LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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AdvLIGO Phase Modulator Assembly Document

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Table of Figures

Table of Tables

1 Introduction

The following document describes the design and assembly procedures of the Advanced LIGO phase modulator. The AdvLIGO EOM is based on a design that was built and tested from the UF-LIGO group in eLIGO.

A single RTP crystal is used to handle the high laser powers and also slightly reduce the optical losses by reducing the number of modulator crystals from three to one. Some additional information on the used RTP crystals can be found in the "Upgrading the Input Optics for High Power Operation" document (LIGO- T060267-00-D).

1.1 Three Modulations / Single Crystal design

The design uses only one crystal but three separate pairs of electrodes to apply three different modulation frequencies. The following picture shows a view of the inside of the modulator. The electrodes are connected via D-Sub connectors, using two pins per electrode, to a separate box that holds the resonant circuit.

In the left picture of figure 1 the electrode configuration can be seen (an older version of the electrode configuration is shown, the AdvLIGO final design uses 7 mm, 22 mm, 7 mm), the right picture shows a side view of the assembly with an RTP crystal.

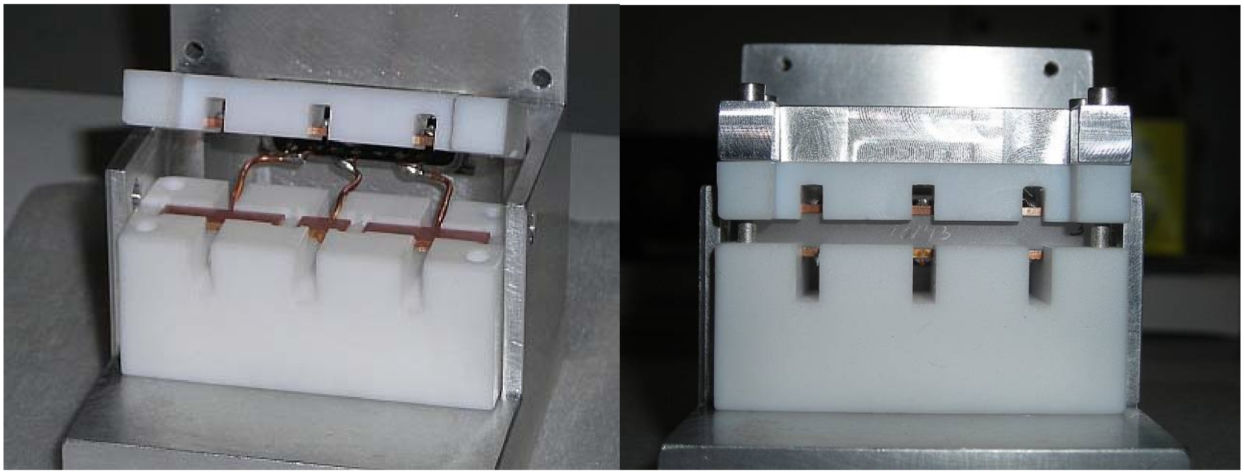

Figure 1 (left): Electrode configuration; (right) Side view with RTP crystal.

The final assembled modulator with the separate electronics box that holds the resonant circuits is shown in figure 2. The crystal box and the electronics box are separated because of the following reasons:

1. All required soldering during the tuning process, see section 2.5.3, can be performed without being close to the crystal – this avoids possible contamination.
2. A change of the electronics box can be performed without disturbing the optical layout – the crystal box stays in place while the electronics box is detached.

