Electro-optics for high power operation

... of Enhanced/Advanced LIGO

Volker Quetschke, Muzammil Arain, Rodica Martin, Wan Wu, Luke Williams,
Guido Mueller, David Reitze, David Tanner

LIGO power upgrades

After finishing the current S5 science run, LIGO will be upgraded to an enhanced configuration (E-LIGO), that will include among other things an increase in laser power from 10 W to 30 W. At the new power level, electro-optic modulators (EOMs) must be replaced – current LiNbO3-based EOMs suffer from severe thermal lensing, and possibly photorefractive effects and long term damage.
The new modulators presented here are also intended to be used in Advanced LIGO and are therefore designed to be operated at 165 W while satisfying the more stringent requirements on optical modulation, including modulation frequencies, modulation depths, and relative stability of the modulation frequency and amplitude [1].

Modulator material properties

To select the electro-optics material for Enhanced and Advanced LIGO, we examine the properties of several candidate EO materials. The following table shows the optical and electro-optical properties of rubidium titanyl phosphate ($RbTiOPO_4$ or RTP), rubidium titanyl arsenate ($RbTiOAsO_4$ or RTA) and lithium niobate ($LiNbO_3$). RTP was chosen as the most promising modulator material after a literature survey, discussions with various vendors and corroborating lab experiments. RTA is related to RTP and would be an alternative choice. The standard modulator material, used in initial LIGO, lithium niobate ($LiNb0_3$), is not satisfactory from the point of view of thermal lensing, damage threshold and residual absorption.

Properties	Units/conditions	RTP	RTA	$LiNbO_3$
Damage Threshold	MW/cm^2, (10ns, 1064 nm)	>600 (AR coated)	400	280
n_x	1064nm	1.742	1.811	2.23
n_y	1064nm	1.751	1.815	2.23
n_z	1064nm	1.820	1.890	2.16
r_{33}	pm/V	39.6	40.5	30.8
r_{23}	pm/V	17.1	17.5	8.6
r_{13}	pm/V	12.5	13.5	8.6
$n_z^3\ r_{33}$	pm/V	239	273	306
Dielectric const., e_z	500 kHz, 22 °C	30	19	
Conductivity, s_z	$\Omega^{-1}cm^{-1}$, 10 MHz	$\sim10^{-9}$	$3x10^{-7}$	
Loss Tangent, d_z	500 kHz, 22 °C	1.18	-	

Data from Raicol, Crystal Associates, Coretech, Note that the reported data are not all consistent. Moreover, many values are strongly temperature and frequency dependent, particularly the conductivity and loss tangent.

The largest EO-coefficient is r_{33}. The optimum configuration is propagation direction in the y-direction; applied electrical field and polarization of the light field in the z-direction. The modulation depth is proportional to $n_z^3\ r_{33}$ and given by:

$$\Delta\Phi = m = \frac{\pi L}{\lambda} r_{33} n_z^3 \frac{U_z}{d}$$

This shows that RTP has a slightly smaller modulation for the same voltage than LiNbO3 but the following table shows that it is superior in its thermal/absorption properties.

$$Q \equiv \frac{dn}{dT}\frac{\alpha}{\kappa}$$

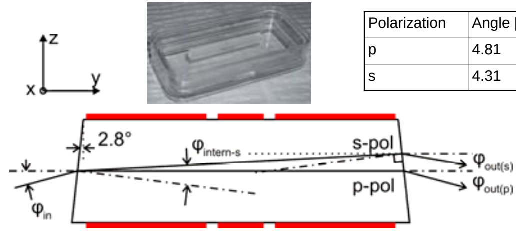
Thermal lensing scales with the Q parameter given above making RTP a good choice for the modulator material.

Properties	Units	RTP	RTA	$LiNb0_3$
dn_x/dT	10^{-6}/K	-	-	5.4 (b)
dn_y/dT	10^{-6}/K	2.79 (a)	5.66 (a)	5.4 (b)
dn_z/dT	10^{-6}/K	9.24 (a)	11.0 (a)	37.9 (b)
$k_{x,y,z}$ (c)	W/Km	3	1.6 (a)	5.6 (b)
α @1064nm	cm^{-1}	< 0.0005	< 0.005	< 0.005
Q_x	10^{-6}/W	-	-	0.48
Q_y	10^{-6}/W	0.047	1.77	0.48
Q_z	10^{-6}/W	0.15	3.44	3.38

a) *Temperature-dependent dispersion relations for RbTiOPO4 and RbTiOAsO4,* Appl. Phys. B 79, 77 (2004), b) Crystal Technology, Inc., c) only one value given, no axis specified.

