LIGO

High power optical components for Enhanced and Advanced LIGO

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Outline

- eLIGO phase modulator
- AdvLIGO Mach-Zehnder
- eLIGO/AdvLIGO Faraday isolator

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eLIGO phase modulator

- After S5 LIGO will be upgraded to eLIGO
- Laser power will be increased to 30 W
- Electro-optic modulators (EOMs) must be replaced.
  - LiNbO3 modulators would suffer from severe thermal lensing or might even break

- Faraday isolators (FIs) must also be replaced
  - Absorption in the FI leads to thermal lensing, thermal birefringence, and beam steering

- eLIGO devices (techniques) will be used in AdvLIGO

Overview eLIGO EOMs

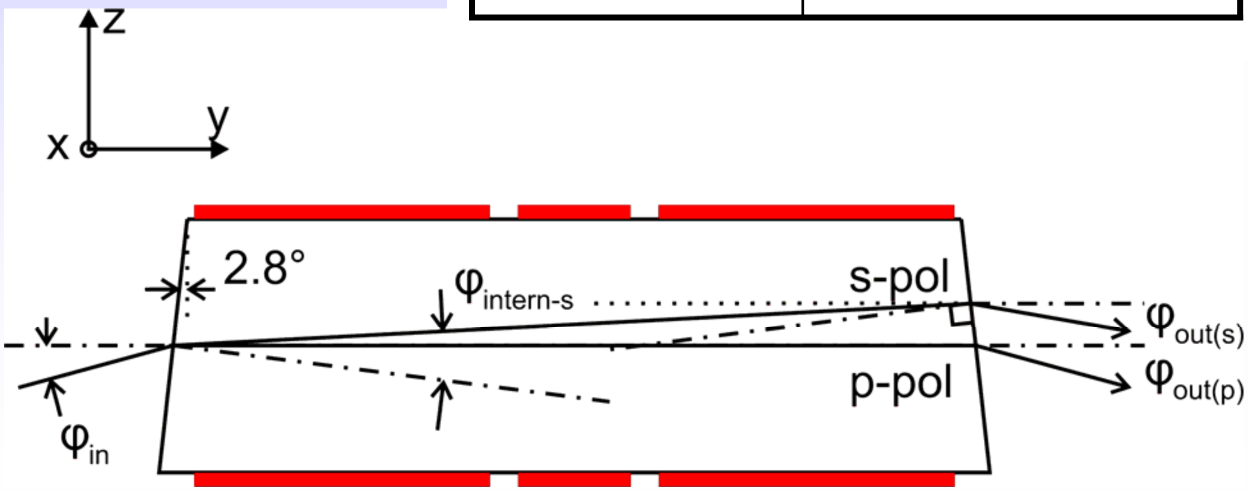
- eLIGO EOMs
  - Lithium niobate (LiNb03), used in initial LIGO, not satisfactory
    - Thermal lensing / Damage / Residual absorption
  - Choose RTP (rubidium titanyl phosphate - RbTiOPO4) as EO material
    - RTP has significantly lower absorption and therefore thermal lensing.
  - Use custom made housing to separate the crystal housing from the housing for the resonant circuit.
    Advantage: Resonant frequencies can be changed without disturbing the optical alignment.
  - Use wedged crystals to reduce spurious amplitude modulation
    Additional advantage: EOM acts as polarizer

Wedged RTP crystal

- Wedged crystal separates the polarizations and acts as a polarizer.
  - This avoids cavity effects and reduces amplitude modulation.

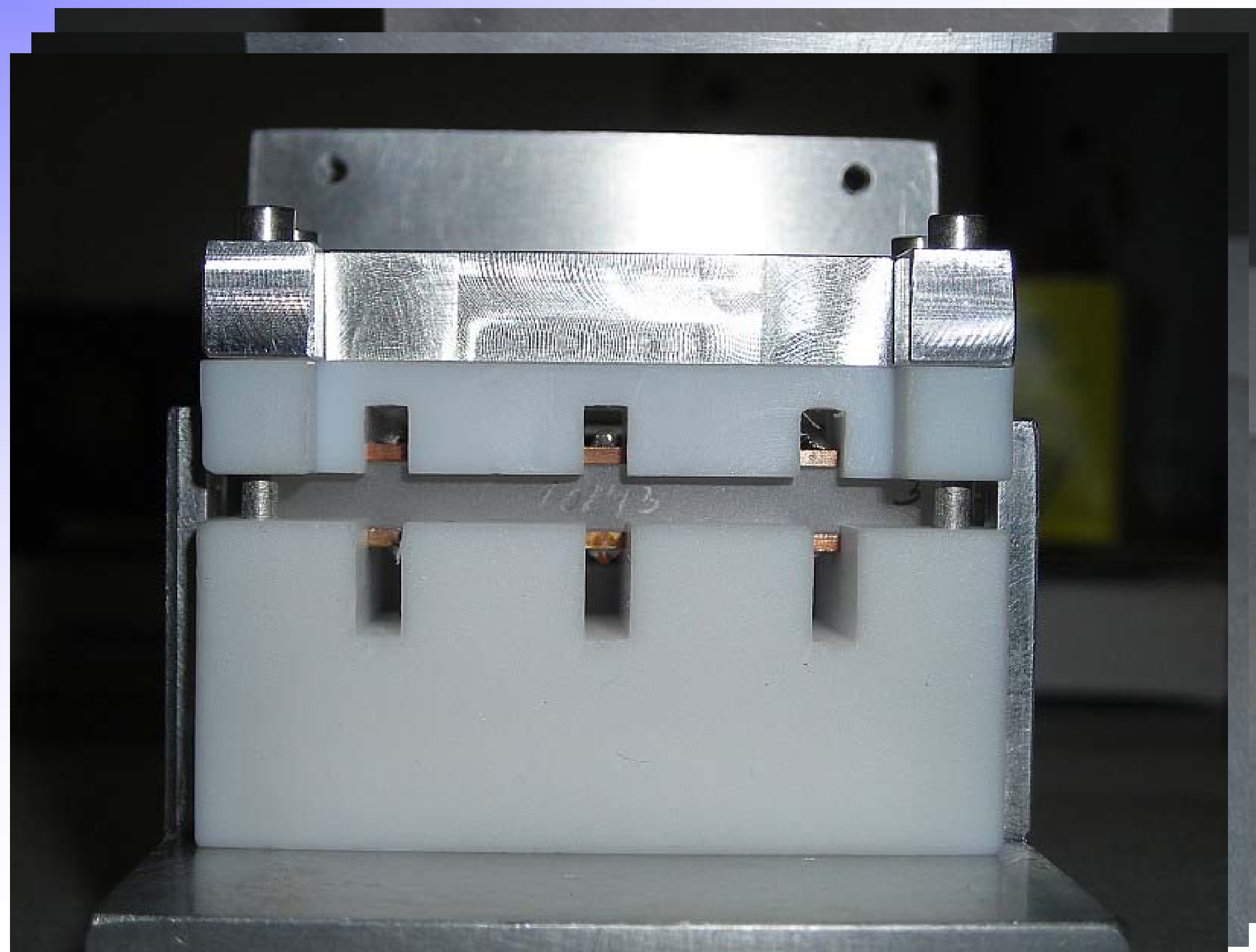
Polarization	Angle [degrees]
p	4.81
s	4.31

