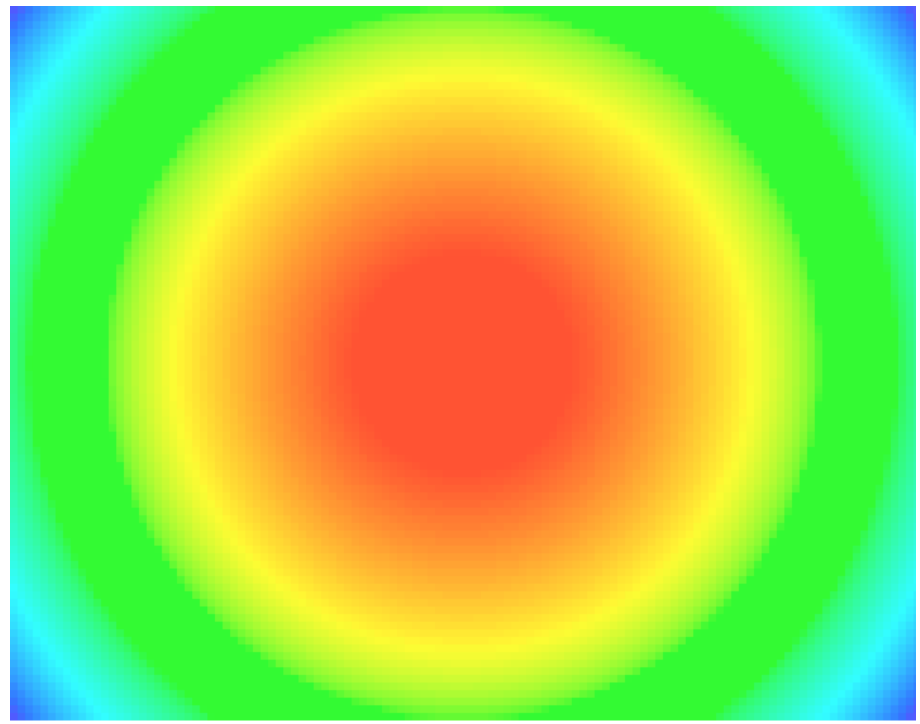


Temp dependence of Verdet Constant

Temperature gradient in crystal due to beam profile results in a non-uniform polarization rotation



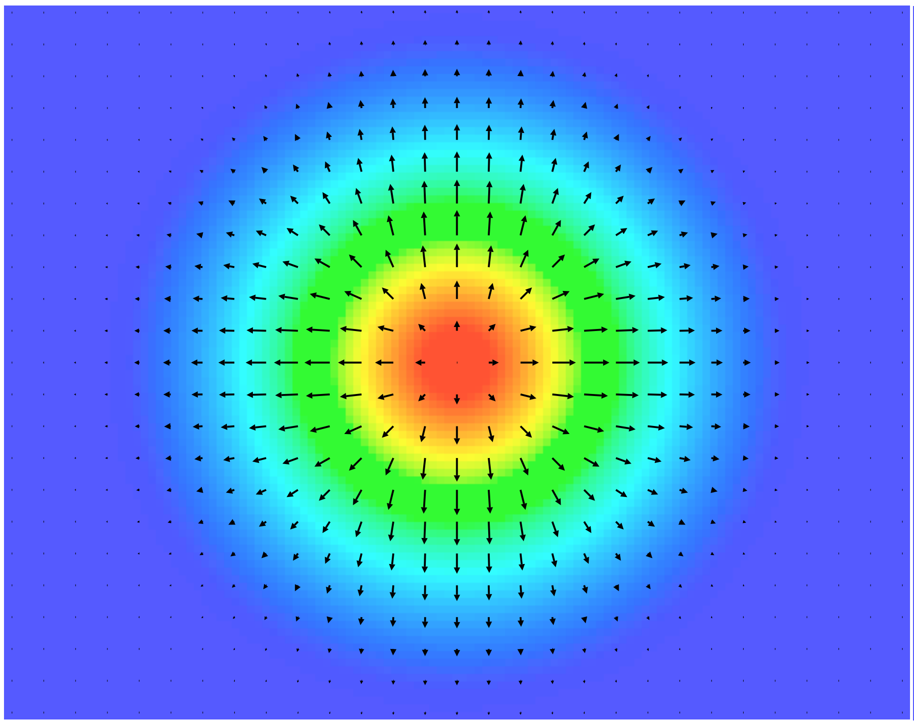
TEM_{00} mode power distribution and thermally induced strain field



