LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Faraday Isolator Alignment Procedure
40M IFO

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Abstract

In this technical note, an analysis of the extinction ratio of an idealized Faraday isolator will be given using the method of Jones matrices. An idealized Faraday isolator consists of half-wave plates that preserve linear polarization, lossless polarizers, and a lossless Faraday rotator without birefringence, but with a rotation angle error. An alignment procedure will be described for optimizing the rotation angles of the half-wave plates.

1 Introduction

A Faraday isolator is used in the input optics path of the 40 M interferometer to block the reflected beam from the symmetric port that returns to the PSL. The input polarizer of the Faraday isolator also serves to provide a pick-off mirror for extracting the symmetric port reflected beam.

1.1 Scope

In this technical note, an analysis of the extinction ratio of an idealized Faraday isolator will be given. An idealized Faraday isolator consists of half-wave plates that preserve linear polarization, lossless polarizers, and a lossless Faraday rotator without birefringence, but with a rotation angle error. In a real Faraday isolator, the ultimate extinction ratio and transmissivity will be limited by the phase retardation errors of the half-wave plates, by the birefringence of the Faraday rotator, and by the absorption and reflection losses in the various optical components.

An alignment procedure will be described for optimizing the rotation angles of the half-wave plates.

2 Analysis

The performance of a Faraday isolator will be analyzed using the method of Jones matrices. The extinction ratio, which is the ratio of the reflected power to the incident power, and the transmitted power ratio will be calculated as a function of the misalignments of the input half-wave plate and the output half-wave plate, and the Faraday rotation angle error.

A schematic diagram of the Faraday isolator optical train in shown in Figure 1. The forward beam comes from the PSL. The reflected beam is reflected from the symmetric port of the interferometer and traverses the Faraday isolator optical train in the reverse direction.

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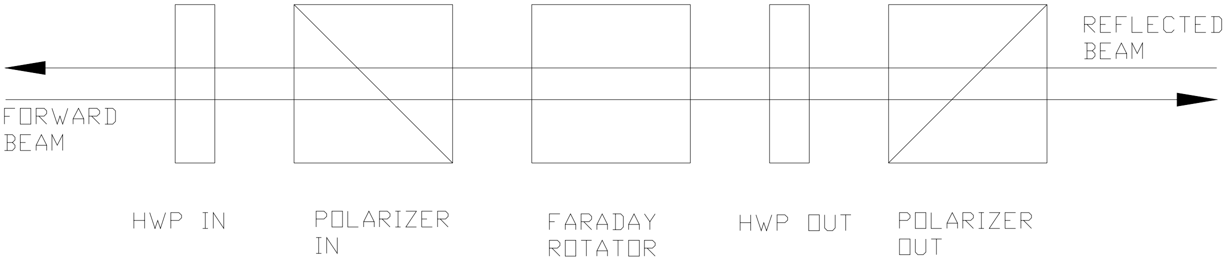

Figure 1: Faraday isolator optical train

2.1 Forward Direction

The input electric field vector of the forward beam is polarized in the vertical direction,

$$E_{in} := \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

We will assume that the input half-wave plate preserves the linear polarization. It rotates the input electric field vector to align it with the vertical axis of the input polarizer. In general, there will be a slight misaligned rotation angle of the input half-wave plate,

$$\delta_{R1} := 0$$

and the Jones matrix for the input half-wave plate is given by,

$$HW_1(\delta_{R1}) := \begin{pmatrix} \cos(\delta_{R1}) & -\sin(\delta_{R1}) \\ \sin(\delta_{R1}) & \cos(\delta_{R1}) \end{pmatrix}$$

The input polarizer is assumed to be perfectly aligned in the vertical direction,

$$P_1 := \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

The Faraday rotator rotates the electric field vector by π/4 plus a rotation error ε. The Jones matrix of the Faraday rotator is given by,

$$FR(\varepsilon) := \begin{pmatrix} \cos\left(\frac{\pi}{4} + \varepsilon\right) & -\sin\left(\frac{\pi}{4} + \varepsilon\right) \\ \sin\left(\frac{\pi}{4} + \varepsilon\right) & \cos\left(\frac{\pi}{4} + \varepsilon\right) \end{pmatrix}$$