- AR coatings (< 0.1%) on crystal faces.



Three Modulations / Single Crystal design

- Use one crystal but three separate pairs of electrodes to apply three different modulation frequencies at once.



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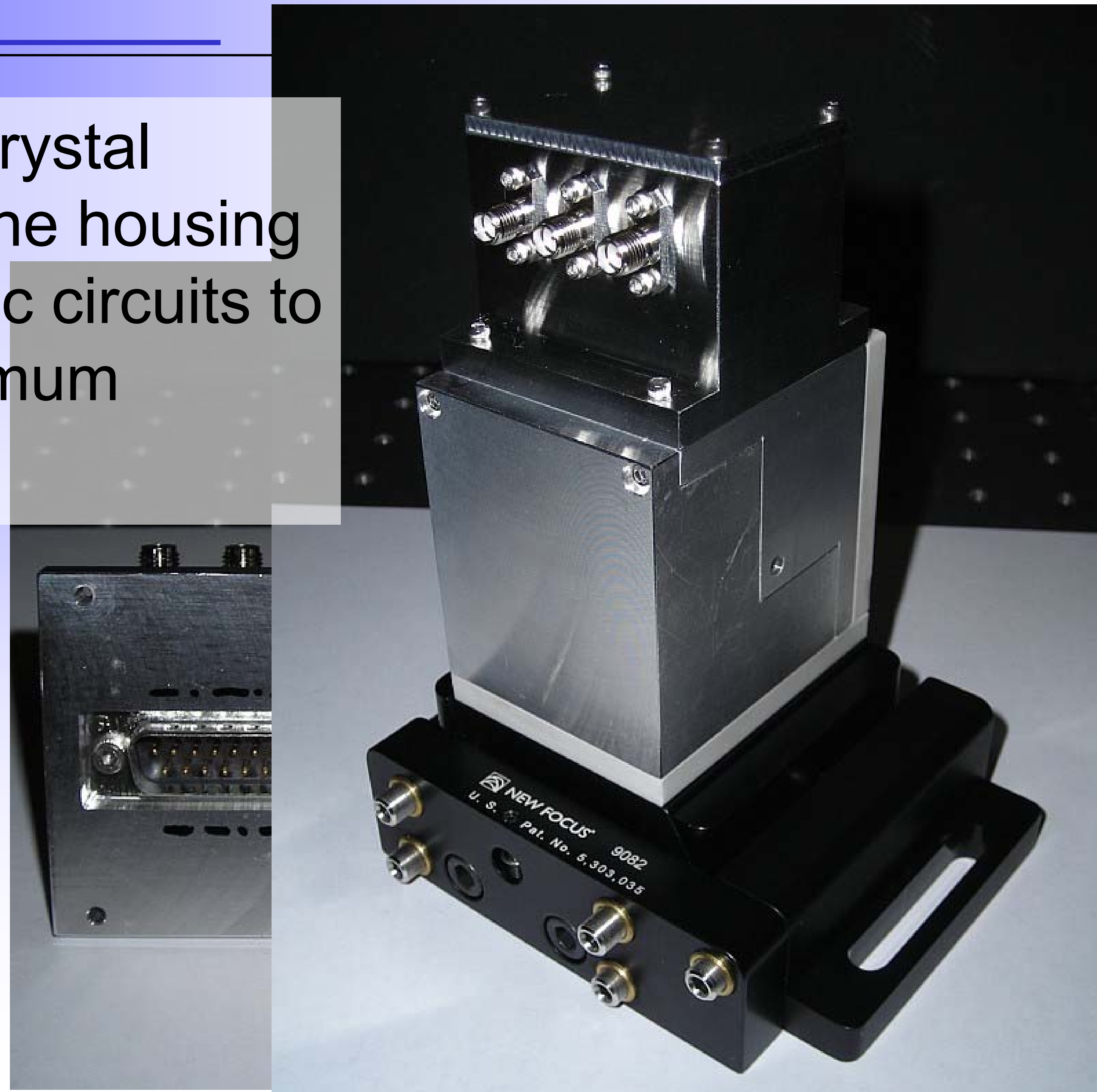
Industry-quality housing