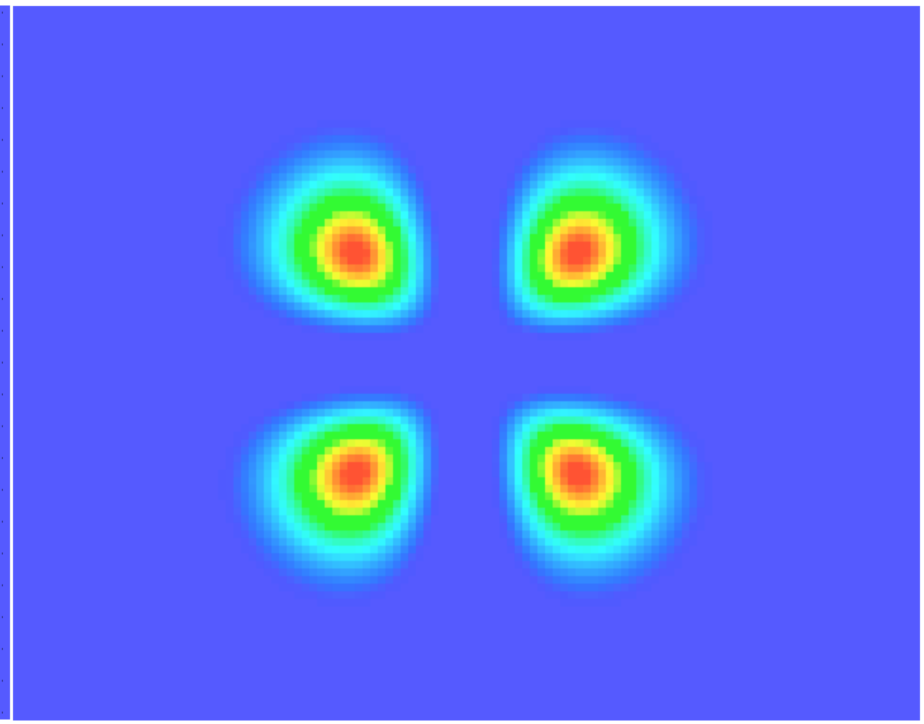
parabolic distribution of depolarization