The output half-wave plate rotates the electric field vector by an additional π/4 less the error of the Faraday, but it is itself misaligned by an angle

$$\delta_{R2} := 0$$

so the Jones matrix is given by,

$$HW_2(\delta_{R2}, \varepsilon) := \begin{pmatrix} \cos\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) & -\sin\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) \\ \sin\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) & \cos\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) \end{pmatrix}$$

Finally the forward beam traverses the horizontally aligned output polarizer,

$$P_2 := \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

The output electric field vector of the forward beam is transformed by the ordered products of the various Jones matrices,

$$E_{outF}(\delta_{R1}, \delta_{R2}, \varepsilon) := P_2 \cdot HW_2(\delta_{R2}, \varepsilon) \cdot FR(\varepsilon) \cdot P_1 \cdot HW_1(\delta_{R1}) \cdot E_{in}$$

We can check that the optical components have the right orientations by calculating the output electric field vector with all the rotation errors set to zero. With

$$E_{in} := \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

the output electric field vector is calculated to be

$$E_{outF}(\delta_{R1}, \delta_{R2}, \varepsilon) = \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

Thus we see that the Faraday isolator rotates the vertically polarized input electric field vector into a horizontal polarization at the output, as required.

The incident beam power and the transmitted beam power are equal to the squares of the respective electric fields,

$$P_I := E_{in}^T \cdot E_{in}$$

and

$$P_T(\delta_{R1}, \delta_{R2}, \varepsilon) := E_{outF}(\delta_{R1}, \delta_{R2}, \varepsilon)^T \cdot E_{outF}(\delta_{R1}, \delta_{R2}, \varepsilon)$$

The transmitted power ratio is equal to the ratio of the beam powers,

$$ET(\delta_{R1}, \delta_{R2}, \varepsilon) := \frac{P_T(\delta_{R1}, \delta_{R2}, \varepsilon)}{P_I}$$

2.2 Reflected Direction

The reflected electric field from the symmetric port has a sign reversal,

$$E_{inR}(\delta_{R1}, \delta_{R2}, \varepsilon) := \begin{pmatrix} -1 & 0 \\ 0 & 0 \end{pmatrix} \cdot E_{outF}(\delta_{R1}, \delta_{R2}, \varepsilon)$$

then passes through the output polarizer in the reverse direction. When the reflected beam traverses the output half-wave plate its polarization is rotated in the opposite sense from before,

$$HW_{2R}(\delta_{R2}, \varepsilon) := \begin{pmatrix} \cos\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) & \sin\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) \\ -\sin\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) & \cos\left(\frac{\pi}{4} - \varepsilon + \delta_{R2}\right) \end{pmatrix}$$

However, the reflected beam polarization is rotated in the same sense when it traverses the Faraday isolator in the reverse direction,

$$FR(\varepsilon) := \begin{pmatrix} \cos\left(\frac{\pi}{4} + \varepsilon\right) & -\sin\left(\frac{\pi}{4} + \varepsilon\right) \\ \sin\left(\frac{\pi}{4} + \varepsilon\right) & \cos\left(\frac{\pi}{4} + \varepsilon\right) \end{pmatrix}$$

The reflected beam traverses through the input polarizer. And again, the reflected beam polarization is rotated in the opposite sense when it traverses the input half-wave plate,

$$HW_{1R}(\delta_{R1}) := \begin{pmatrix} \cos(\delta_{R1}) & \sin(\delta_{R1}) \\ -\sin(\delta_{R1}) & \cos(\delta_{R1}) \end{pmatrix}$$

The reflected electric field vector, after traversing the Faraday isolator optical train in reverse, is given by the ordered product of the component matrices,

$$E_{outR}(\delta_{R1}, \delta_{R2}, \varepsilon) := HW_{1R}(\delta_{R1}) \cdot P_1 \cdot FR(\varepsilon) \cdot HW_{2R}(\delta_{R2}, \varepsilon) \cdot P_2 \cdot E_{inR}(\delta_{R1}, \delta_{R2}, \varepsilon)$$

