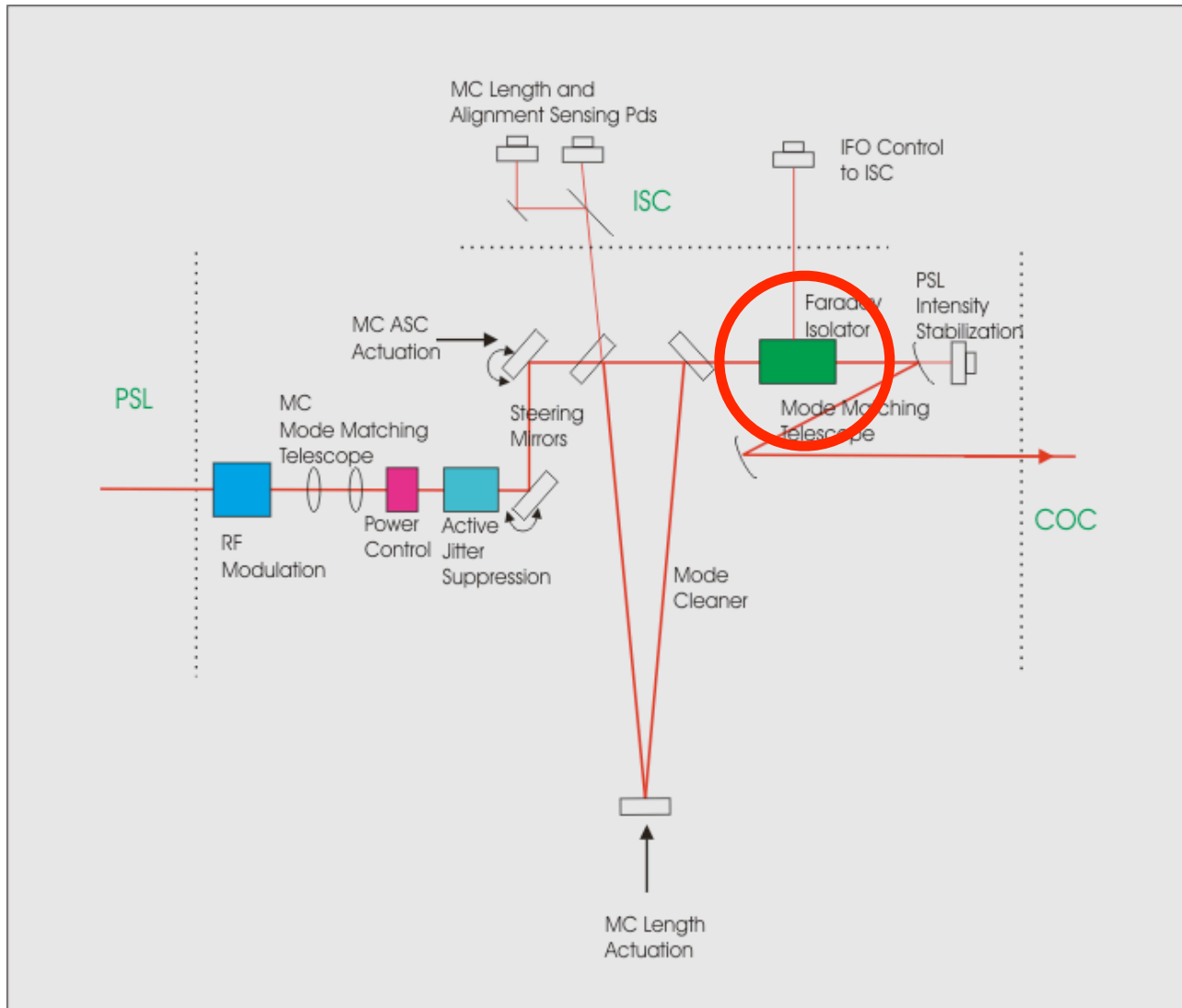


Case Study: Faraday Rotators in LIGO

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	<i>ADVANCED LIGO</i>	10/06/05
Faraday Isolator Specifications for Advanced LIGO		
UF Group		

Distribution of this document:
LIGO Science Collaboration

This is an internal working note
of the LIGO Project.

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Optical Requirements

- 0–180 W CW power
- $T_{\text{forward}} > 96\%$
- $T_{\text{backwards}} > 80\%$
- “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 $\lambda = 5893 \text{ \AA}$

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

1 IA New Original	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794	2 He Helium 4.002602	3 Li Lithium 6.941	4 Be Beryllium 9.012182	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00644	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797	11 Na Sodium 22.989770	12 Mg Magnesium 24.3050	13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.059	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.8457	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.409	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.796
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 to 71 Lanthanide series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 to 103 Actinide series	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)

Atomic masses in parentheses are those of the most stable or common isotope.

Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

57 La Lanthanum 138.9055	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
89 Ac Actinium (227)	90 Th Thorium 232.0381	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

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

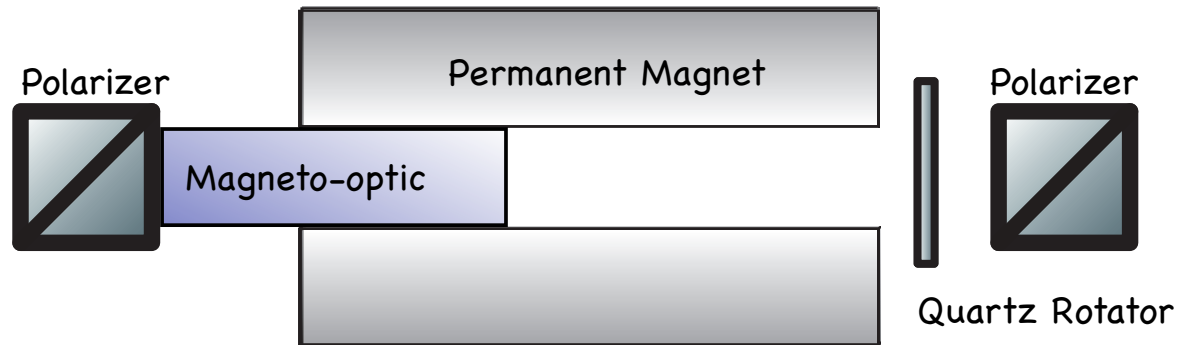
Material Properties of TGG

Terbium Gallium Garnet – TGG ($\text{Tb}_3\text{Ga}_5\text{O}_{12}$)



Crystal structure	cubic	
Lattice constant, Å	12.347	
Thermal conductivity, $\text{W} \times \text{cm}^{-1} \times \text{K}^{-1}$	0.045	← Thermal conductivity is an order of magnitude higher than for terbium doped glasses
Refractive indexes:		
at 1060 nm	1.954	
at 600 nm	1.978	
Birefringence, %	< 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), $\text{deg} \times \text{gauss}^{-1} \times \text{mm}^{-1}$		
at 1058 nm	1.2×10^{-4}	← Verdet constant is twice that of terbium doped glasses
at 633 nm	4.6×10^{-4}	
Pulse damage threshold, MW/cm^2	>300	
Operation temperature range, $^{\circ}\text{C}$	23 ± 5	
Orientation of the rod axis	<100> or <111> crystallographic direction ($\pm 15'$)	

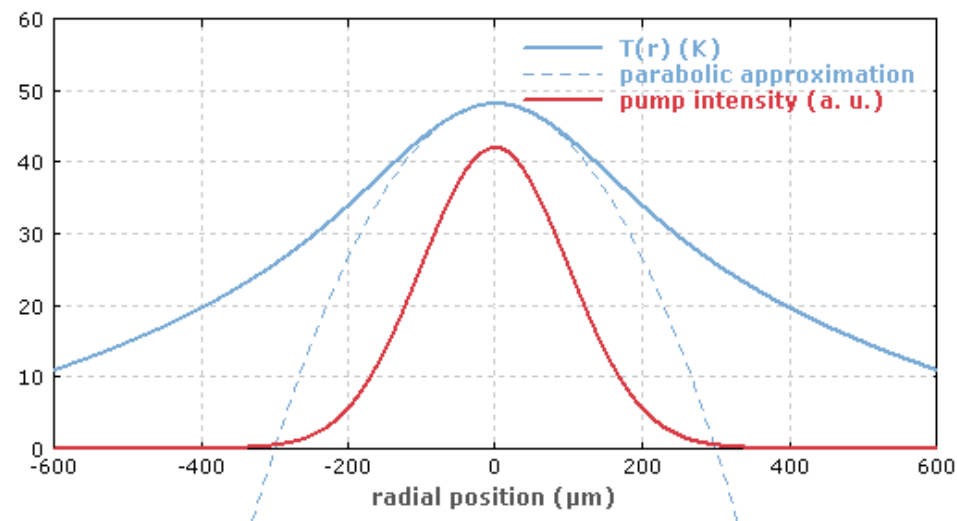
Typical Faraday Isolator Design



- 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 as a function of wavelength.
- Quartz rotator restores polarization of forward beam to match the input polarization.
- Polarizers redirect retro-reflected beams

