Study of a Universally Tunable Electro-Optic Modulator

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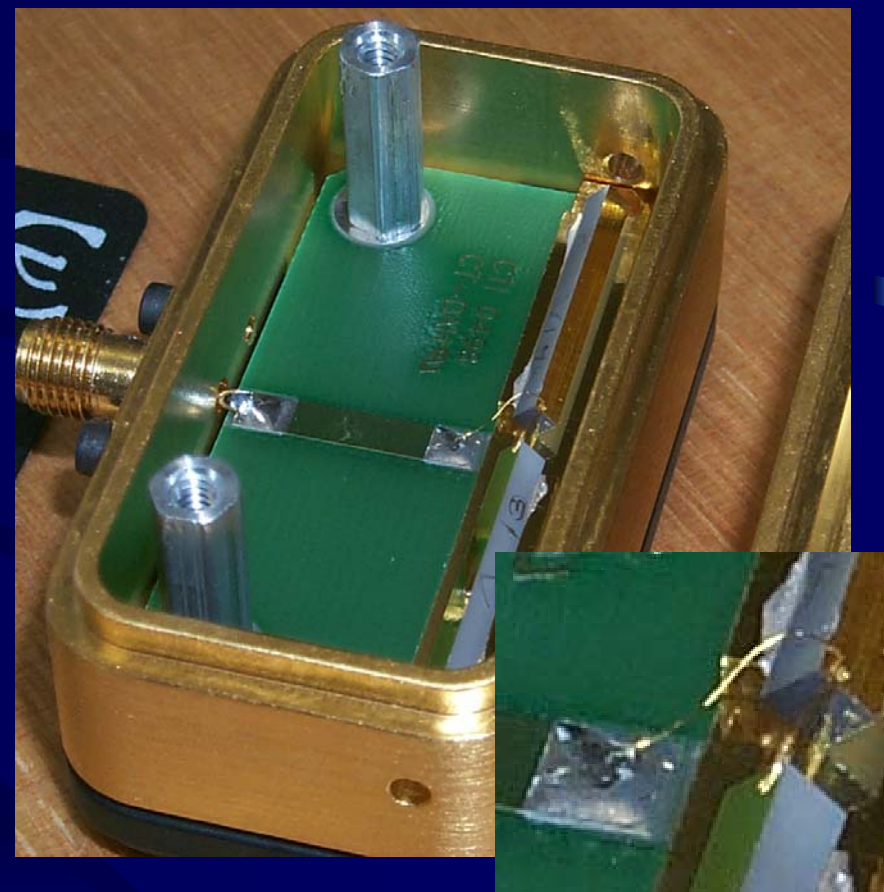
Universally Tunable Modulator

- Our UTM = modified Amplitude Modulator
  - New Focus 4104
  - Re-wire to have separate control of two crystals
- UTM is capable of PM and AM with selectable phase relation