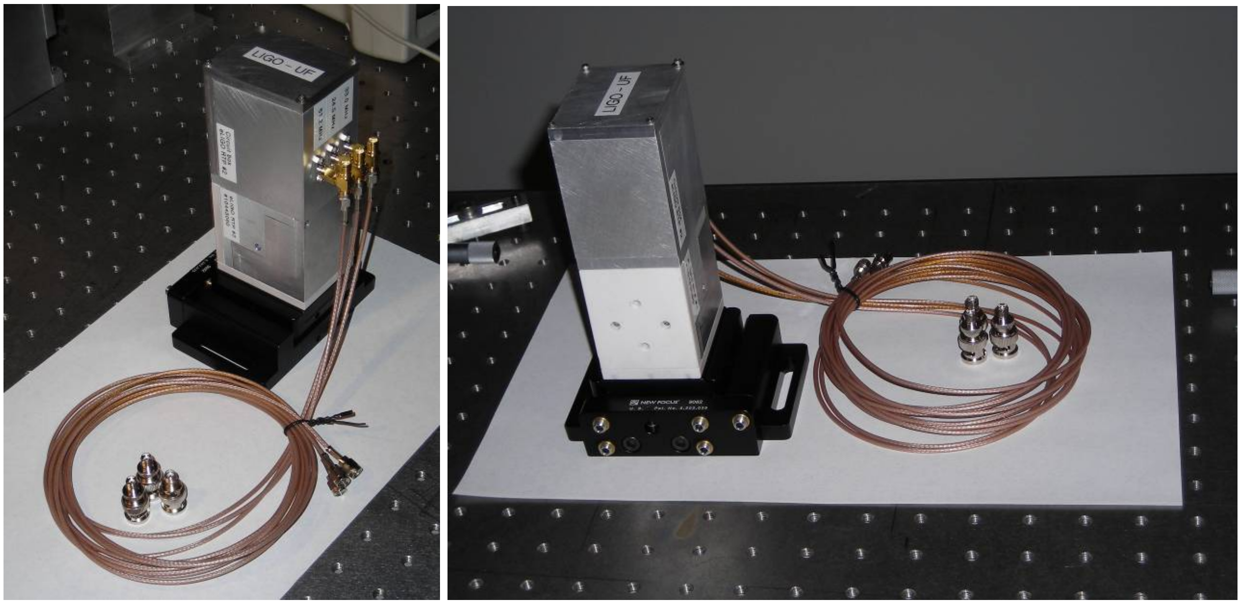

Figure 2: Fully assembled modulator system

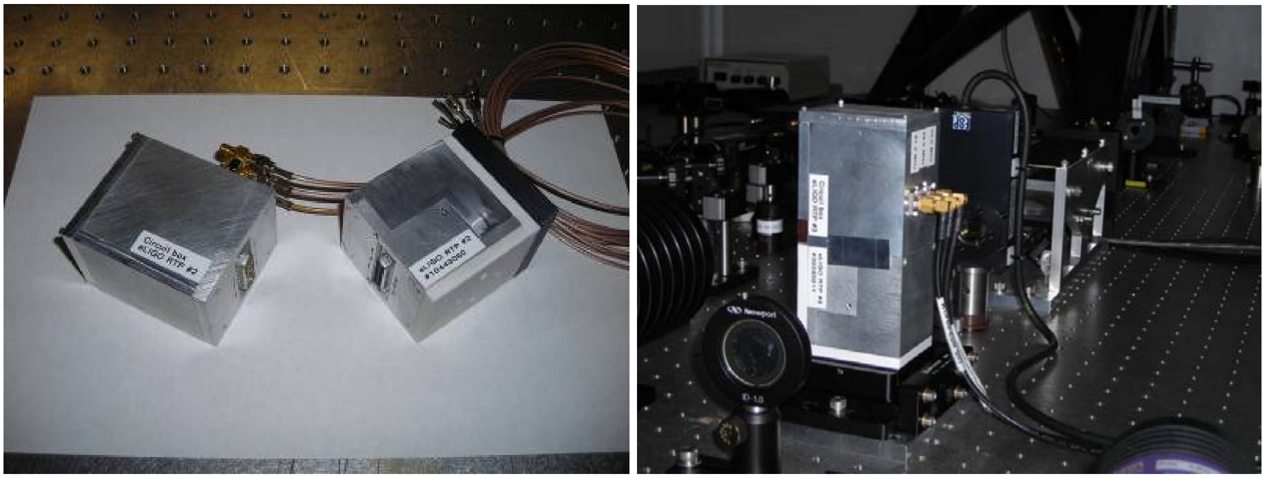

Figure 3 (left): Separate crystal and electronics box; (right) Modulator on LHO PSL table.

1.2 Modulator crystal

To avoid cavity effects in the crystal and reduce RF-AM the RTP crystal was ordered with 2.85±0.1 degree wedges on the faces. The red rectangles in the following figure 4 represent the area where the electrodes are affixed. For p-polarized light the steering occurs in the plane of the table (the electrodes are perpendicular to the table):

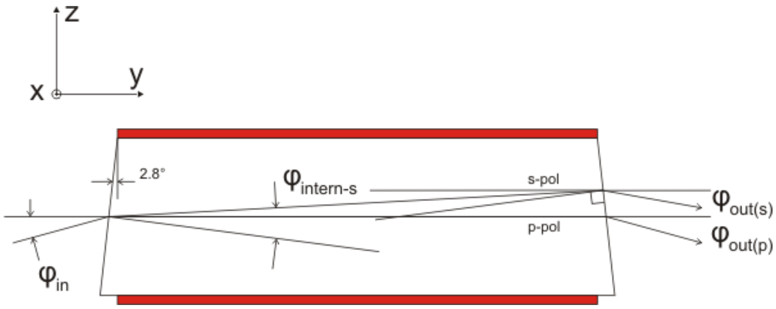

Figure 4: Separation of s- and p-polarization.