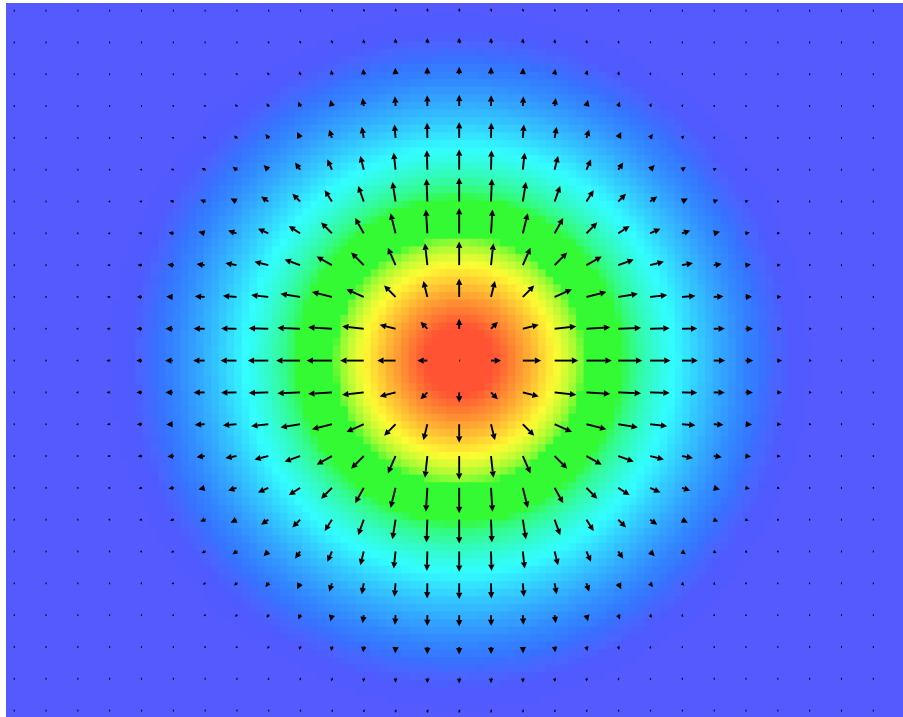
Thermal Lensing

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

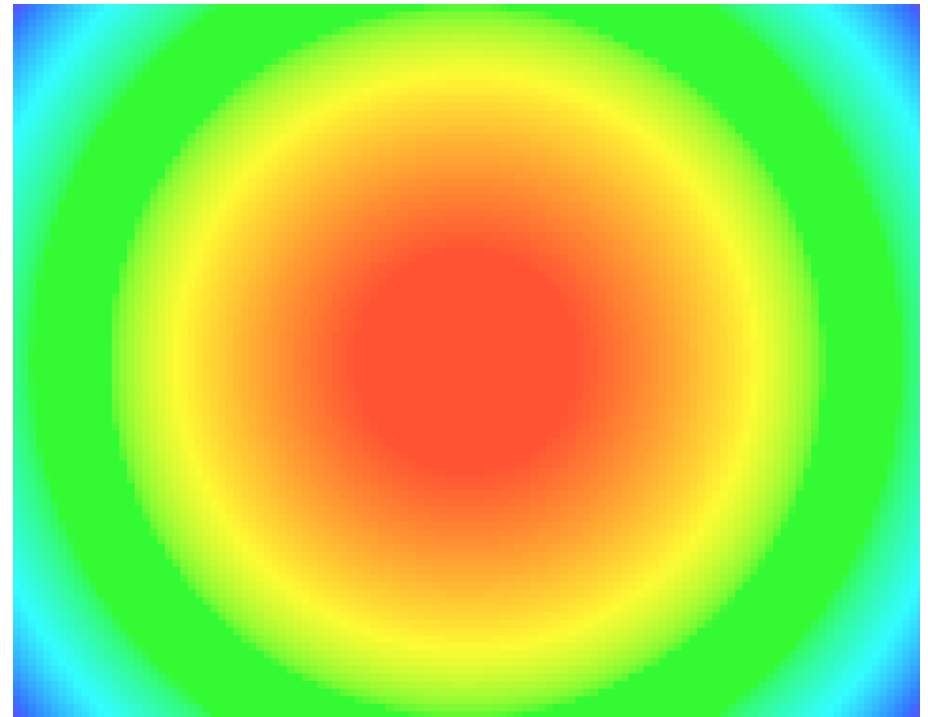


Temp dependence of Verdet Constant

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



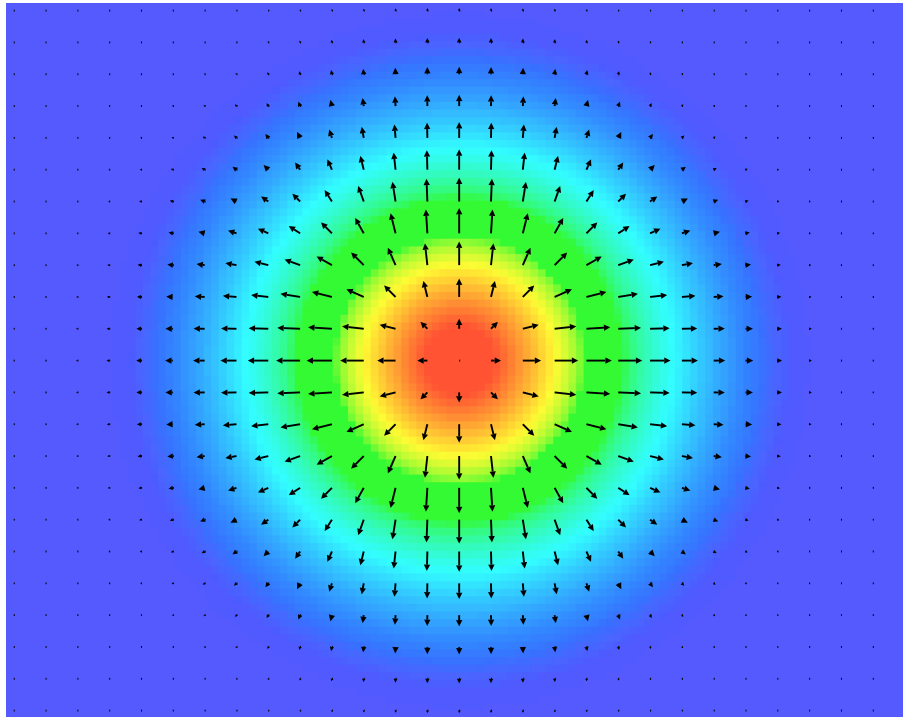
TEM₀₀ mode power distribution and
thermally induced strain field