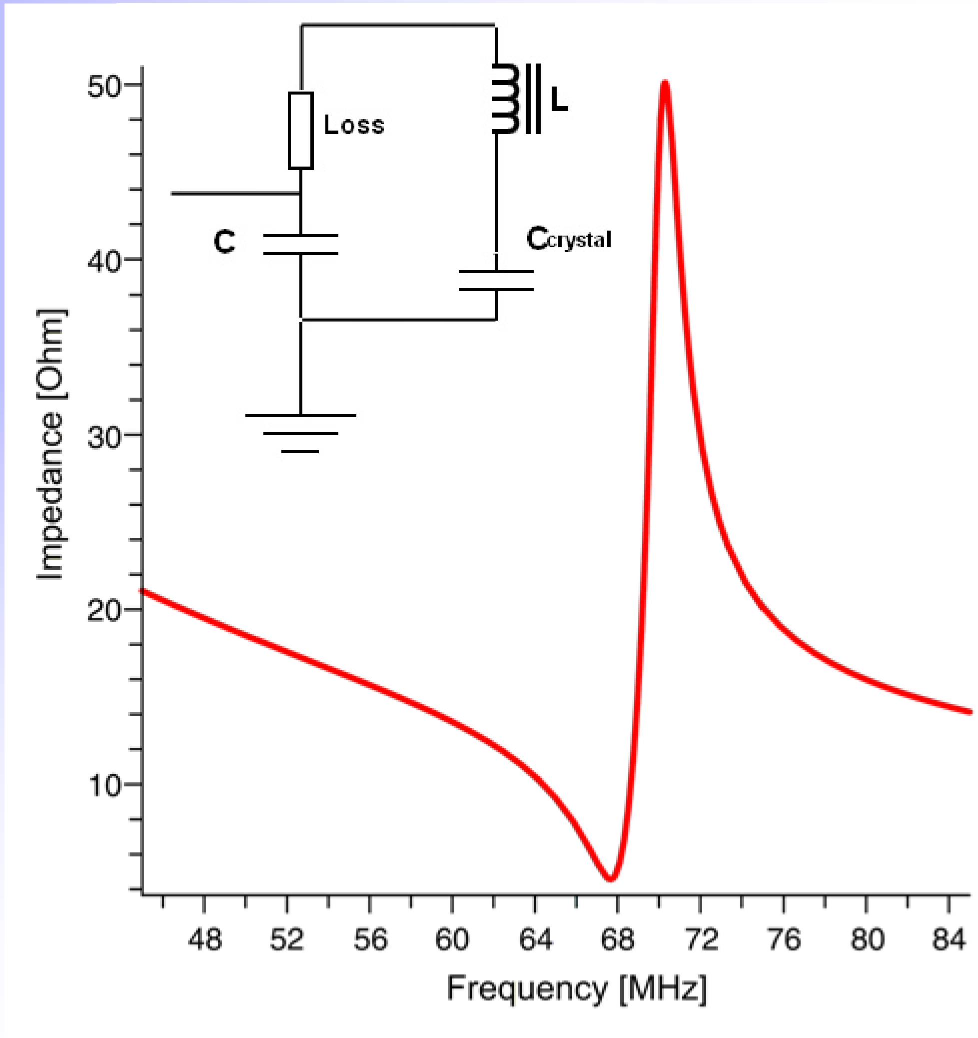
- Separate the crystal housing from the housing of the electronic circuits to maintain maximum flexibility.



Resonant circuit

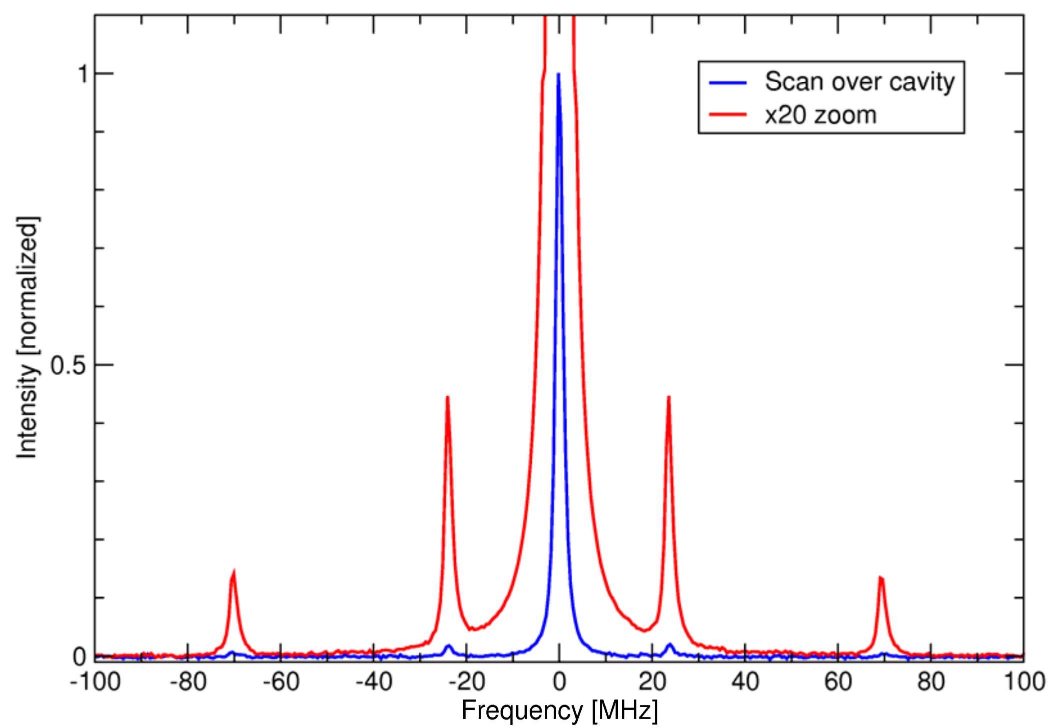
- Impedance matching circuit in separate housing.
- Resonant circuit with 50 Ω input impedance.