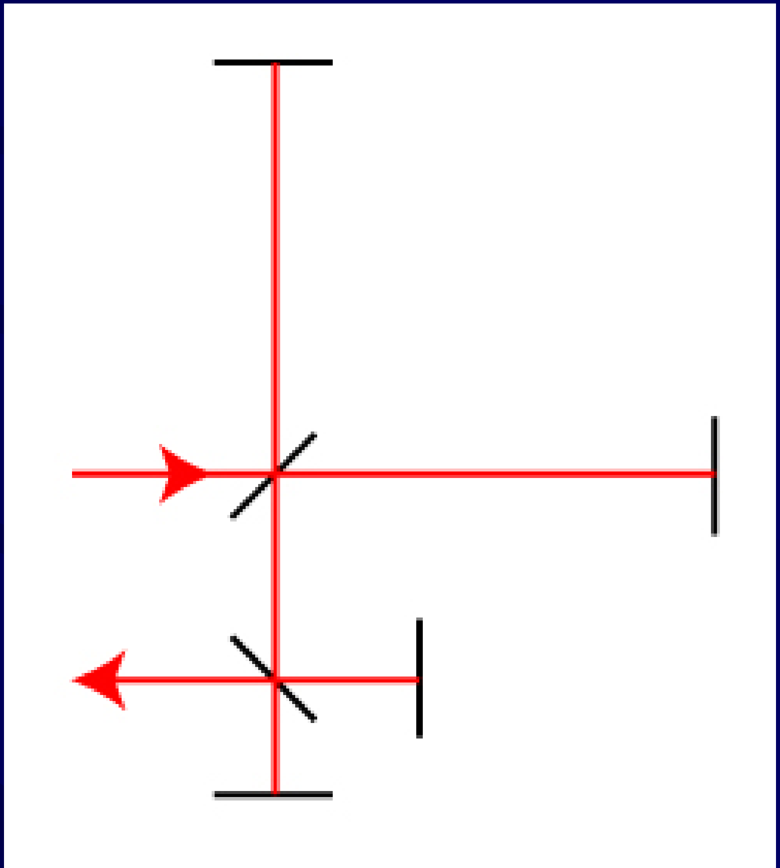


What is the UTM for?

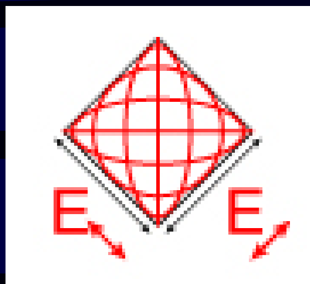
- GW rf control systems are based on injecting PM
  - GW inteferometer optical freq response can convert PM to AM according to its state
  - AM is detectable → readout/error signals
- UTM innovation: inject AM along with PM such that actuators overcompensate
  - Result: tunable lock points

Tuning GW detector responses

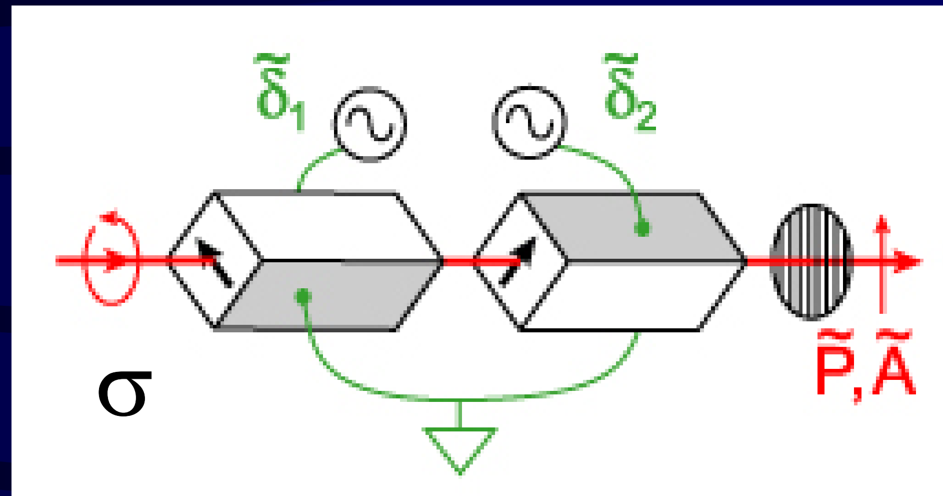
- Consider simplified GW detector →
- Signal cavity and 2nd Michelson phase conditions determine detector response
  - Cavity and Michelson require AM of orthogonal phases → UTM can do this
  - Potential to tune-lock **both** dof with a single UTM