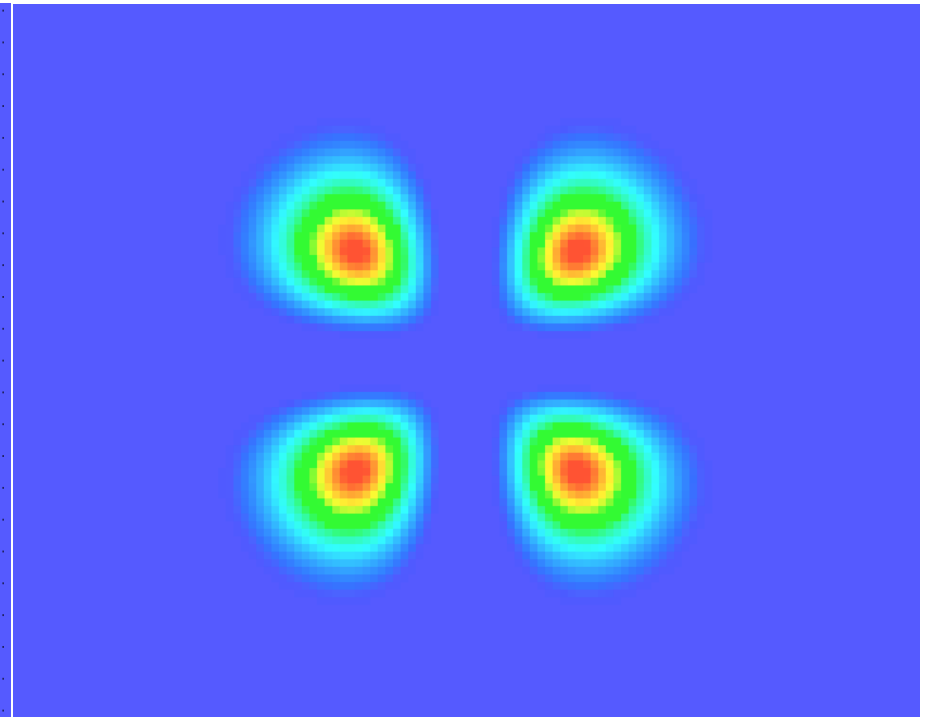
parabolic distribution of depolarization