The wedging leads to the following bending angles, see table 1 (measured against the incident beam):

Polarization	**Angle [degree]**
P	4.7
S	4.2

Table 1: Angular changes

1.3 Impedance matching circuit

The used impedance matching circuit provides 50 Ohm input impedance on resonance and is based on a capacitive voltage divider (idea by R. Schilling / G. Heinzel) building two resonances (a parallel and a series resonance), see figure 5. This combination allows the creation of the 50 Ohm impedance on (very near) the desired resonant frequency. Another advantage of this resonant circuit is its very high impedance for low frequencies and DC.

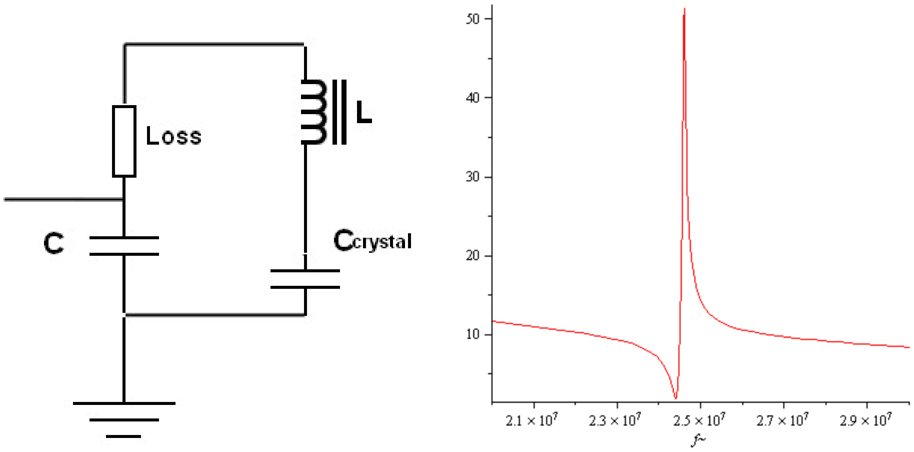

Figure 5: Pi-network resonance circuit (left) and simulated impedance (right).

The realized design places three resonant circuits like the one in figure 5 in a separate box that can be modified and tuned without removing the box that holds the crystal from the setup.

1.4 Performance measurements

The following measurements, see figure 6, represent the performance of the device in its final configuration. The modulator was simultaneously driven with three modulation frequencies with a 10 Vpp signal. The frequencies were 33 MHz, 24.5 MHz and 61.2 MHz. The measurement was performed with two phase-locked (at 8 MHz) lasers and the beat was recorded with a spectrum analyzer. The modulation indices were measured to be.

- $m_{33.0} = 0.14$
- $m_{24.5} = 0.37$
- $m_{61.2} = 0.14$

The subscript denotes the resonance frequency.