How the UTM works

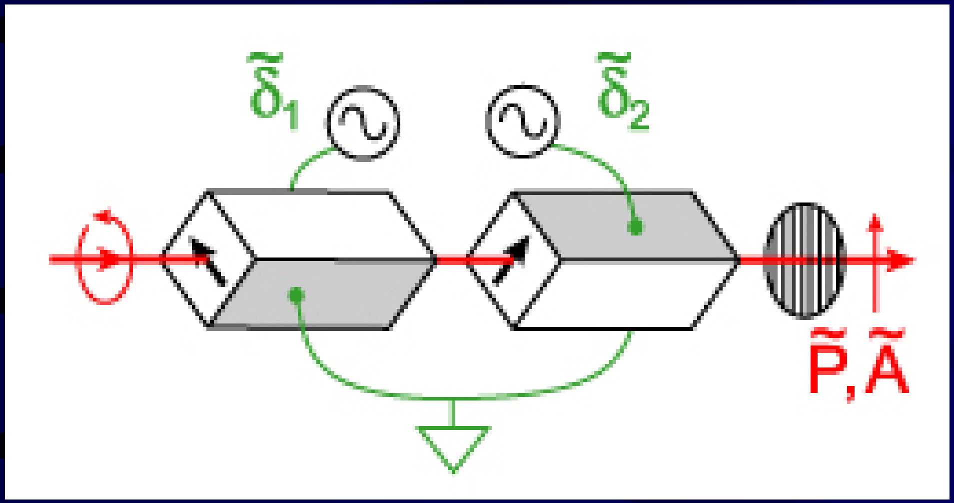


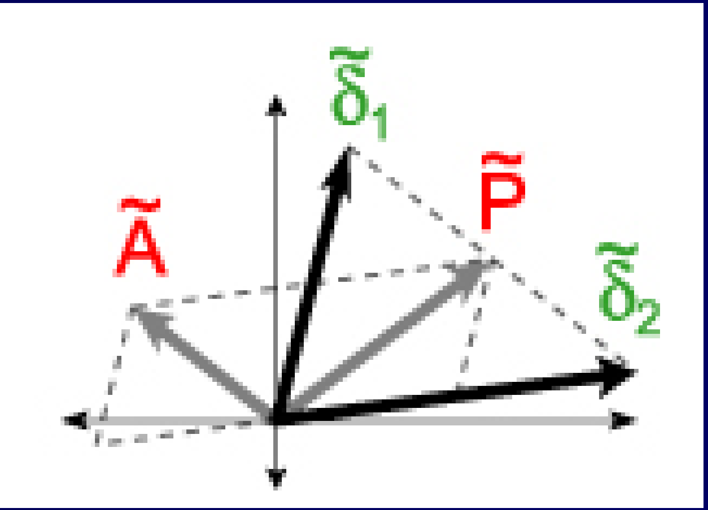
$\sigma = 0 \rightarrow$ vertical
$\sigma = 90 \rightarrow$ circular
$\sigma = 180 \rightarrow$ horiz'l



- 2 PM crystals, 2 V-sources, linear polariser
- Circular (elliptical) polarisation input: σ
  - **Choose small σ to avoid dumping too much power**
- Equivalent to Mach-Zehnder modulator
  - polarisation interferometry, spatially degenerate