Stress Induced Birefringence

Like high power rod lasers, stress induced birefringence causes depolarization

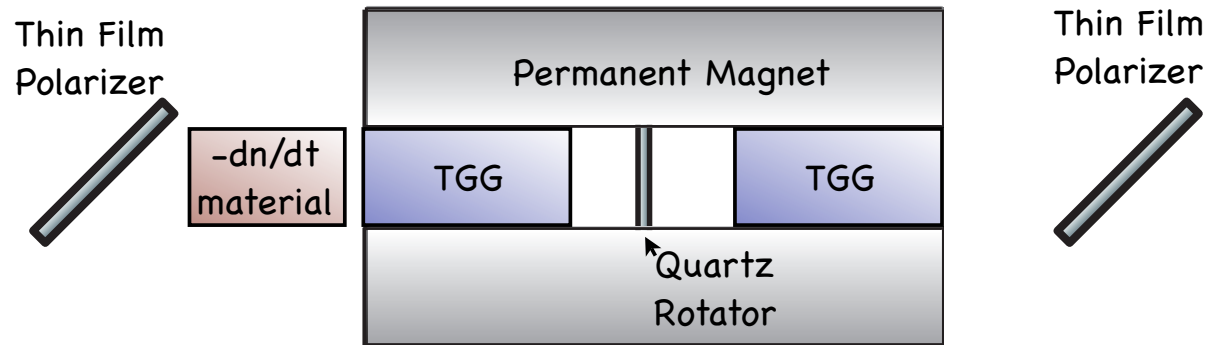


TEM₀₀ mode power distribution and thermally induced strain field



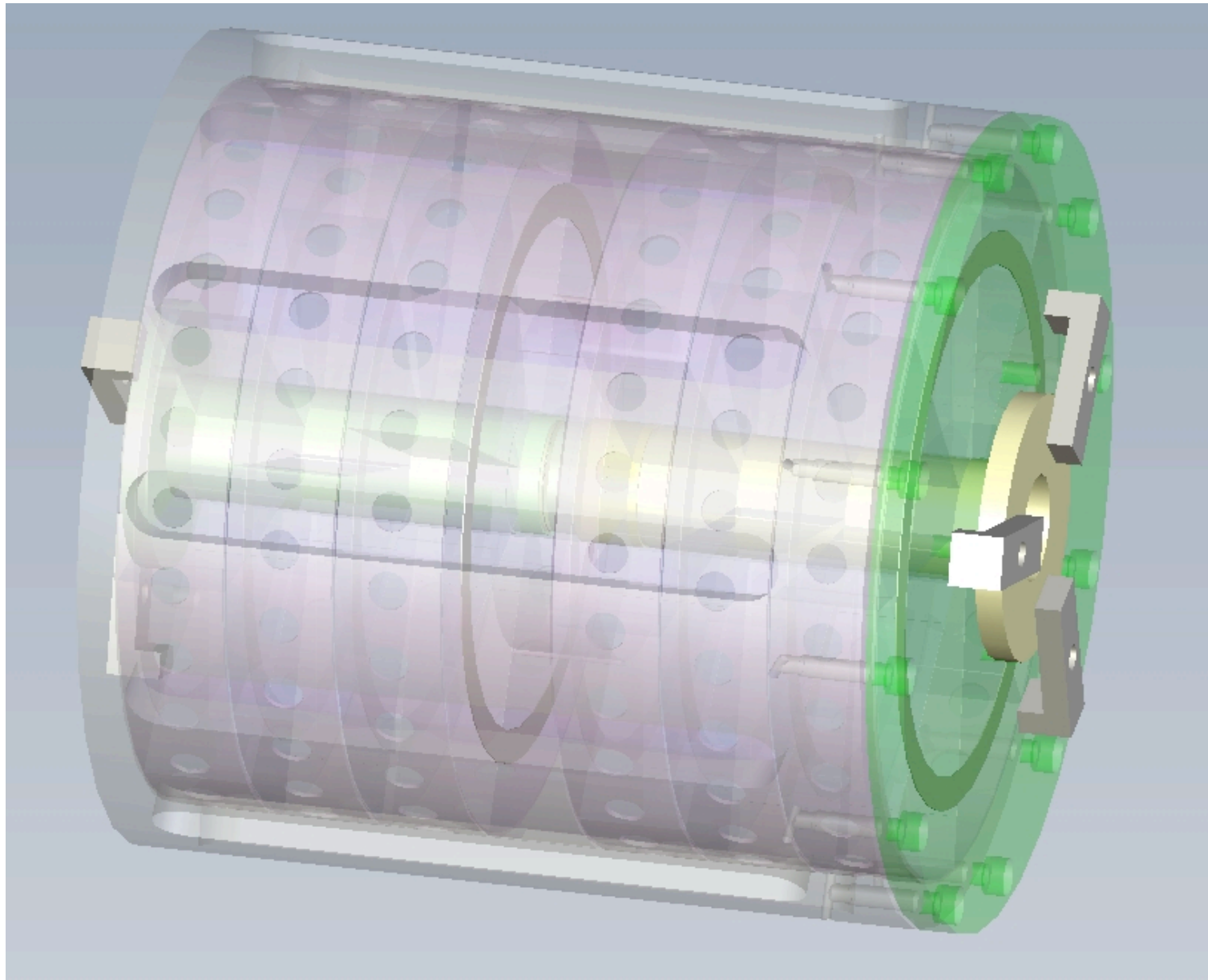
Spatial map of polarization conversion by stress induced birefringence