- Current prototype has two resonant circuits:
  – 23.5 MHz and 70 MHz



Modulation index measurement

- Sideband measurement with 10 V_{pp} drive into 23.5 MHz and 70 MHz input.
  - $m_{23.5} = 0.29$
  - $m_{70} = 0.17$



Thermal properties

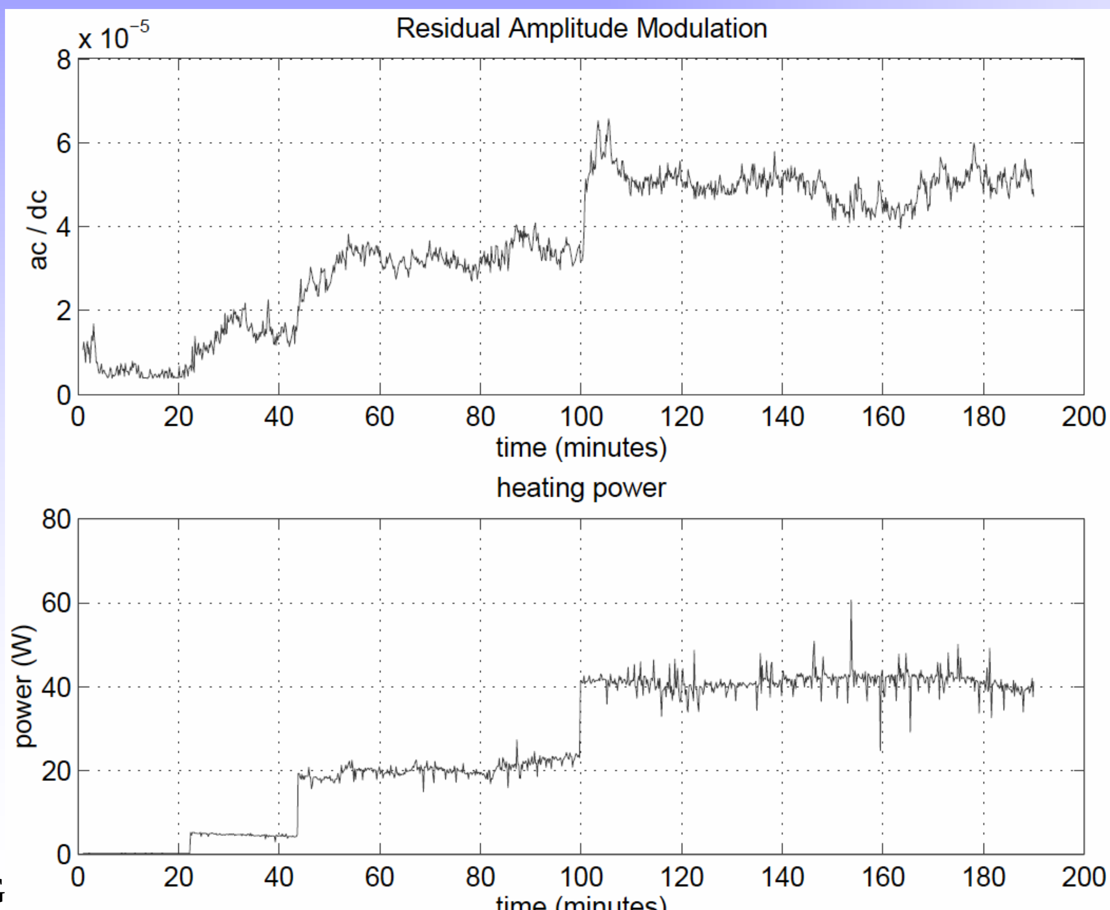
- Use a YLF laser was used to measure the thermal lensing.
  - Full Power = 42 W
  - Beam Waist = 0.5 mm (at RTP)
  - 4x4x40 mm RTP crystal

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

- compare with $LiNbO_3$ (20 mm long): $f_{thermal} \sim 3.3$ m @ 10 W

RFAM

- Measurement of RFAM, for RTP crystal with parallel faces (previous prototype @19.7 MHz, comparable with current LiNbO3 EOMs but better thermal properties)



- Preliminary result for the new prototype:
  $\Delta I/I < 10^{-5}$ at Ω_{mod}
  Ω_{mod} = 25 MHz
  m = 0.17

LIGO AdvLIGO Mach-Zehnder (parallel) modulation

- Not really a high power issue, but needs to be addressed also.
- Objective:
  – Solve the sidebands on sidebands problem by using parallel modulation.
  – Currently used in the 40m prototype
- Problems:
  – Sideband power reduced by a factor of 4
  – Additional intensity noise at modulation and mixing (sum/difference) frequencies
  – Excess intensity, frequency and sideband noise is possible depending on the stability of the MZ and the corner frequencies of the MZ stabilization loop.
- Only address the last point for now ..