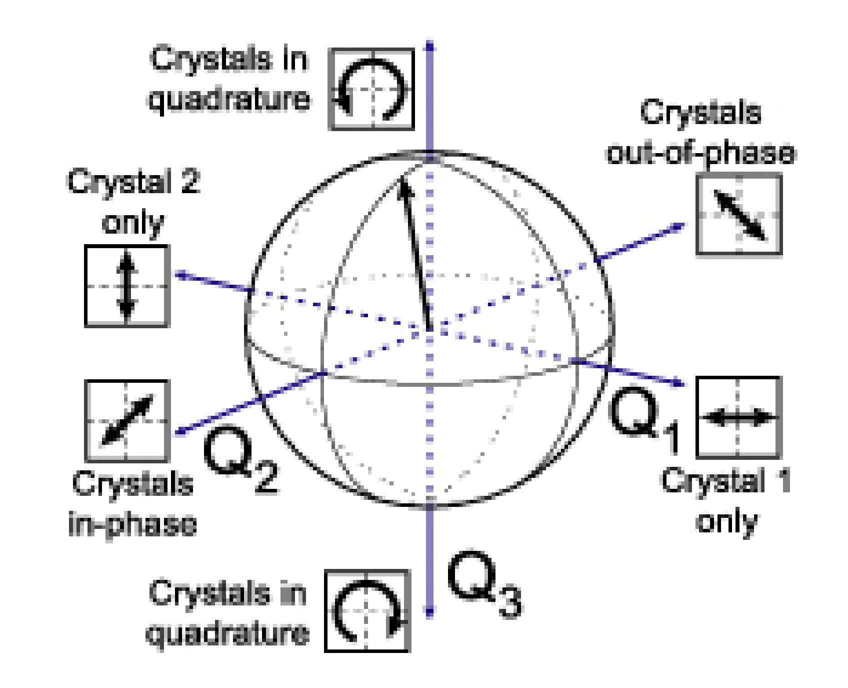
UTM Transfer Function





$$\tilde{P} = \frac{1}{2}\cos\left(\frac{\sigma}{2}\right)\left(\tilde{\delta}_1 + \tilde{\delta}_2\right)$$
$$\tilde{A} = \frac{1}{2}\sin\left(\frac{\sigma}{2}\right)\left(\tilde{\delta}_1 - \tilde{\delta}_2\right).$$

The Modulation Sphere



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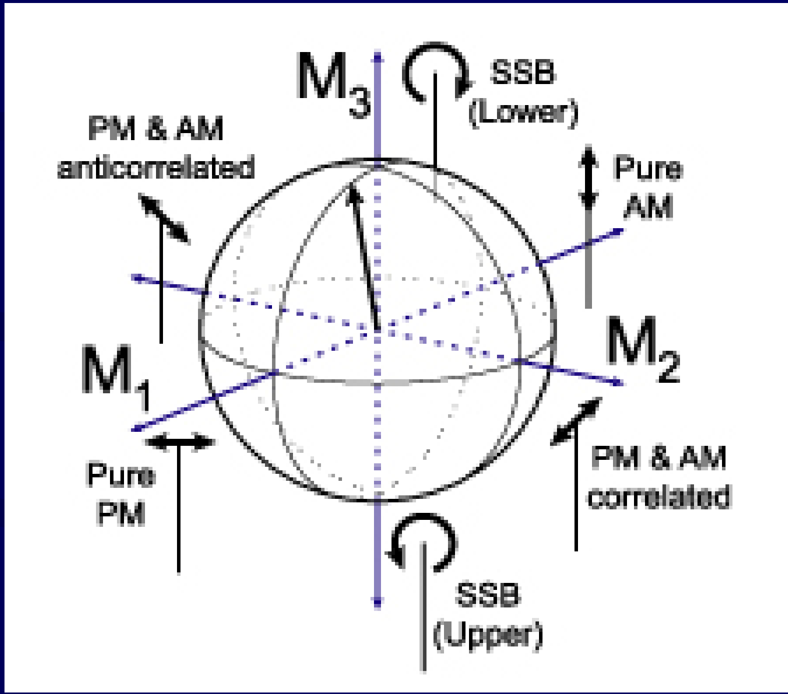


If σ = 90 (circular)

$$M_0 = \frac{1}{4}Q_0$$

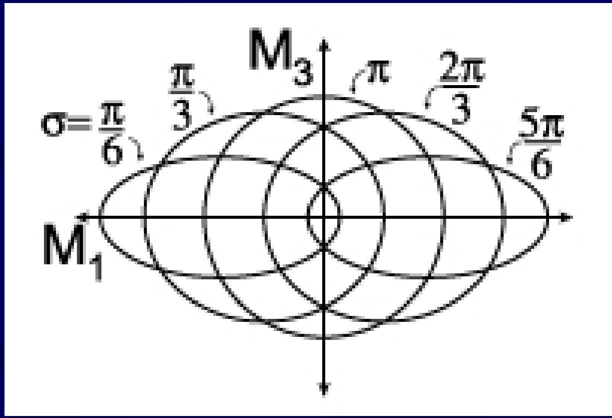
$$M_1 = \frac{1}{4}Q_2$$

$$M_2 = \frac{1}{4}Q_1$$

$$M_3 = -\frac{1}{4}Q_3$$

Modulation Ellipse

- If $\sigma \neq 90$, a sphere in "Q-space" maps to an **ellipse** in "M-space"
- M-space ellipse is:
  - off-centre
  - prolate (along M_1)
  - one focus at origin
  - orthogonality of axes preserved (important!)