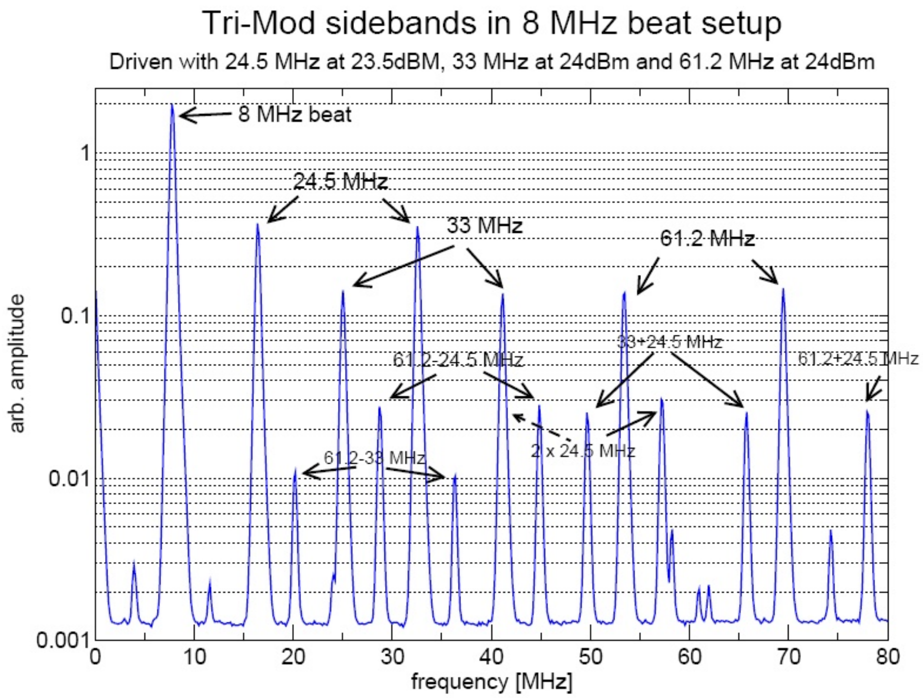

Figure 6 Measurement of modulation depth of the three modulation frequencies.

2 Assembly procedures

References to technical drawings of all mechanical parts can be found in appendix A. The assembly of the case components is a straightforward procedure that does not require extra explanations, but the procedure to connect the electrodes, mount the crystal and how to tune the resonant circuits additional information and are explained in the following sections.

2.1 Preparation

Assembly should be carried out on a laminar flow bench to prevent contamination. Gloves should be worn at all times during the assembly procedure.

All mechanical parts should be cleaned before assembly:

- 45 minutes in an ultrasonic bath of high purity acetone, followed by a methanol rinse and clean dry air or nitrogen
- The electro-optic crystal should be blown with clean dry air or nitrogen and inspected. In particular, make sure that the faces are RTP crystal ore absolutely free of dust or surface damage and discoloration

2.2 Tools for Assembly and Tuning

The following tools will be needed during various stages of the assembly and later tuning process of the modulators.

Preparation:

- Ultrasonic bath
- Clean tissue
- Mechanical tools: Small pliers, set of Allen Keys, wire, electrical tape

Assembly:

- Soldering iron
- Mechanical tools: Set of fine files, fine (400 grit) abrasive paper

Tuning:

- Copper tape
- Spectrum/Network Analyzer
- Experimental setup with laser and optical spectrum analyzer to measure sideband strength
- Three function generators, and amplifiers as needed to simultaneously prepare the three modulation frequencies with 24 dBm drive power.

2.3 Connecting the electrodes

The pictures in figure 7 show pictures taken during the assembly of the electrodes. The following steps describe the connection of the electrodes to the D-sub connector in the case.

1. Cut and bend the electrode wires so that they reach from the electrode to the D-sub connector in the case wall.
2. Solder the wires to the electrodes. This can be easily done when they are placed upside down in the respective place in the Boron-Nitride electrode holder.
3. Assemble the crystal mount using a dummy “crystal” made from metal, see figure 8. Tighten the screws to get the electrodes to their final destination. The wires ends can now be bent and soldered to their place on the D-sub connector.
4. Remove any residue from the soldering process and re-clean the housing.

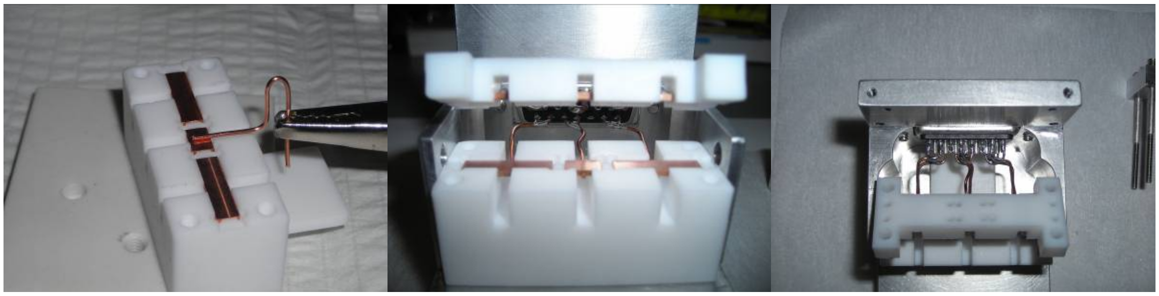

Figure 7 (left): Connect electrodes to copper wire; (middle + right): Electrodes connected to D-sub connector.

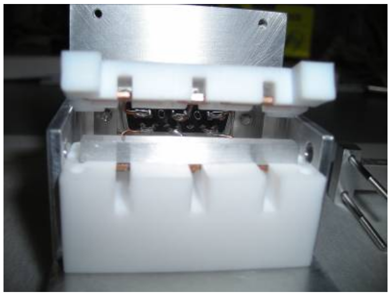

Figure 8: Dummy crystal on electrodes.