LIGO Faraday Isolator Design

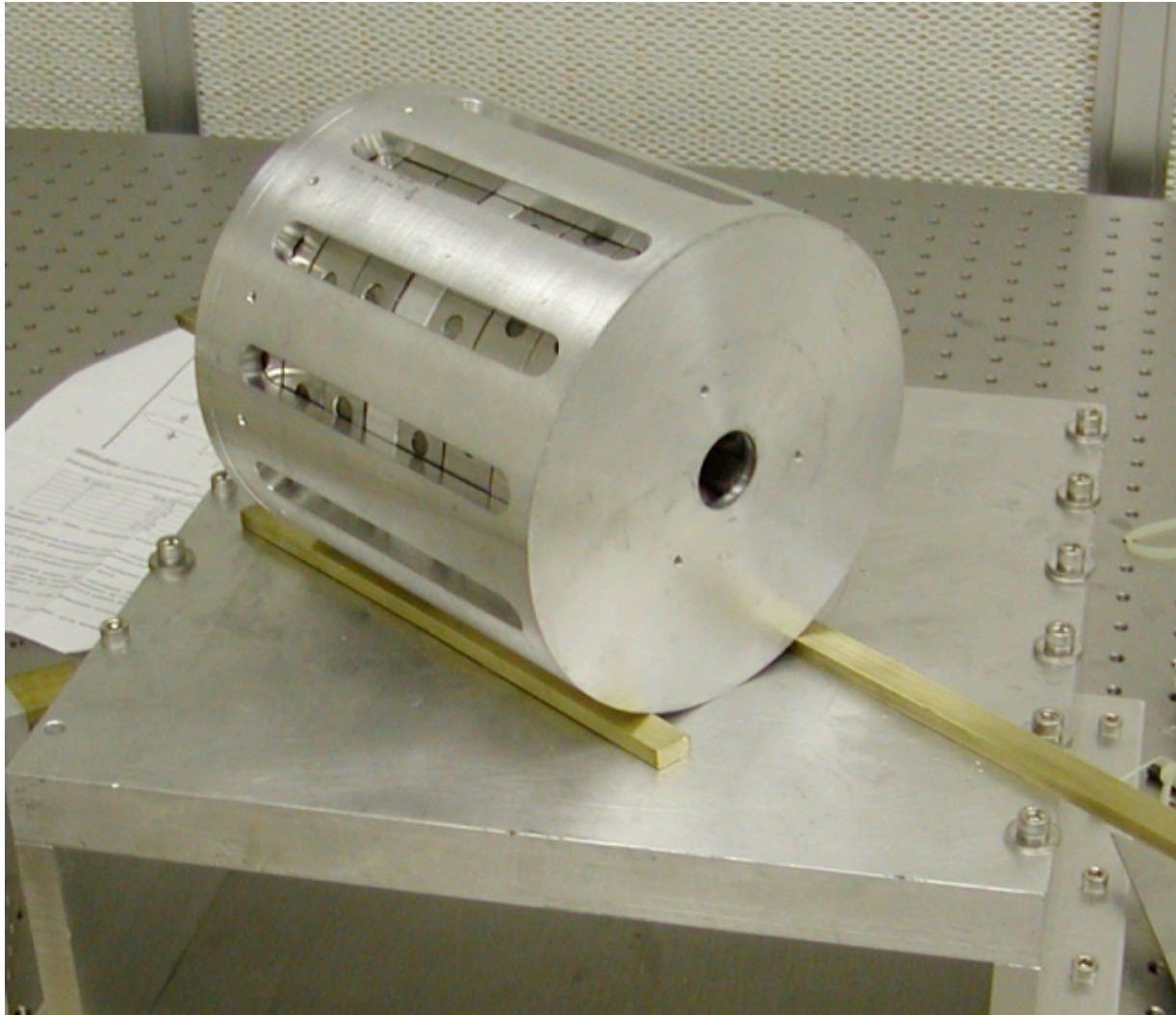


- Material with negative thermal lens compensates for thermal lensing in the magneto-optic crystal (TGG)
- Quartz rotator ($\lambda/2$ plate at 22.5°) is placed between the two halves of the TGG crystal, allowing one crystal to compensate for the depolarization in the other one.
- Thin Film Polarizers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