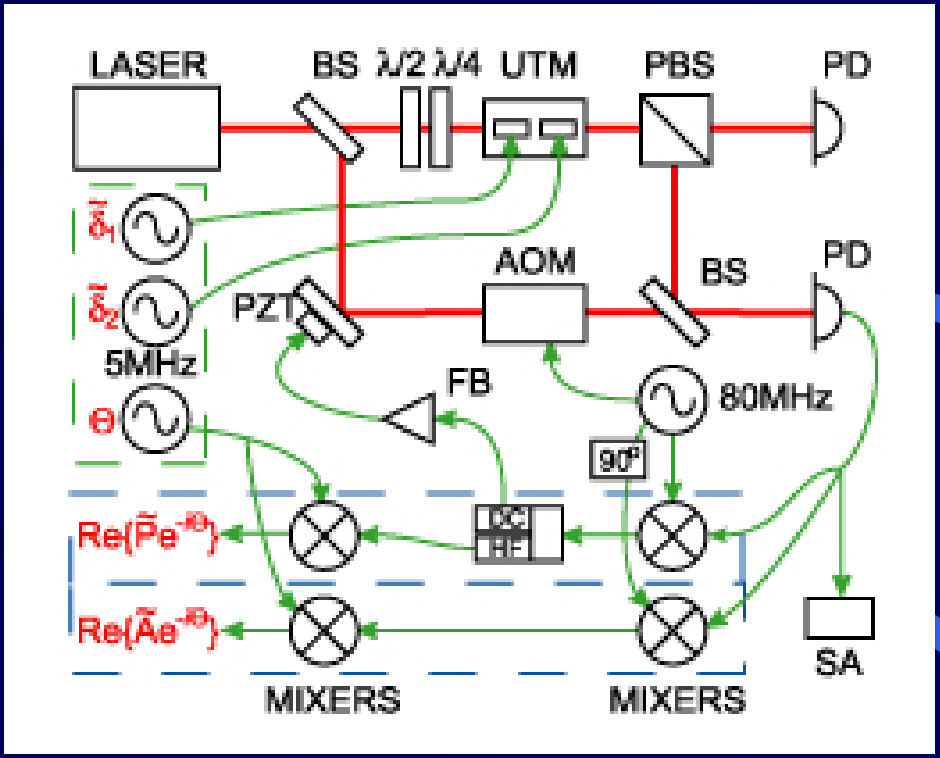
$$
\begin{aligned}
M_0 &= \frac{1}{4}\left(Q_0 + Q_2\cos(\sigma)\right) \\
M_1 &= \frac{1}{4}\left(Q_0\cos(\sigma) + Q_2\right) \\
M_2 &= \frac{1}{4}\sin(\sigma) Q_1 \\
M_3 &= -\frac{1}{4}\sin(\sigma) Q_3
\end{aligned}
$$