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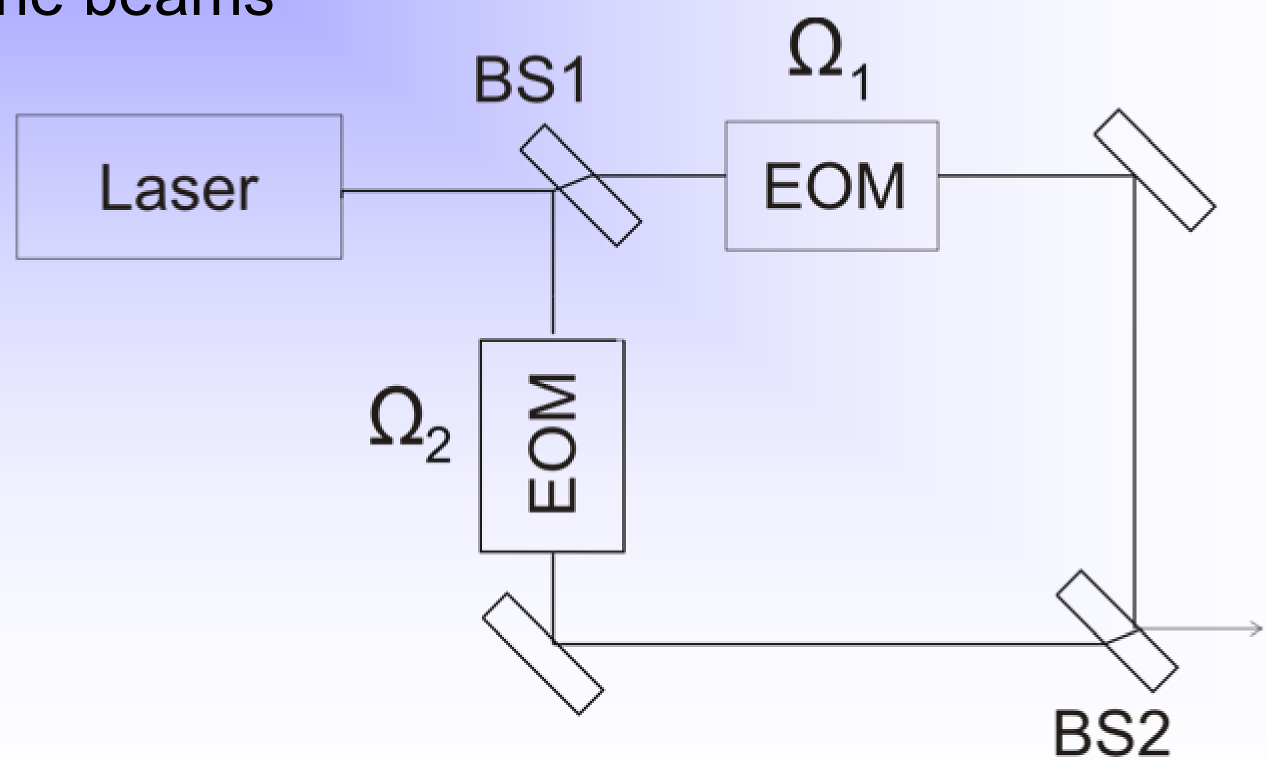
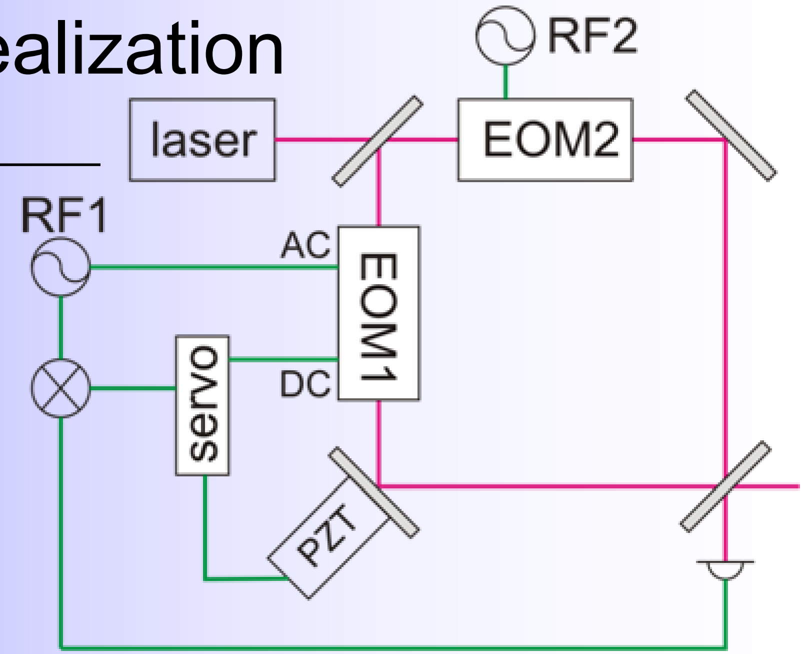
MZ modulation scheme

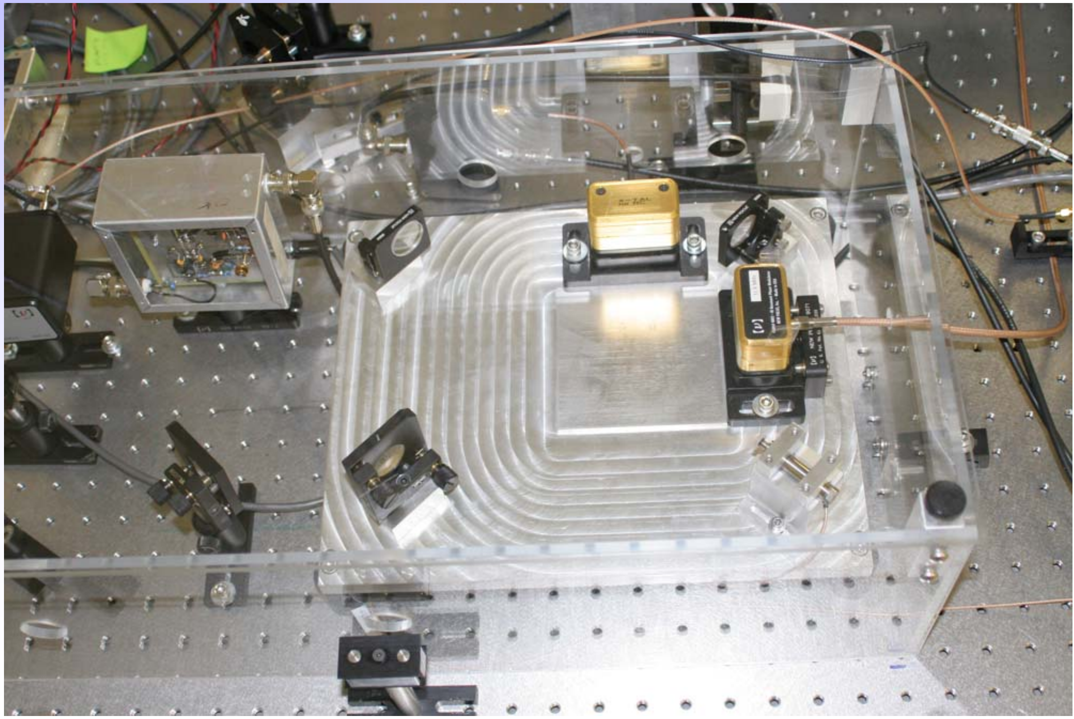
- Parallel modulation with two modulation frequencies
- Avoid the sideband-on-sideband problem by separating the beams



Experimental realization



- Slow length control with big dynamic range with PZT
- Fast phase control with phase correcting EOM
- Stable mechanical “quasi-monolithic” design
- Reduce environmental effects with a Plexiglas enclosure.
- Modulation at 25 MHz and 31.5 MHz