LIGO faraday Isolator Design

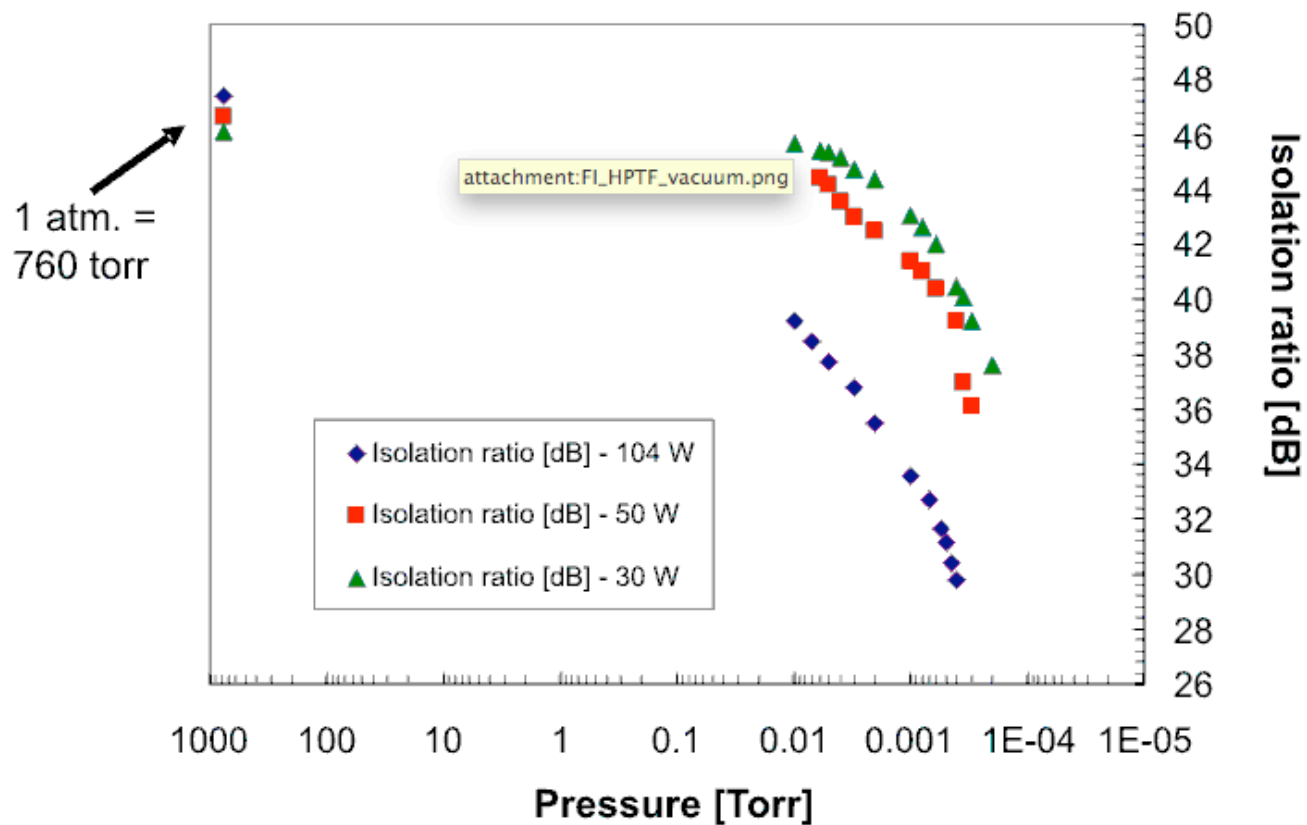


LIGO faraday Isolator Design



Faraday Isolator Performance

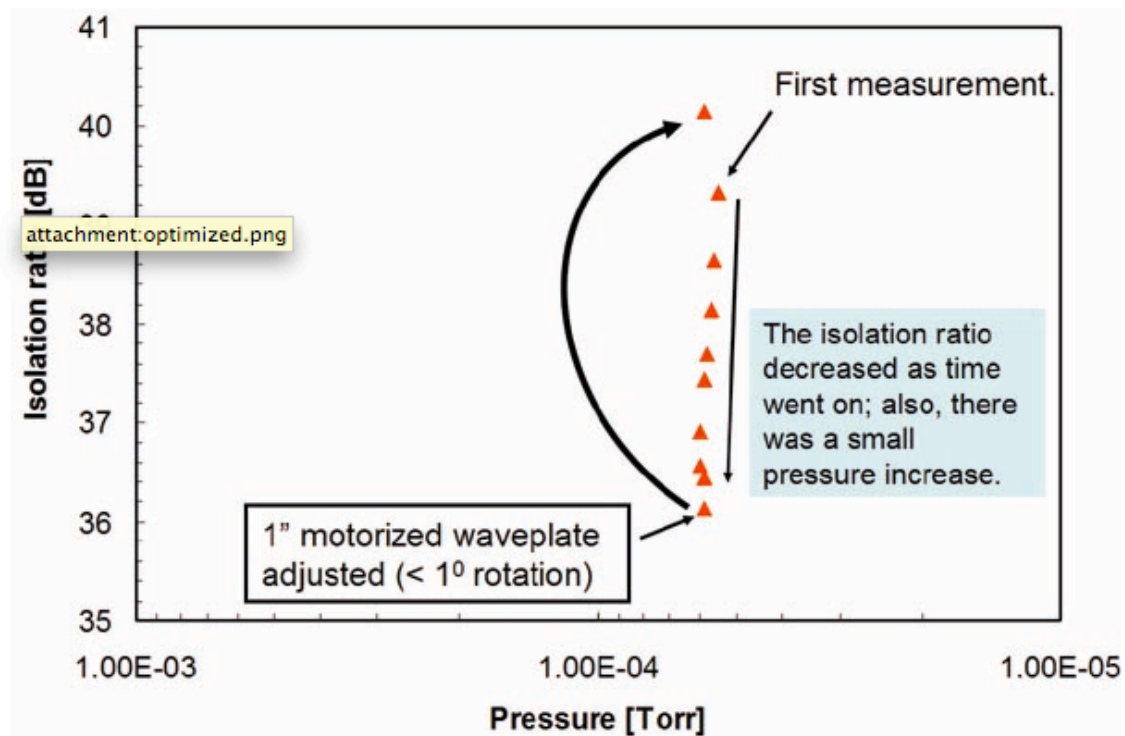
Isolation ratio as a function of vacuum chamber's pressure for three different incident laser powers (104 W, 50 W, 30 W)



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

Faraday Isolator Performance

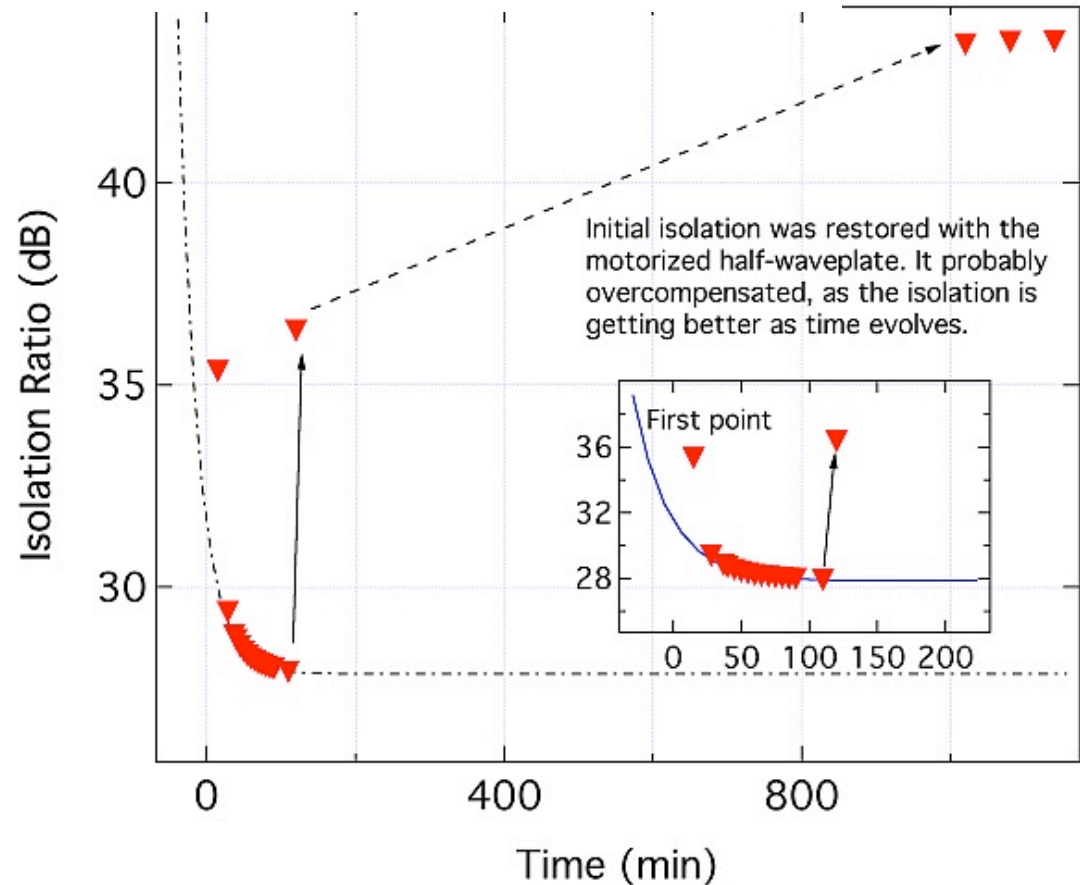
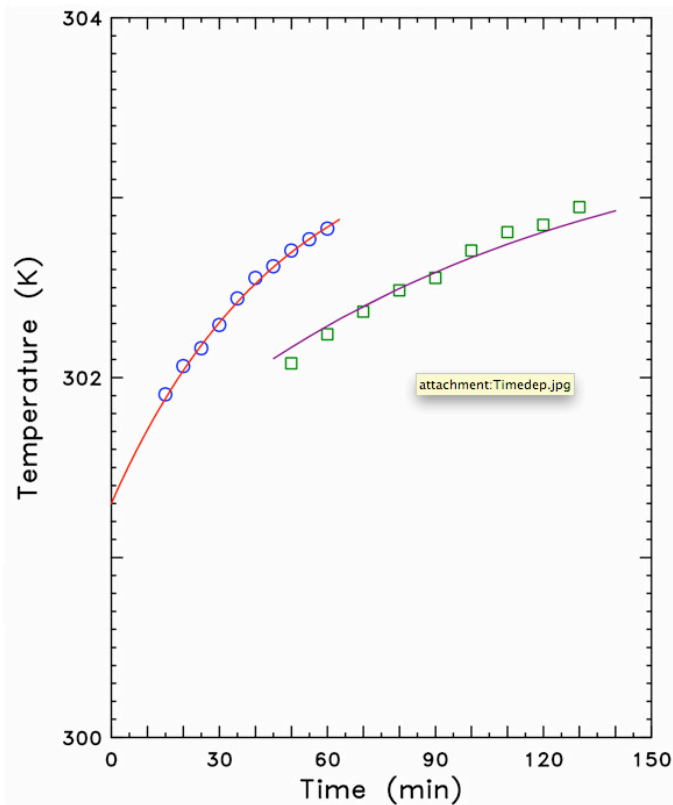
Isolation Ratio Optimized by in situ adjustment of the wave plate