The incident beam power and the reflected beam power are equal to the squares of the respective electric fields,

$$P_I := E_{in}^T \cdot E_{in}$$

and

$$P_R(\delta_{R1}, \delta_{R2}, \varepsilon) := E_{outR}(\delta_{R1}, \delta_{R2}, \varepsilon)^T \cdot E_{outR}(\delta_{R1}, \delta_{R2}, \varepsilon)$$

The extinction ratio is equal to the ratio of the two beam powers,

$$ER(\delta_{R1}, \delta_{R2}, \varepsilon) := \frac{P_R(\delta_{R1}, \delta_{R2}, \varepsilon)}{P_I}$$

2.3 Numerical Results

2.3.1 Transmitted Power Ratio

The transmitted power ratio through the Faraday isolator depends primarily on the alignment of the input half-wave plate, as shown in Figure 2, where the Faraday rotation error was set to zero, and the three curves are for output half-wave plate alignment errors of –0.02, 0, and 0.02 rad respectively. The transmissivity is not affected by the Faraday rotation error, as shown in Figure 5.

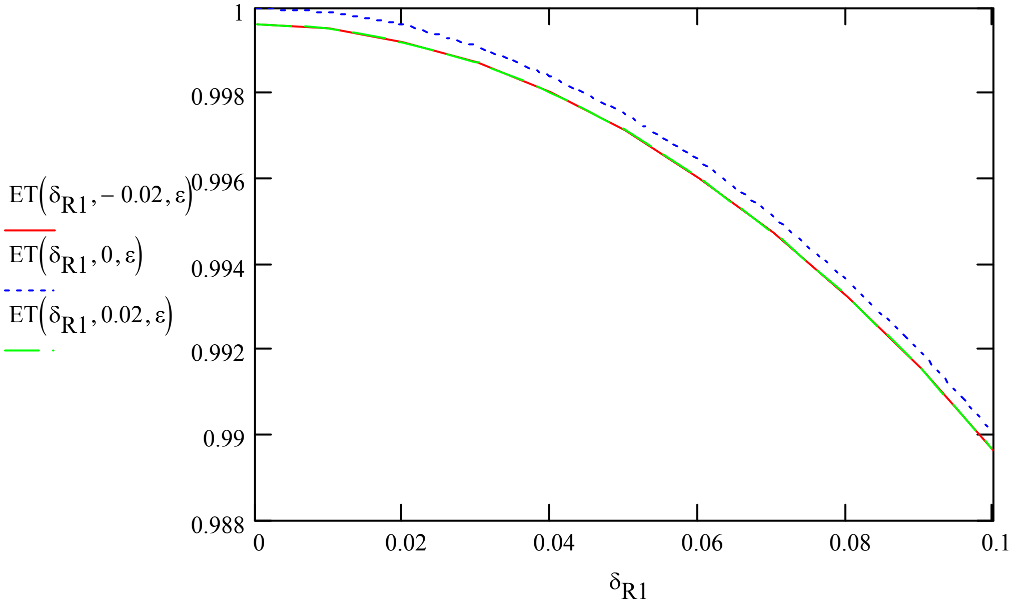

Figure 2: Transmitted power ratio

2.3.2 Extinction Ratio

The extinction ratio depends on both the rotation error of the Faraday rotator and the misalignment of the output half-wave plate. Misalignment of the input half-wave plate does not affect the extinction ratio. This is shown in Figure 3, in which the extinction ratio is plotted versus the misalignment of the output half-wave plate. The Faraday isolator error was set to zero, and three curves, with the misalignment errors of the input half-wave plate of –0.1, 0, and 0.1 rad are superimposed.

A misalignment of the output half-wave plate of approximately 0.03 rad can be tolerated while still maintaining an extinction ratio of <0.001.