2.4 Mounting the crystal

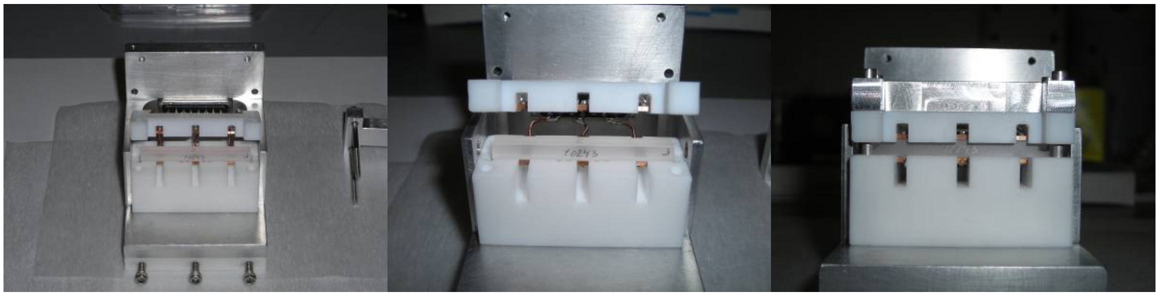

Figure 9: Mount the RTP crystal

Now the RTP crystal can be mounted. From this step on the utmost carefulness and cleanliness must be applied. Again, wear gloves at all times and do not touch the crystal optical surfaces.

1. After the electrodes are soldered the mounting screws can be removed again, the electrodes and Boron-Nitride blocks are now kept in place by the wires.
2. Carefully bend the upper part of the electrode assembly up and remove the “dummy” crystal. Clean the electrodes again.
3. Place the RTP crystal on the electrode mount and carefully move it to the right position. Move the upper part back down and secure it with the screws. The electrodes/Boron-Nitride parts should fit snuggly on the crystal, DO NOT APPLY FORCE to make it fit. You risk breaking the crystal if you do.

After tightening the screws the crystal holding part of the case can be closed. When not in use place tape over the apertures to protect the crystal and keep dust away from its facets.

2.5 Tuning the resonant circuits and input impedance

After assembling the crystal box, the following describes how to prepare the resonant circuit box.

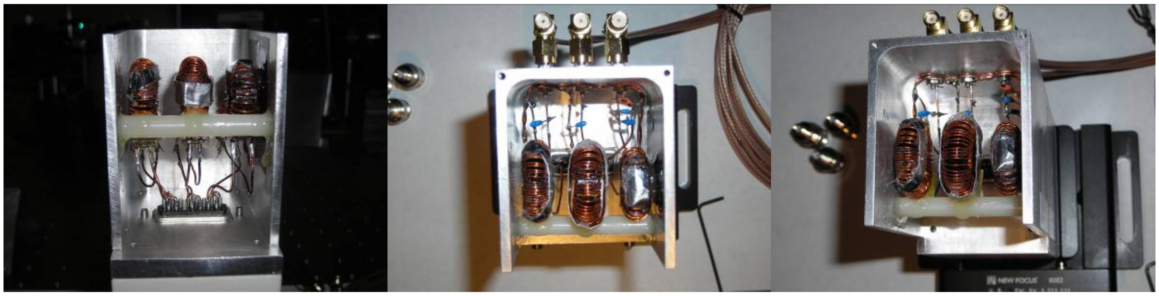

Figure 10: Resonant circuits with aluminum strips used to tune the resonant frequencies.

The resonant circuit, see section 1.3, is based on a capacitance placed parallel to the LC-circuit build by the crystal and a coils. A few leading remarks: The coils are hand wound air coils because commercial coils showed saturation effects for the required parameters - a gain of ten at 24 dBm.

The coils are wrapped using AWG 26 (if more than 50 turns are needed) or AWG 24 enamel wire around Polyurethane flat discs (0.515” ID, 0.875” OD, 0.25” thick – McMaster 94045K212).

The compensation capacitance uses one or more (in parallel) ceramic capacitors.

2.5.1 Calculate coil inductance

Although the resonance frequency is slightly shifted by the Pi-network the required coil inductance for the respective resonance frequencies can be calculated using the (measured) capacitance of the crystal:

$$L_{coil} = \frac{1}{(2\pi f_{res})^2 C_{EOM}}$$

L_{coil} denotes the calculated inductance, f_{res} the desired resonance frequency and C_{eom} the measured capacitance of the crystal. This value is only a target guideline as the actual resonance needs to be tuned to match exactly the desired frequency. The capacitance for the electrodes is about 12 pF for the long electrode and about 6 pF for the short electrodes.

