TIME-LINE

- **Start of September 2011:** Decision on which crystal size. Placing order at Leysop/Raicol. Estimated delivery time will be about 12-14 weeks.
- **Start of October 2011:** Decide if we want to buy better (balanced) feedthroughs for the modulation signals? If so place corresponding order.
- **December 2011:** Assembly of the whole modulation electronics on a testbed in Glasgow. Optimisation of matching circuits. Also check the achievable modulation index (scanning FP).
- **January 2012:** High power test of EOM crystals at AEI-Hannover. Measurement of thermal lensing + purchasing of required modematching lens for MU3.
- **Beginning of February 2012:** Ready for opening the tanks.

Discussion on GEO-HF EOMs

- Do we have all the required info to make an informed decision? Any points we missed?
  - Any strange polarisation effects?
  - Any effects, if we use an odd number of crystals per EOM?

Advanced LIGO design

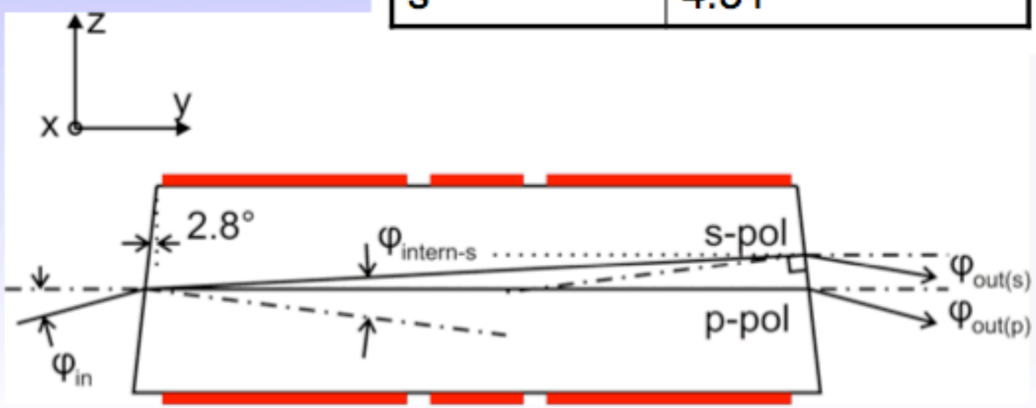
LIGO

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.



Discussion on GEO-HF EOMs

- Do we have all the required info to make an informed decision? Any points we missed?
  - Any strange polarisation effects?
  - Any effects, if we use an odd number of crystals per EOM?
- Discussion mainly focused on MU3 as this is the most important decision.
  - MU2 and MU1 also need new crystals, but requirements would be much more relaxed.
- Some side aspects:
  - Do we want to replace the feed-throughs by balanced versions?
  - Probably also rebuild some of the modulation electronics as we run out of spares for the current system.

SUMMARY

Option	8x8x10mm	6x6x35mm
Modulation level for a single crystal	1/4.5 of old EOM	1/1.04 of old EOM
Number of crystals required	3-4	2
Modulation voltage	Need to increase	Same as today
Price	£ 9000	£ 12600
Free aperture on MU3	6.4 w	5.89 w
Availability	standard	First time

EXTRA SLIDES

40 Meter Lab. Development of Triple Resonant EOM for Advanced Detectors

K.Izumi[A], S.Erickson[B], K.Arai[C], R.Adhikari[C] and 40m-collaborators
[A]University of Tokyo, [B]Smith College, [C]California Institute of Technology

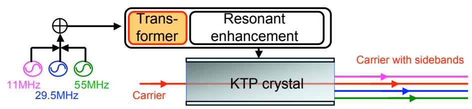
We have developed a triple resonant EOM which can impose a set of three phase modulation sidebands with one crystal. Essentially it works with a resonance enhancement circuit and a transformer to make it resonate at desired frequencies and to step up the voltage. So far we have made a prototype circuit that was tuned for an EOM made from KTP. We have successfully got triple resonance. A reasonable gain of 9 and 8 were obtained at 11 and 55MHz respectively.

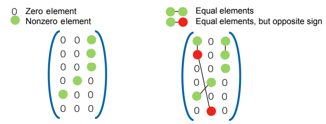
1. Motivation

- The **40m** is a prototype interferometer to develop **advanced interferometric configurations**
- In advanced and complex interferometers, multiple phase modulation sidebands are needed
- Avoid the parallel modulation style by Mach-Zehnder which leads to noise issues and complexities

2. Principle idea

- Use one EO crystal of KTP, a transformer and a triple resonant enhancement circuit
- Three phase modulation sidebands can be imposed with the thee different frequencies at once
- Univ. of Florida (UF) had developed a similar system, but they used three resonant circuits instead of one