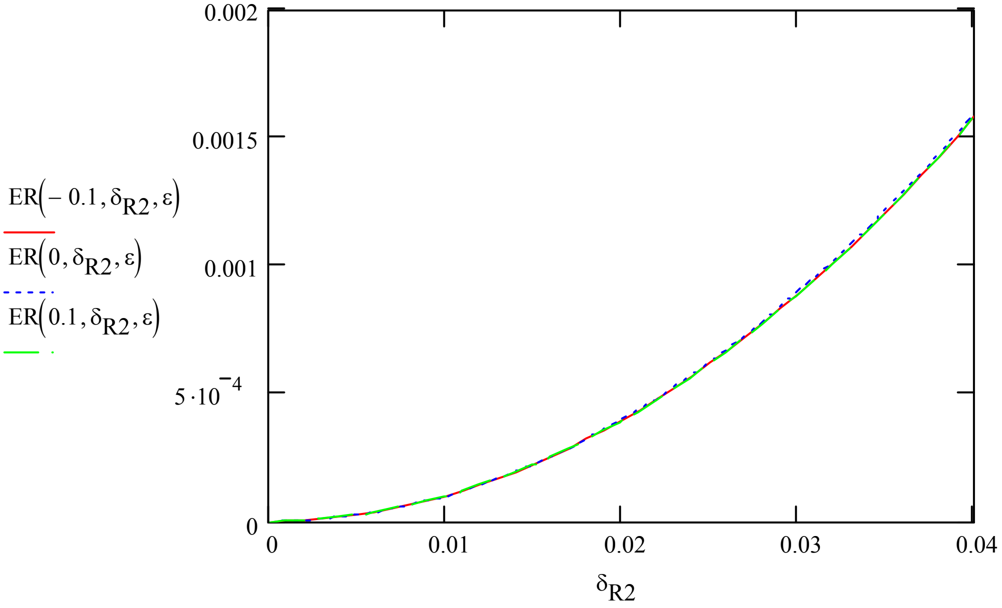

Figure 3: Effect of output half-wave plate misalignment on the extinction ratio

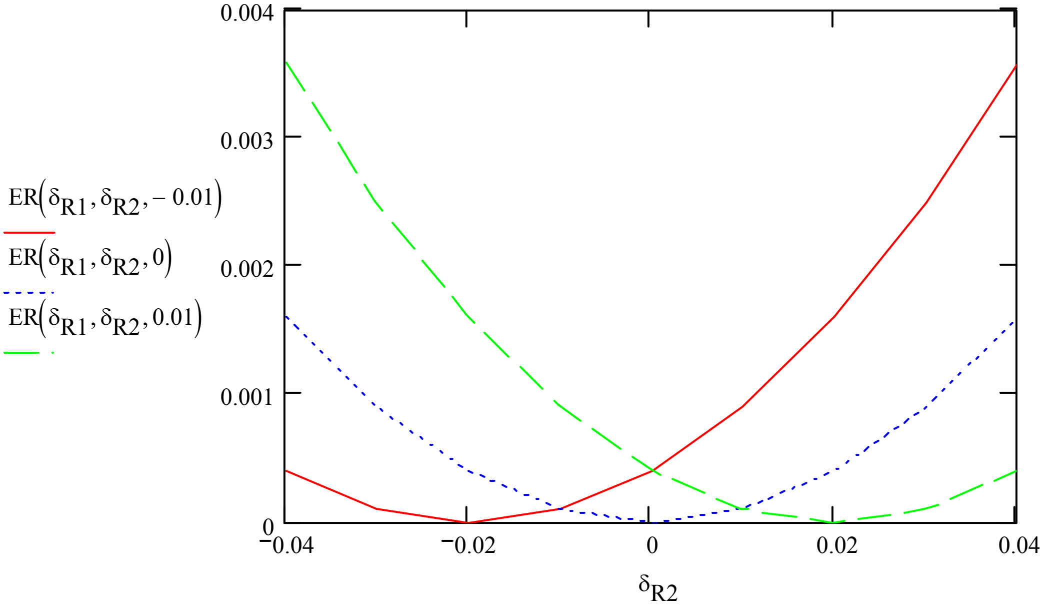

Figure 4: Correcting the Faraday rotation error by misaligning the output half-wave plate

It is interesting to note that the rotation error of the Faraday rotator can be corrected with an intentional misalignment of the output half-wave plate, as seen in Figure 4, where the three curves are shown for Faraday rotational errors of –0.01, 0, and 0.01 rad respectively. The correction results in a small loss of transmissivity through the Faraday isolator, as shown in Figure 5.