Stress Induced Birefringence

Like high power rod lasers, stress induced birefringence causes depolarization

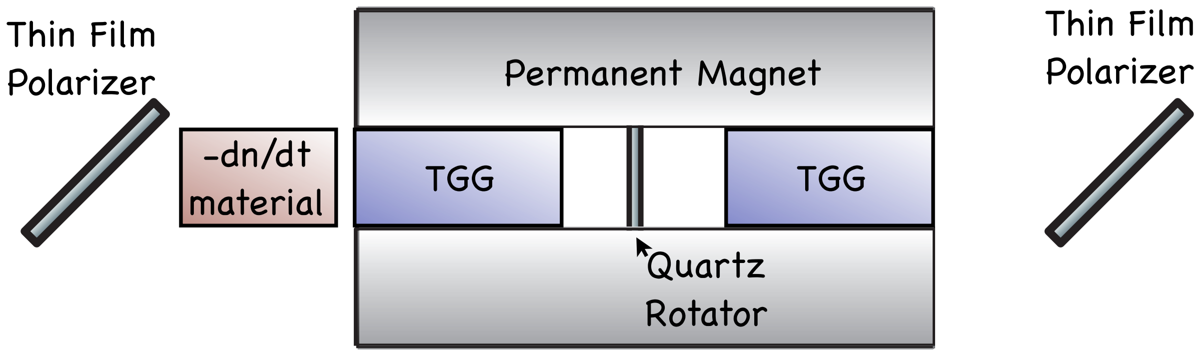


TEM_{00} mode power distribution and thermally induced strain field



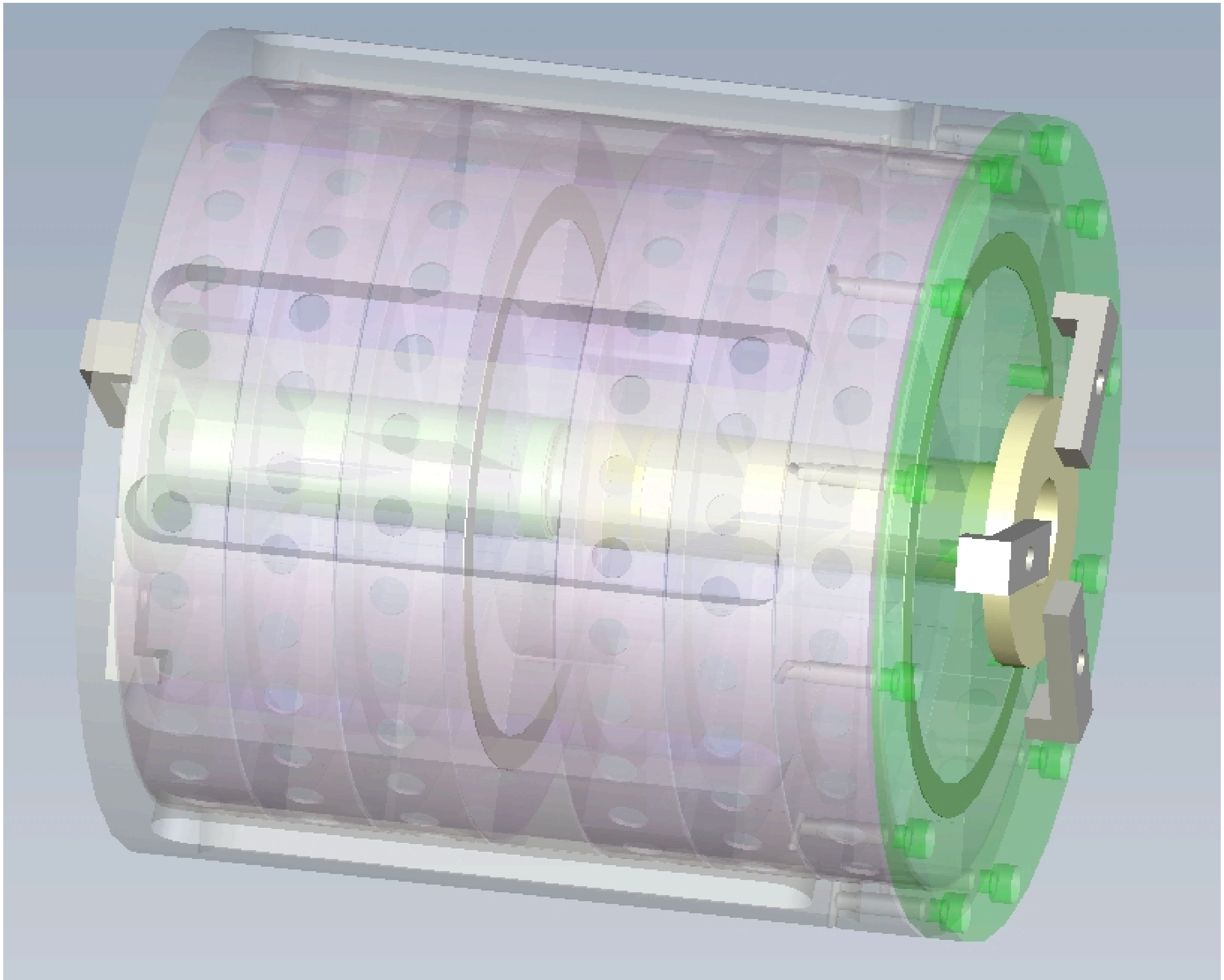
Spatial map of polarization conversion by stress induced birefringence