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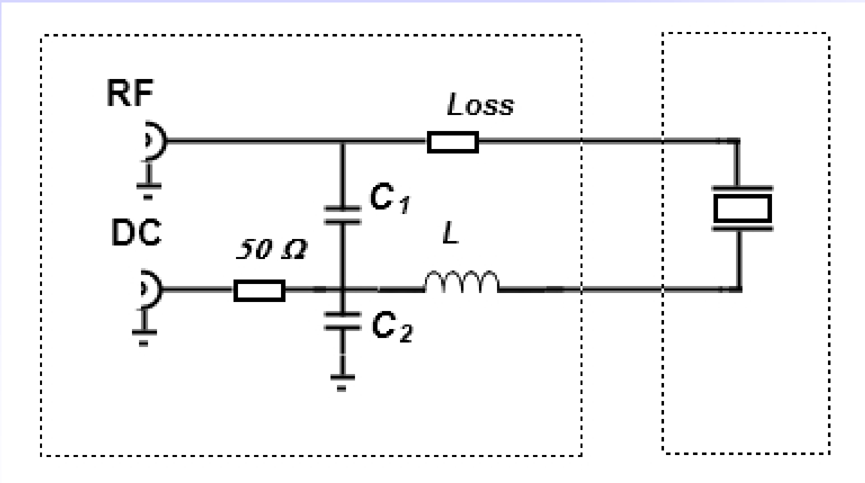
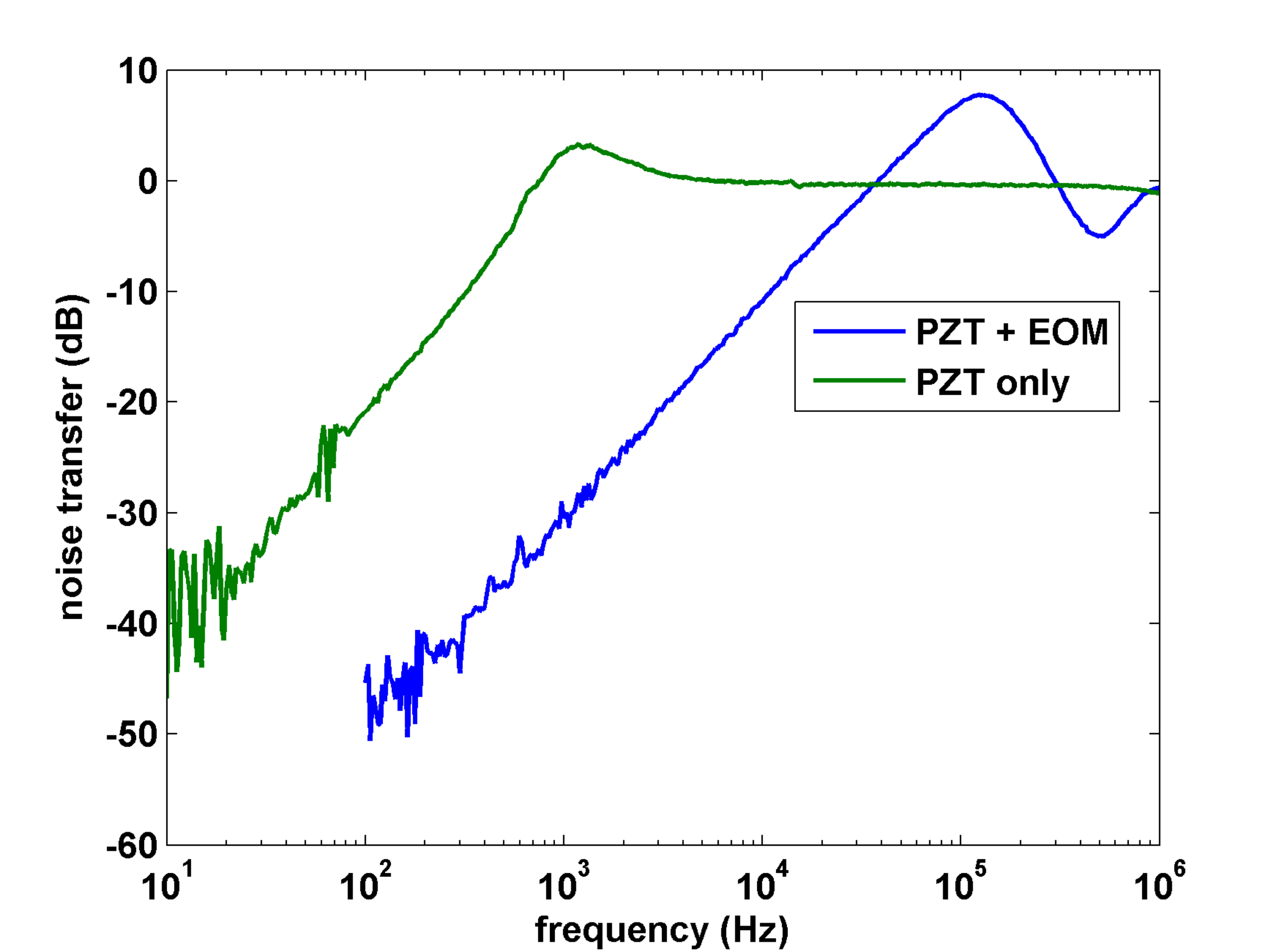
Resonant/DC EOM

- To realize the fast phase correcting without using an additional EOM a slightly modified resonant circuit was used.
  - Simultaneous modulation at resonant frequency
  - DC phase changes up to 1 MHz possible



Noise suppression TF



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MZ summary

- Low noise performance of the PZT control (driven directly out of an OpAmp provides ~4 μm dynamic range)
- Fast phase correcting EOM currently limits the unity-gain frequency to 50 kHz but is only limited by the current servo electronics

eLIGO/AdvLIGO Faraday isolator

- Objective:
  - Strong suppression of back reflected light.
    - eLIGO ~ 30 W
    - AdvLIGO ~ 130 W
  - Minimal thermal lensing
  - Minimal thermal beam steering