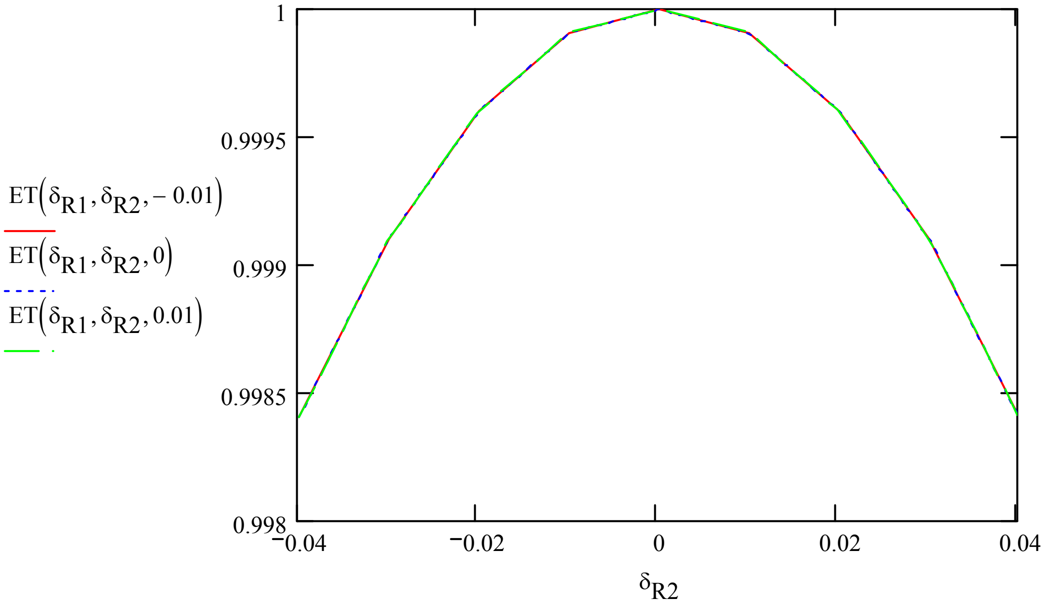

Figure 5: Transmissivity with misaligned output half-wave plate

3 Alignment Procedure

The Faraday isolator assembly will be aligned by transmitting a polarized 1064 nm laser through the assembly in the forward direction and subsequently reflecting the output beam with a mirror back through the assembly in the reverse direction. The transmitted and reflected beam powers will be measured at various test points to aid in the rotational alignment of the half-wave plates and to determine the transmissivity and the extinction ratio of the Faraday isolator.

The apparatus for aligning the Faraday isolator is shown schematically in Figure 6. It consists of an NPRO laser with a vertically aligned polarizer cube, a 50% beam splitter to sample the reflected beam, the Faraday isolator under test, a mirror to reflect the output beam, and a suitable power meter to measure the beam power at the identified test locations.