LIGO Faraday Isolator Design

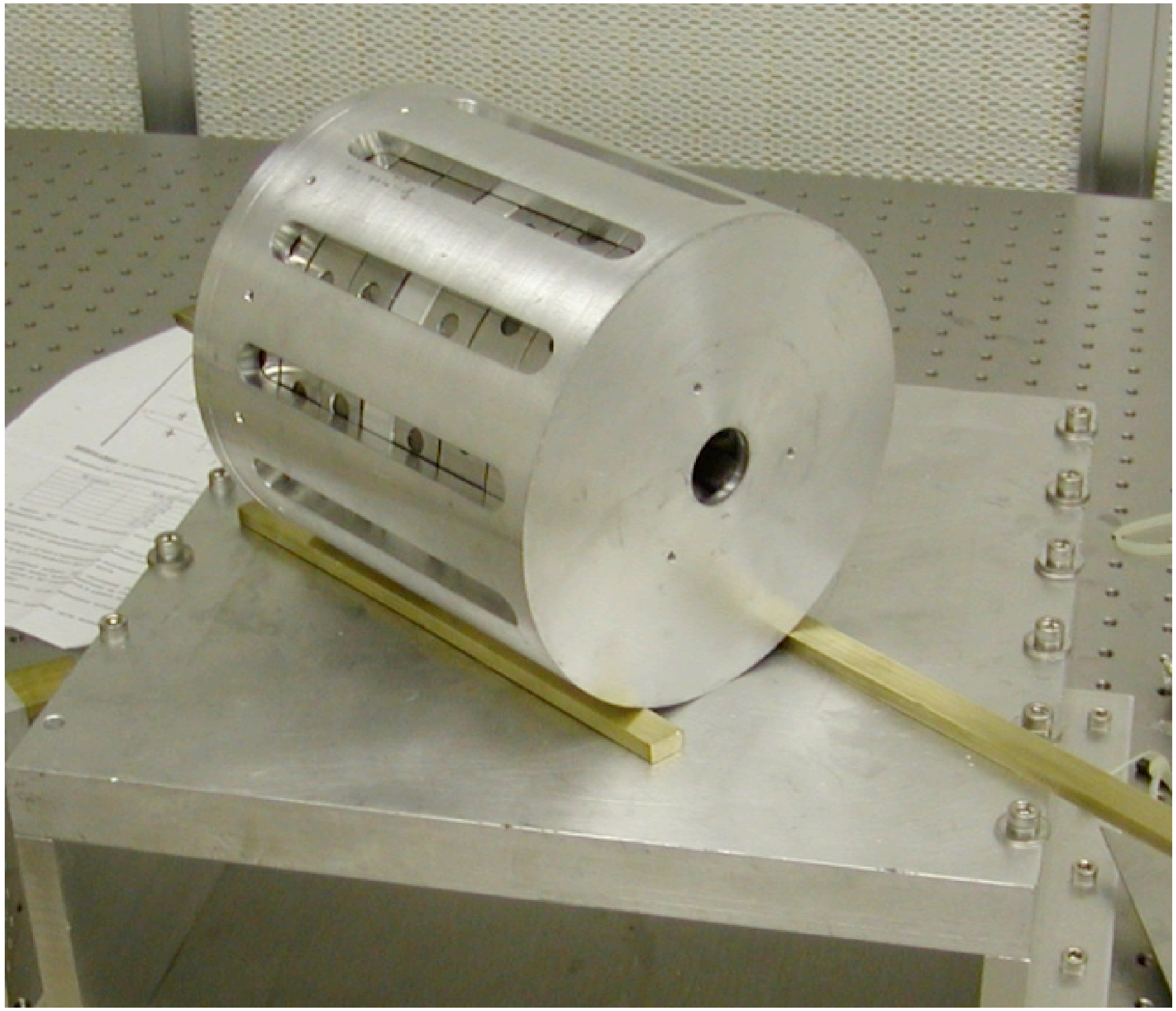


- Material with negative thermal lens compensates for thermal lensing in the magneto-optic crystal (TGG)
- Quartz rotator ($\lambda/2$ plate at 22.5°) is placed between the two halves of the TGG crystal, allowing one crystal to compensate for the depolarization in the other one.
- Thin Film Polarizers replace cube polarizers to reduce thermal drift of beam steering