Split Electrode Wedged RTP crystal

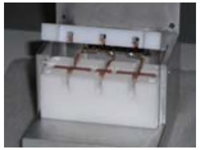
To avoid the unwanted generation of amplitude modulation by polarization modulation because of imperfect alignment of the incident light and also to avoid etalon interference effects we choose to wedge the faces of the RTP crystal. The birefringence of the RTP material separates the different polarizations and avoids the rotation of the polarization that leads to amplitude modulation. The table below shows the different angles for the s- and p-polarization. The crystal faces are AR coated with less than 0.1% remaining reflectivity.



Polarization	Angle [degrees]
p	4.81
s	4.31

Three Modulations / Single Crystal design

To reduce the optical losses the number of modulator crystals is reduced from three to one with three separate pairs of electrodes to apply three different modulation frequencies. The pictures below show the inside of the modulator while the crystal is mounted. The length of the electrodes is increased for modulation frequencies that require stronger modulation indices.

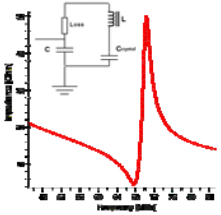


Versatile, Industry-quality housing

The modulator housing is split into two parts, one part holds the crystal the other one holds the impedance matched resonant circuits that increase the modulation strength. The three modulation frequencies are connected to the electronics module via SMA connectors while the two housing parts are connected via D-Sub connectors. Two pins per electrode and short, sturdy copper wires are used to keep the capacitance of the electrodes low.
The use of a separate electronics housing allows one to tune or change the resonant frequencies without affecting the alignment of the modulator crystal. The combined two-part housing is designed in a way that it can be with the electrodes either vertical or horizontal so that the incident light can be chosen to be p- or s-polarized.

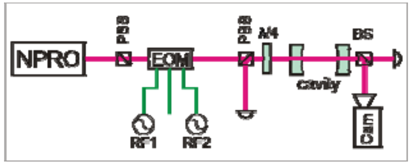
Impedance matched resonant circuit

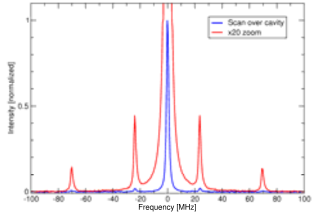
The figure to the right (in the inset) shows the equivalent circuit of the matching network. The matching circuit is designed to have an input impedance of 50Ω and, through resonance, to increase the RF voltage at the crystal by Q, where Q is the quality factor of the resonator. The curve shown in that figure is the projected impedance for a circuit tuned for 70 MHz.



Modulation index measurement

The device that was used for the following measurements contains two resonant circuits for 23.5 MHz and 70 MHz. The inputs were each driven with a 10 V_{pp} signal. The figure to the right schematically shows the experimental setup.





An optical cavity was used to measure the intensity in the modulation sidebands. Photodiodes in transmission and reflection were used verify the alignment of the cavity together with a camera monitoring the TEM modes. The modulation indices were measured to be:
$m_{23.5}$ = 0.29
m_{70} = 0.17
The measurement is shown to the left.

Thermal testing

A YLF laser was used to measure the thermal lensing. The table to the right shows the focal lengths of the thermal lens in the 4x4x40 mm RTP crystal with a 42 W laser beam with a beam waist of 0.5 mm. For comparison: A 20 mm LiNbO3 crystal shows a focal length of ~3 m @ 10 W.

Axis	Focal length
X-axis	3.8 m
Y-axis	4.8 m

RFAM

Pure phase modulated light has a constant intensity. Defects in this are called RFAM. Preliminary result for the prototype show a relative intensity modulation $\Delta I/I < 10^{-5}$ at 25 MHz with m = 0.17.

[1] *Input Optics Subsystem Design Requirements Document*, LIGO-T020020
www.ligo.caltech.edu/docs/T/T020020-00.pdf

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