Faraday Isolator Performance

Recent performance measurement

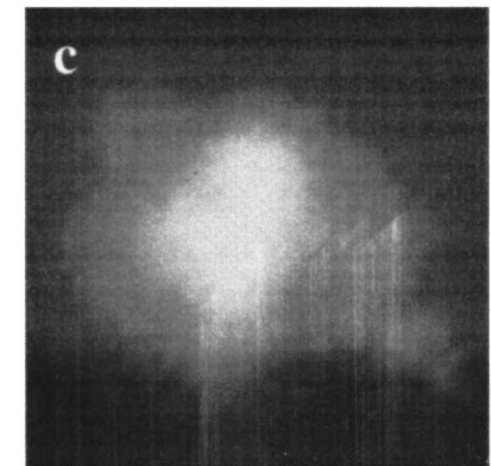
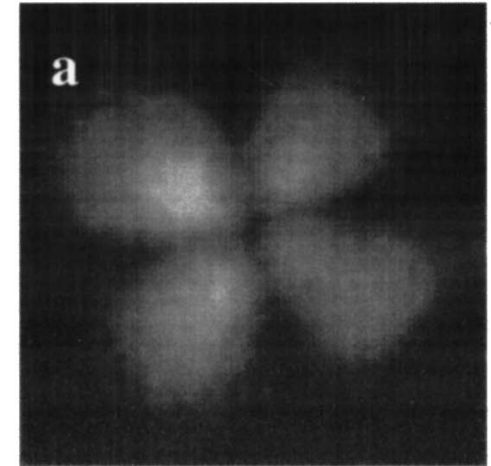
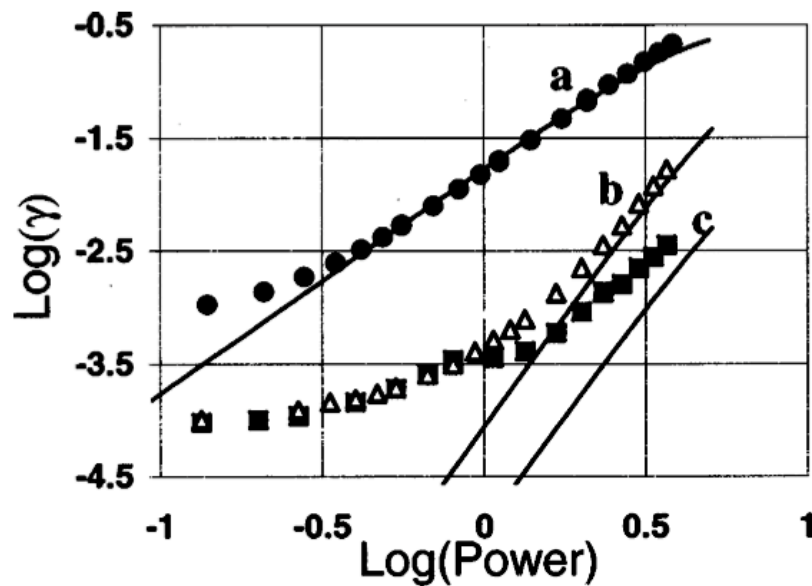
The following measurement shows that the isolation ratio can be restored to be at least 35 dB.
(Over time it drifted to a 43dB isolation ratio.)



Faraday Isolator Performance

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

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



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