LIGO faraday Isolator Design

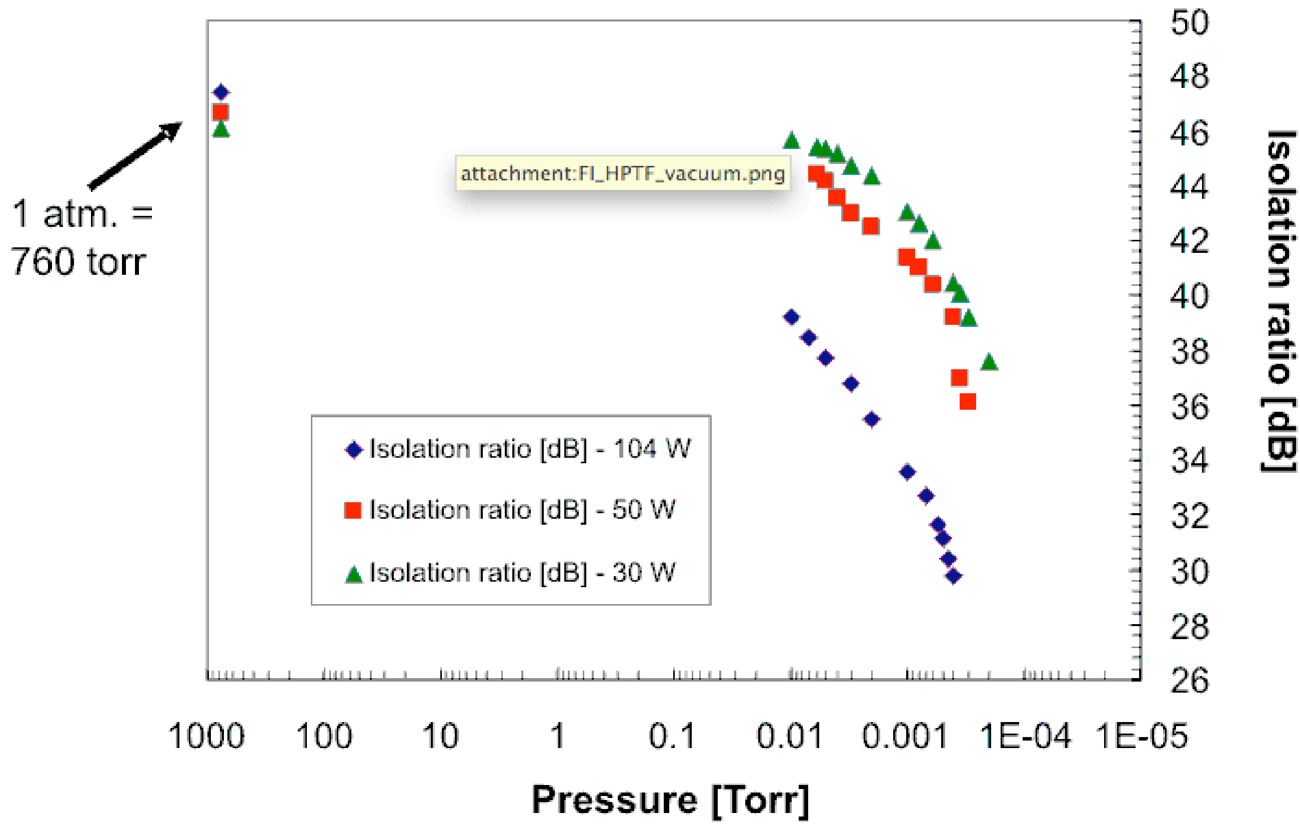


LIGO faraday Isolator Design



Faraday Isolator Performance

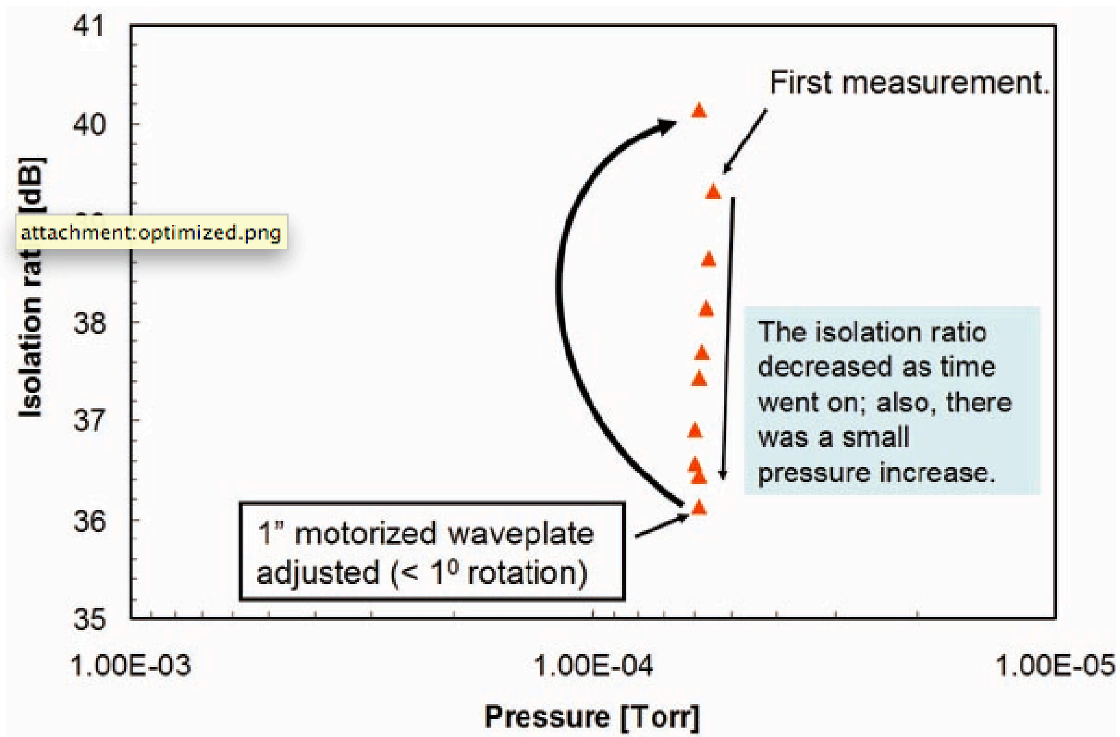
Isolation ratio as a function of vacuum chamber's pressure for three different incident