Electrooptic tensor for KTP Orthorhombic mm2 | LiNbO3 Trigonal 3m

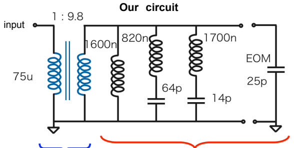
3. Utilize transformer

- Transformers **passively can step up the gain** proportional to the number of the turns ratio n
- Transformers lead to reduction of the impedance by a factor of $1/n^2$
- Optimum condition is found at $Z/n^2=50\,\Omega$ (impedance matching), where Z is impedance of the resonant circuit
- The maximum gain is represented as $G=n=(Z/50)^{1/2}$ under the optimum conditions
- Therefore **high Z is needed** to achieve the high gain at the resonances

4. Design of the resonant enhancement circuit

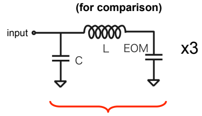
- LC pair creates a resonance so that it becomes high Z
- Since the resonant frequency is expressed by $f_0=(2\mathrm{pi}(LC)^{1/2})^{-1}$, it allows to have **similar solutions** (e.g. $L'=L/k$, $C'=kC$)
- To determine the set of optimum L and C from similar solutions, we searched for the highest impedance configuration by inserting the loss model
- Finally n=9.8 for the turns ratio of the transformer has been chosen
- UF employed **three separated resonant circuits** with a RTP crystal

Our circuit



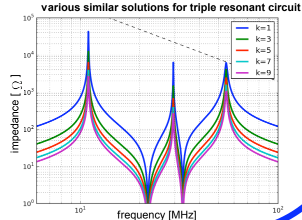
transformer | **triple** resonant enhancement circuit (including EOM)

UF style [1] (for comparison)



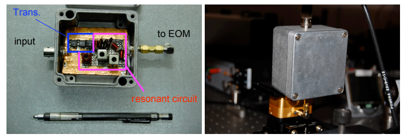
single resonant enhancement circuit (including EOM)

various similar solutions for triple resonant circuit



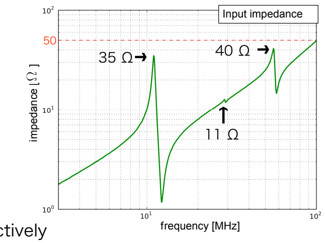
5. Assembly and health check of prototype

- The circuit is covered with a metal box to eliminate the radiation from the circuit
- The circuit is attached to the commercial EOM (NewFocus 4064) with a SMA cable as short as possible.



assembled circuit | the circuit attached with the EOM

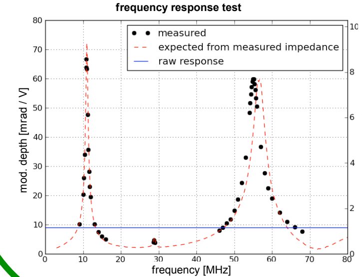
- To check the health of the system, the **input impedance** had been measured.
- An input impedance of 35, 11 and 40Ω at each of the resonances were yielded, these are close to 50Ω



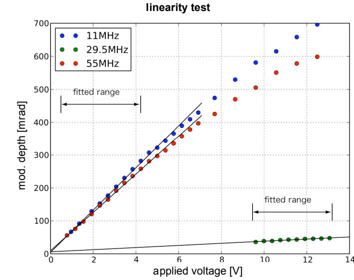
6. Performance tests of prototype

- Optical tests by using an optical spectrum analyzer
- Obtained the triple resonances at designed frequencies successfully
- The reasonable gain of 9 and 8 were achieved at 11 and 55MHz respectively
- Although modulation depth at 29.5MHz is low, however this is for the MC lock and is fine

frequency response test



linearity test



- modulation efficiency

11MHz: 64mrad/V (G~9)

29.5MHz: 3.3mrad/V (G~0.5)

55MHz: 58mrad/V (G~8)

- UF modulation efficiency with RTP [2] (for comparison)
24.5MHz: 74mrad/V
33MHz: 28mrad/V
61.2MHz: 28mrad/V