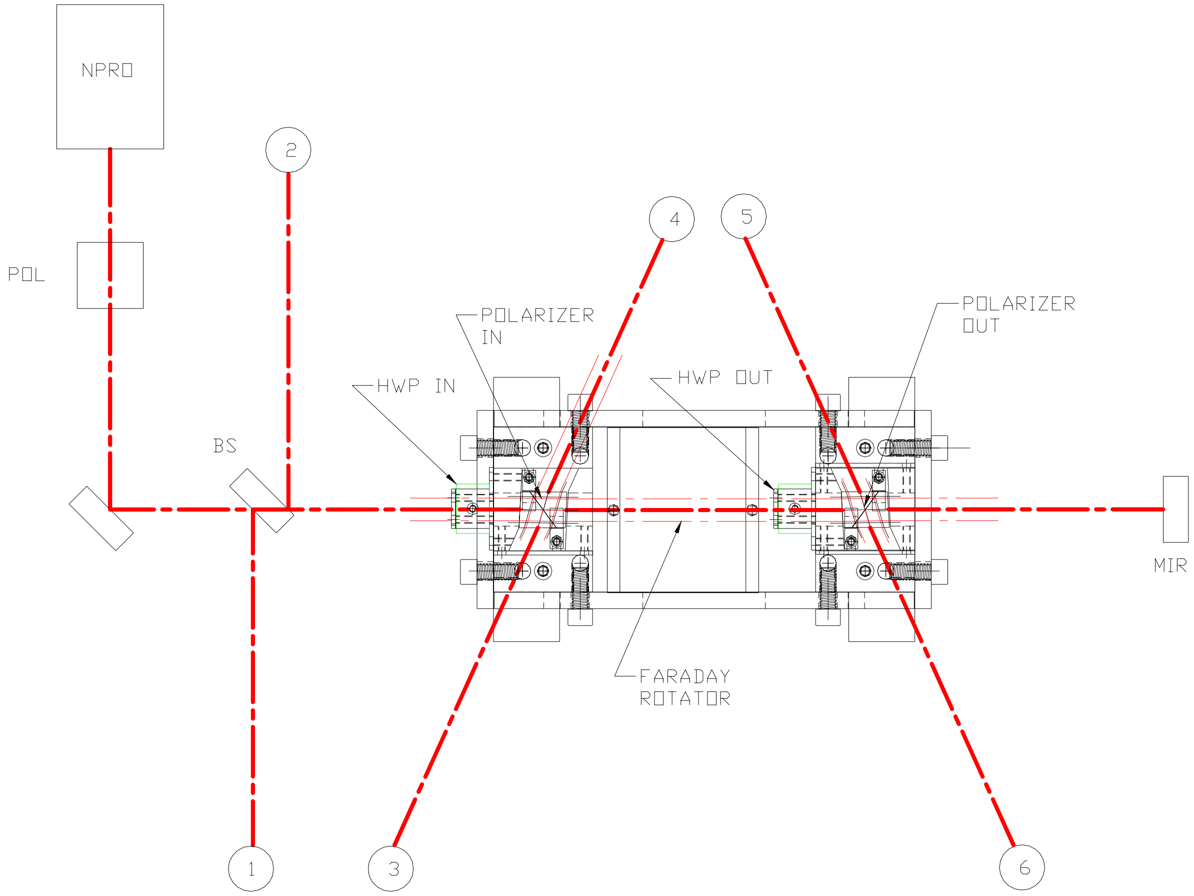

Figure 6: Alignment apparatus

3.1 Alignment of the Input Half-wave Plate

Place the power meter at test position 3, and rotate the input half-wave plate until the power reading is a minimum.

3.2 Alignment of the Output Half-wave Plate

3.2.1 Initial Alignment

Place the power meter at test position 5, and rotate the output half-wave plate until the power reading is a minimum.

3.2.2 Final Alignment

Place the power meter at test position 2, and fine-tune the rotation of the output half-wave plate until the power reading is a minimum. Record the power, P_2.

3.3 Measurement of the Transmissivity

Place the power meter at the input of the Faraday isolator and record the power reading, P_{in}. Place the power meter at the output of the Faraday isolator and record the power reading, P_{out}.

The transmissivity is the ratio, P_{out}/P_{in}.

3.4 Calculation of the Extinction Ratio

3.4.1 Calibration of the Beam Splitter Ratio

Place the power meter just before the beam splitter and record the power reading, P_0. Place the power meter at test position 1, and record the power reading, P_1. The beam splitter ratio can be calculated as follows:

$$\mathrm{BSR}=P_1/P_0.$$

3.4.2 Extinction Ratio

The extinction ratio can be calculated as follows:

$$ER = \frac{P_2}{BSR \bullet P_{in}}$$