laser powers (104 W, 50 W, 30 W)



The isolation ratio strongly decreased with decreasing vacuum chamber's pressure

Faraday Isolator Performance

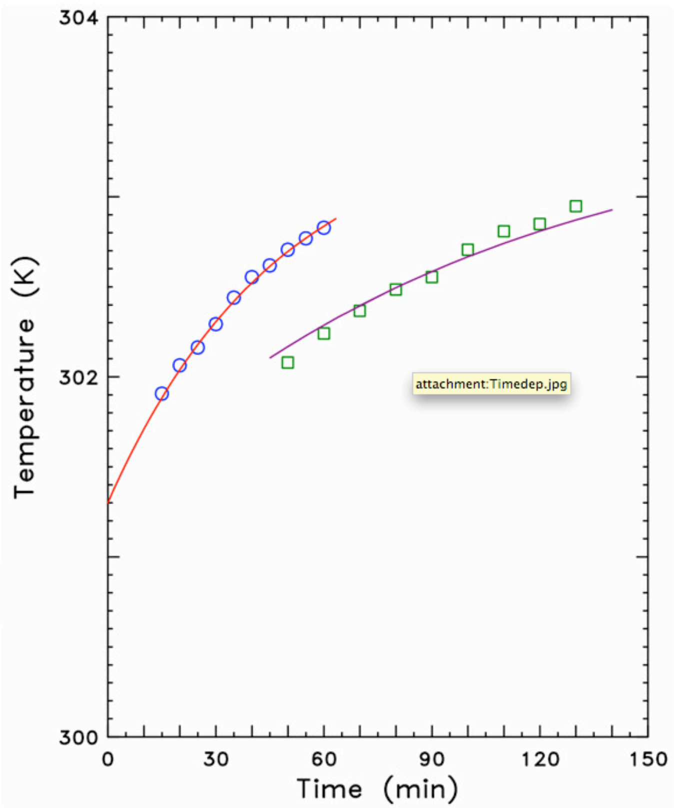
Isolation Ratio Optimized by in situ adjustment of the wave plate