Designed and parts supplied by IAP/UF

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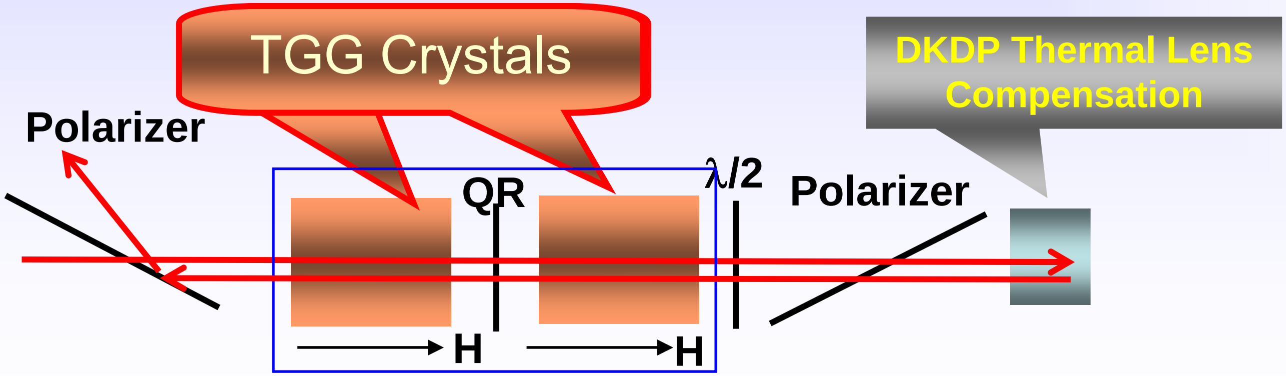
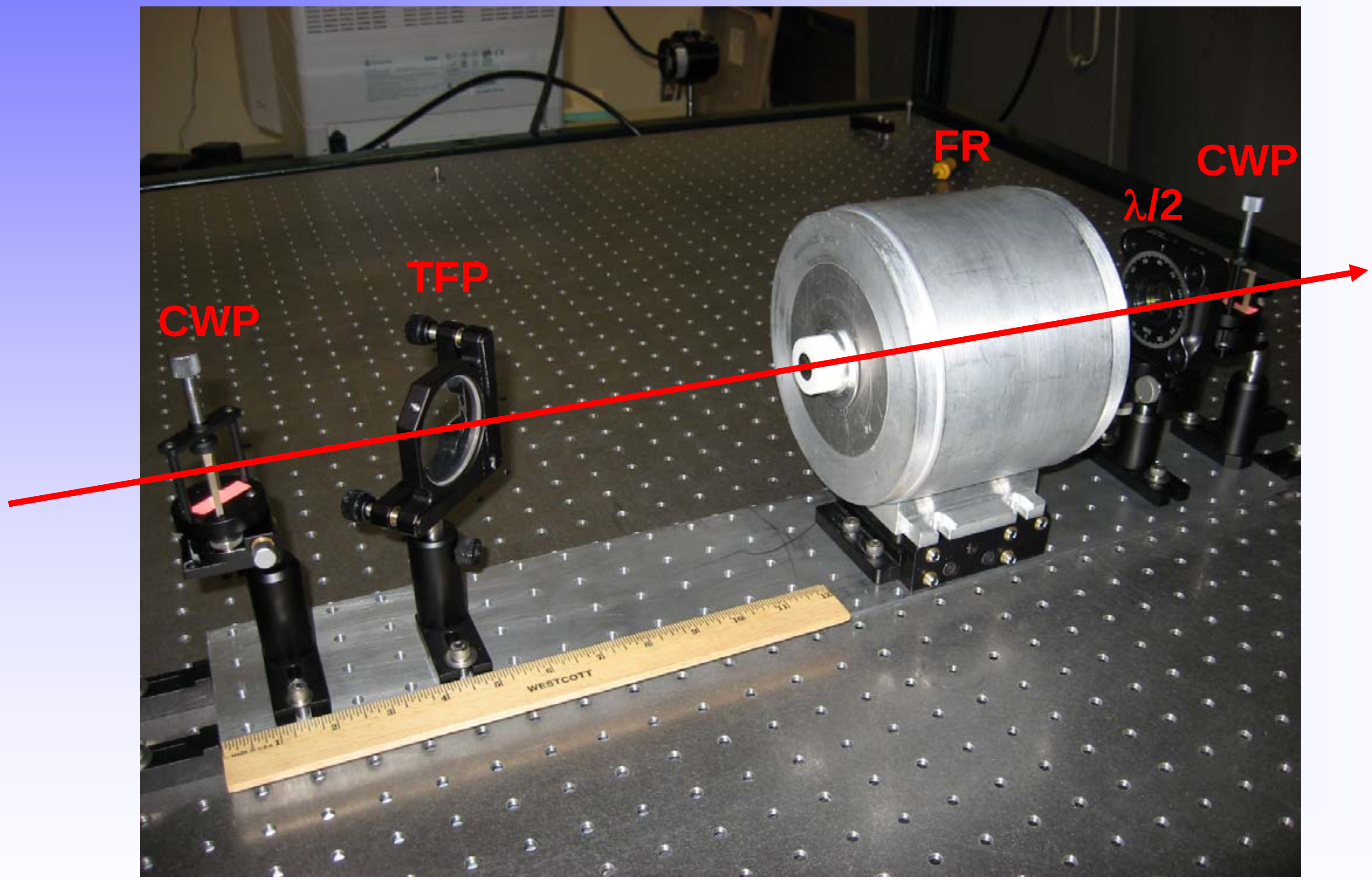
Faraday isolator

- Faraday rotator (FR)
  - Two 22.5° TGG-based rotators with a reciprocal 67.5° quartz rotator between
  - Polarization distortions from the first rotator compensated in the second.
  - ½ waveplate to set output polarization.
  - Thermal lens compensation *via* negative *dn/dT* material: deuterated potassium dihydrogen phosphate, KD_2PO_4, or 'DKDP').
- Calcite wedges or TFP polarizers are possible