2.5.2 Determine compensation capacitance

The "compensation" capacitance that is responsible for the input impedance needs to be chosen so that the impedance peaks to 50 Ohm on the resonance. This is strongly dependent on the losses of the circuit, but a reasonable estimate is to assume about 2 Ohm losses to and to calculate the frequency dependent, complex impedance of the circuit for various compensation capacitances. Again, this value is only a guideline as the actual capacitance needs to be tuned to match exactly the desired 50 Ohm impedance.

2.5.3 Iteratively approaching 50 Ohm impedance and resonance frequency

The only values that can be changed are the inductance of the coil and the capacitance of the shunt capacitor and as the losses of the circuit are undetermined and frequency dependent it is only possible to iteratively (experimental) approach the desired target values.

1. Calculate desired coil inductance
2. Wrap the coil
3. Check the resonance frequency with a network analyzer using the final casing and crystal.
4. If the measured frequency is close (preferably a little higher) to the target frequency continue, otherwise go back to 2.
5. "Guess" a shunt capacitance and solder it in the casing.
6. Measure the impedance with a network analyzer.
7. Repeat from step 5 on until the measured impedance is close to 50 Ohm.
8. Measure the frequency at the peak where the impedance is near 50Ohm.
9. If the measured frequency is close to the target frequency – stop now.
10. If the frequency is too high – tune it down by gradually patching copper or aluminum strips over the coil in question. (See figure 10.)
11. If the frequency is too low – too bad, go back to 2 and repeat.

This process has to be repeated for all three resonant circuits in the electronics box until all three resonant circuits are tuned to the right values.

Next step: Mount the modulator in a test setup, either an optical cavity that can resolve the sidebands or a second laser offset phase locked to the first, drive the electrodes and measure the modulation depth.

Slight tuning of the modulation frequency can now be used to verify how close the resonant circuits are to the desired target frequencies.

2.5.4 Test and verify the performance

After the tuning process the performance with all three modulation frequencies being driven simultaneously needs to be tested. To test the performance an experimental setup with a laser passing through the newly assembled modulator and an optical spectrum analyzer (OSA) is needed. Each electrode pair needs to be driven with 24 dBm – this requires three function generators and amplifiers as needed. The optical spectrum analyzer will measure the power in the sidebands. Tune the frequencies slightly to find the exact resonances by maximizing the sideband power observed with the OSA

Driven simultaneously the optimal modulation frequencies should be close (less than 100 kHz away) to the target frequencies.

Check Piezo resonances:

Piezo or other unwanted resonances can be observed in the generated RFAM. To measure this effect a fast (NewFocus 1811 photodiode) needs to be installed to measure the RFAM of the modulated light. To check for the Piezo resonances drive a modulation input of the modulator with maximum source power from a Network Analyzer and take a transfer function. If resonances are observed they should not be close to the actual target modulation frequencies. Repeat this measurement for all three modulation inputs.

The following table can be used to record the measured characteristic values after a modulator is fully assembled:

Frequency	**Drive Power (dBm)**	**Modulation depth**	**Piezo-Resonances**

Table 2 Table to record modulator characteristics

Appendix A Technical Drawings

The technical drawings for all parts of the modulator housing can be found in the LIGO DCC. The following section provides the links to the respective parts:

ALIGO IO EOM LONG TEFLON SPACER, LIGO-D0902170-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5722

ALIGO IO EOM SHORT TEFLON SPACER, LIGO-D0902171-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5723

ALIGO IO EOM BOX LOWER, LIGO-D0902172-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5724

ALIGO IO EOM CRYSTAL RISER, LIGO-D0902173-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5725

ALIGO IO EOM CRYSTAL MOUNT, LIGO-D0902174-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5726

ALIGO IO EOM ELECTRODE 7mm, LIGO-D0902175-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5727

ALIGO IO EOM ELECTRODE 22mm, LIGO-D0902176-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5728

ALIGO IO EOM STIFFENER, LIGO-D0902177-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5729

ALIGO IO EOM BOX UPPER, LIGO-D0902178-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5730

ALIGO IO EOM INDUCTOR BOX, LIGO-D0902179-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5731

ALIGO IO EOM TOP COVER, LIGO-D0902180-v1,
https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5732