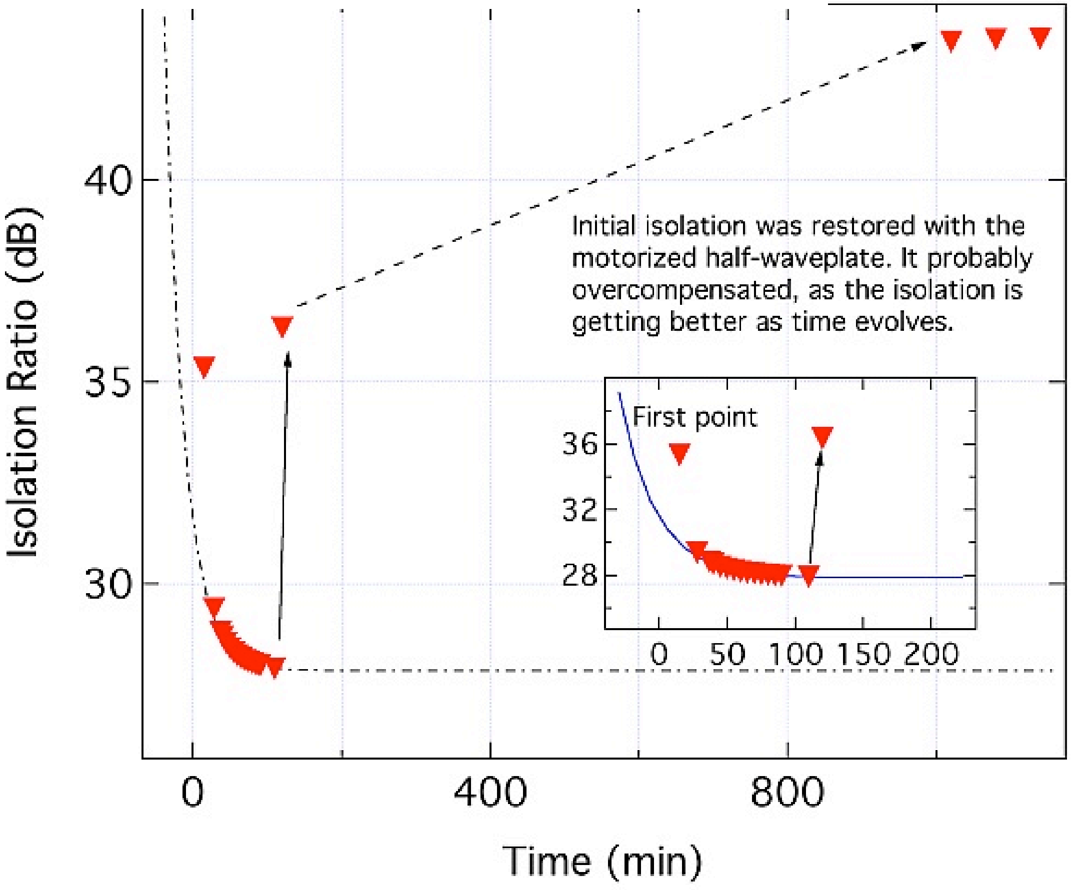


Faraday Isolator Performance

Recent performance measurement

The following measurement shows that the isolation ratio can be restored to be at least 35 dB.
(Over time it drifted to a 43dB isolation ratio.)