FI set up at LLO



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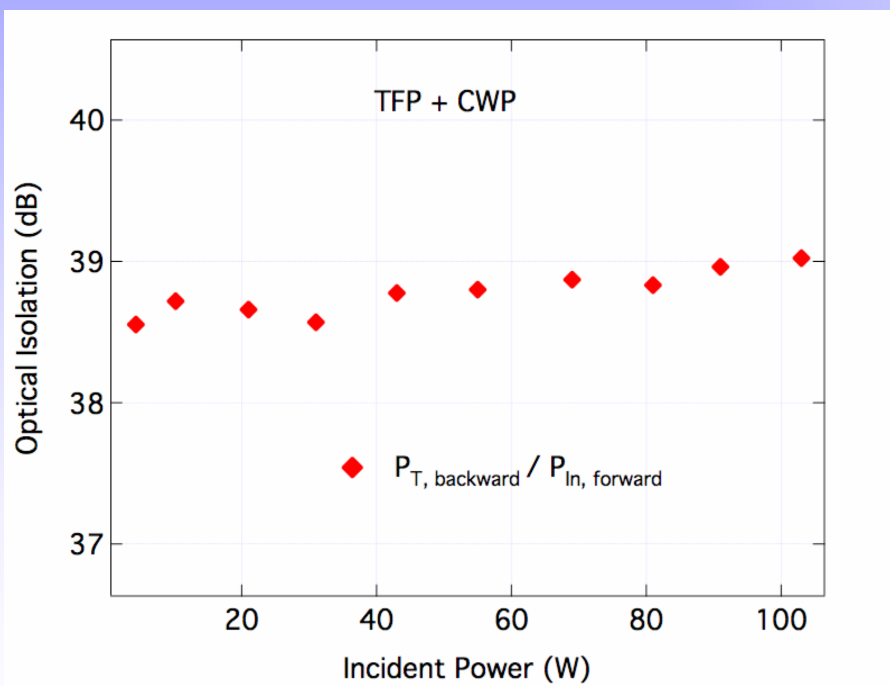
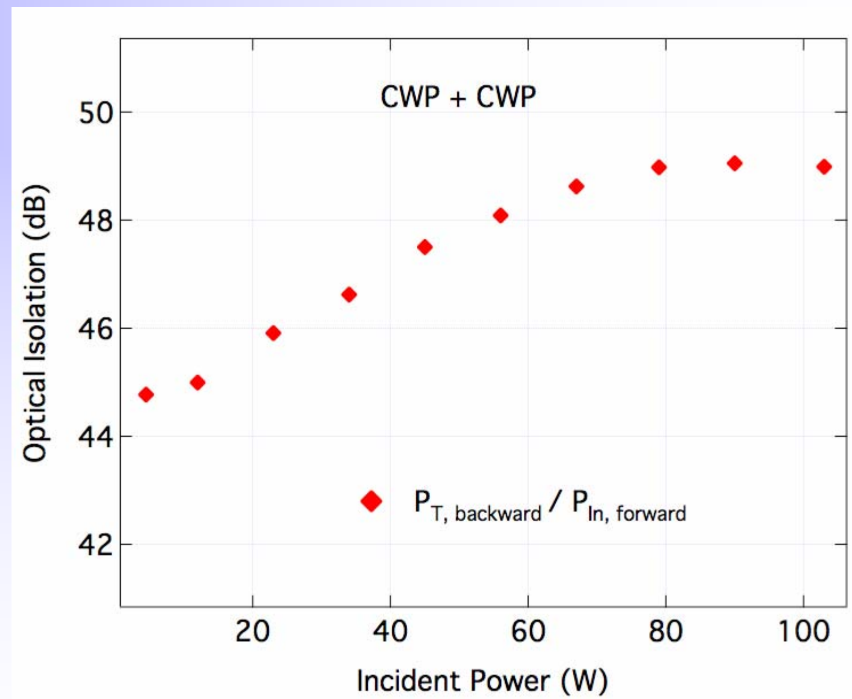
Performance measurements

- Suppression is affected by the polarizers:

TFP and calcite polarizer



Two calcite polarizers



Thermal lensing / steering

- Thermal lensing is compensated by DKDP
- Beam steering is measured to be smaller than (@ 100 W)
  - 80 μrad for two calcite wedges
  - 50 μrad for the TFP / calcite wedge setup

Conclusion

- Everything seems to be on track!

Supplementary material

RTP Thermal properties

Properties	Units	RTP	RTA	KTP	$LiNbO_3$
dn_x/dT	10^{-6}/K	-	-	11	5.4
dn_y/dT	10^{-6}/K	2.79	5.66	13	5.4
dn_z/dT	10^{-6}/K	9.24	11.0	16	37.9
κ_x	W/Km	3		2	5.6
κ_y	W/Km	3		3	5.6
κ_z	W/Km	3		3	5.6
α	cm^{-1}	< 0.0005	< 0.005	< 0.005	< 0.05
Q_x	1/W	-	-	2.2	4.8
Q_y	1/W	0.047	0.94	2.2	4.8
Q_z	1/W	0.15	1.83	2.7	34

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Optical and electrical properties

Properties	Units/conditions	RTP	RTA	$LiNbO_3$
Damage Threshold	MW/cm^2,	>600	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
Absorption coeff. α	cm^{-1} (1064 nm)	< 0.0005	< 0.005	< 0.005
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
r_{42}	pm/V	?	?	28
r_{51}	pm/V	?	?	28
r_{22}	pm/V			3.4
$n_z^3 r_{33}$	pm/V	239	273	306
Dielectric const., ε_z	500 kHz, 22 ^oC	30	19	
Conductivity, σ_z	$\Omega^{-1}cm^{-1}$, 10 MHz	$\sim 10^{-9}$	$3x10^{-7}$	
Loss Tangent, d_z	500 kHz, 22 ^oC	1.18	-	