7. Considerations

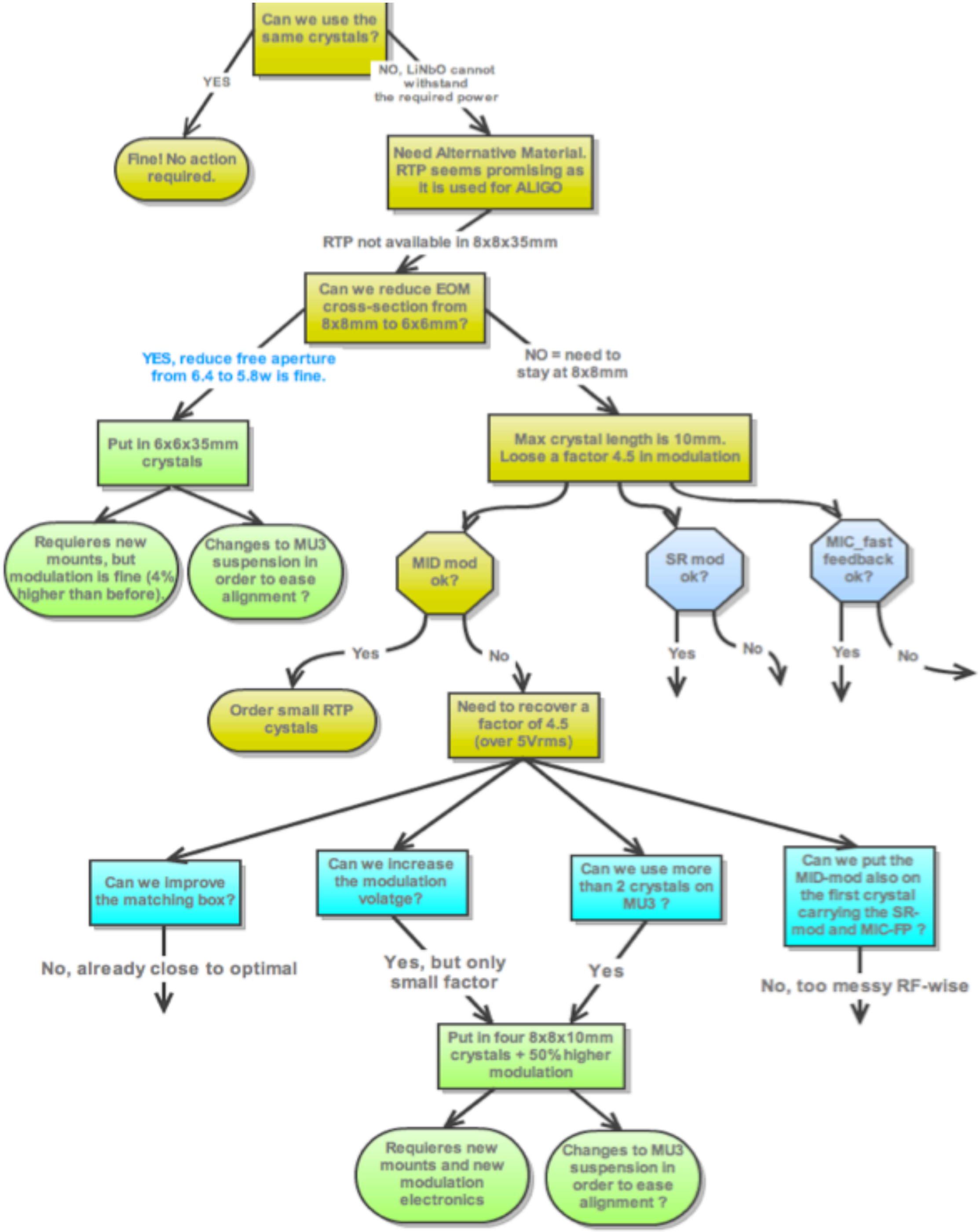
- The losses in the circuit are somehow underestimated in the model calculation
- The transformer seems to have an unexpected insertion loss
- It is hard to match the impedances of all three resonances to 50Ω

8. Next steps

- Final design and assembling onto a RF-quality printed circuit board
- Installation of the triple resonant EOM at the 40m

References [1] V.Quetschke et al., "High power optical components for enhanced and advanced LIGO", LIGO-G070117-00-R
[2] V.Quetschke "Electro optic modulators and modulation for enhanced LIGO and beyond", LIGO-G080406

LIGO-G1000297-v1



University of Glasgow

Table 1 Material parameters at 1,064 nm for four widely used electro-optical materials

	$LiNbO_3$ Uniaxial	KTP Biaxial	RTP Biaxial	BBO Uniaxial
r_{ij} (max) (pm/V)	32	37	39	2.7
n_j	2.16	1.84	1.85	1.66
$\beta = dn_j/dT$ (ppm/K)	39	15	11	–9.3
α_{jj} (ppm/K)	15	9	13	4
κ_{aa} (min) (W/mK)	5.6	2	3	1.2
γ (1/cm)	1.5×10^{-3}	1.2×10^{-4}	10^{-4}	10^{-3}
FOM (Wm/V)	2.7×10^{-3}	2.1×10^{-2}	4.1×10^{-2}	2.7×10^{-4}

The thermal properties of MgO:$LiNbO_3$ are similar to the properties of $LiNbO_3$ with the exception of the photorefractive damage threshold. BBO is a potential candidate for shorter wavelength. These parameters were extracted from several different references (see text and references) and should be used with caution as several of these values depend also on the specific composition of the crystal. For example r_{33} of stoichiometric (mole ratio Li/Nb = 1)$LiNbO_3$ is 30% higher than of congruent (mole ratio Li/Nb = 0.946)$LiNbO_3$ [26]

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RESEARCH ARTICLE

Lasers and optics: looking towards third generation gravitational wave detectors

Nergis Mavalvala · David E. McClelland · Guido Mueller · D. H. Reitze · Roman Schnabel · Benno Willke