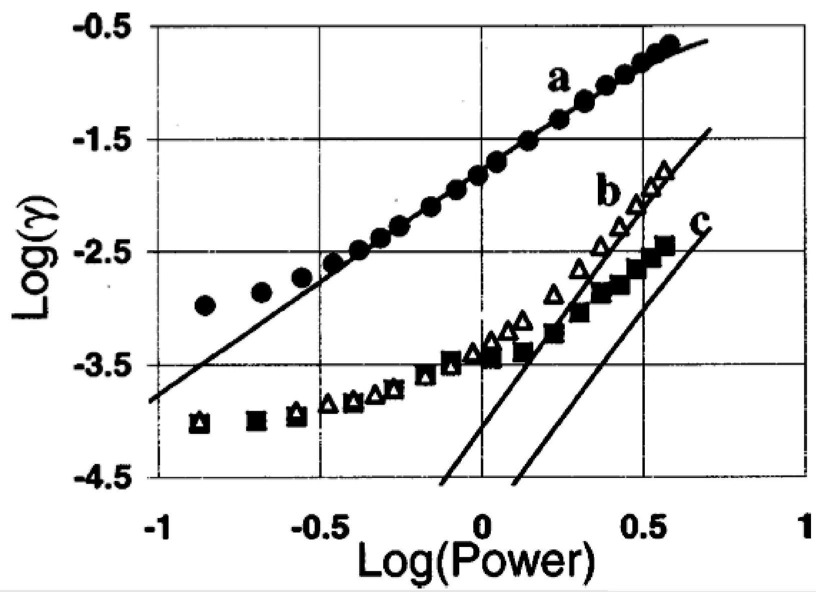


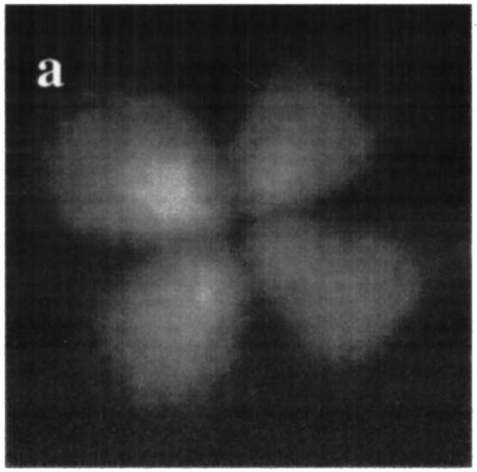


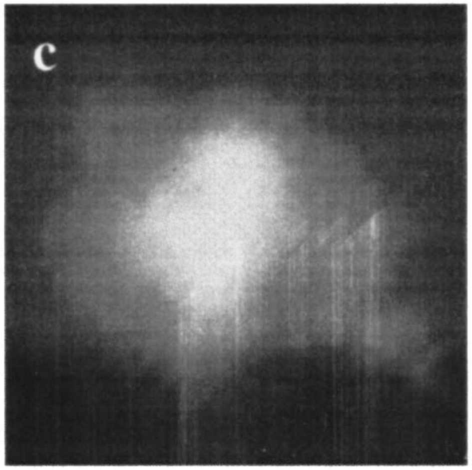
Faraday Isolator Performance

Depolarization ratio (γ) measued versus input power for traditional configuration (a) and LIGO configuration (c)

$$\gamma(H=0) = 0.017\left(\frac{P_h Q}{\lambda\kappa}\right)^2 = 0.017p^2$$







References

- Güido Mueller, "Faraday Isolator Specifications for Advanced LIGO", LIGO document number LIGO-T050226-00-D
- Efim Khazanov, Nikolay Andreev, Alexey Babin, Alexander Kiselev, and Oleg Palashov, "Suppression of self-induced depolarization of high-power laser radiation in glass-based Faraday isolators", JOSA B, Vol. 17, 2000
- Yariv & Yeh "Optical Waves in Crystals" chapter 4