Prototype Characterisation

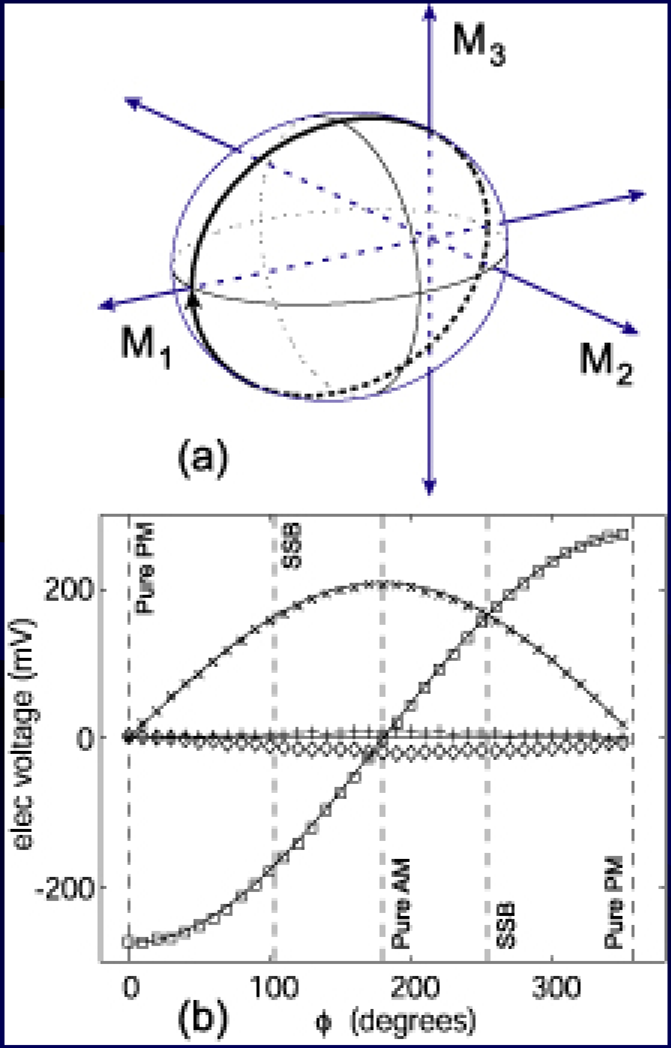
- Chose two properties of merit to evaluate:
- *Variability*:
  - – device continuously tunes around M-space in a predictable, repeatable manner
    - should be able to “dial-up” modulation once calib’d
- *Purity*:
  - – specific modulation states attainable with high precision and time-stability

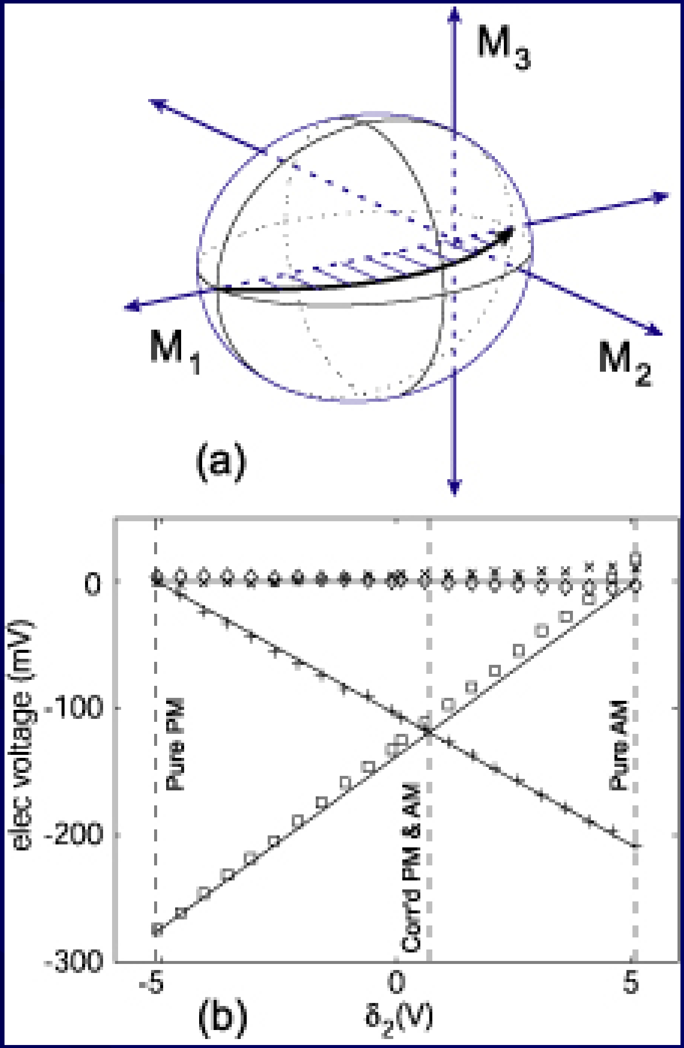
The Experiment Itself

- Half- & quarter-wave-plates to prepare polarisation input
- PBS to tap off vert.
- AOM for heterodyne
- Dual double-demodulation circuits
  - Individually measure PM and AM via mixdown

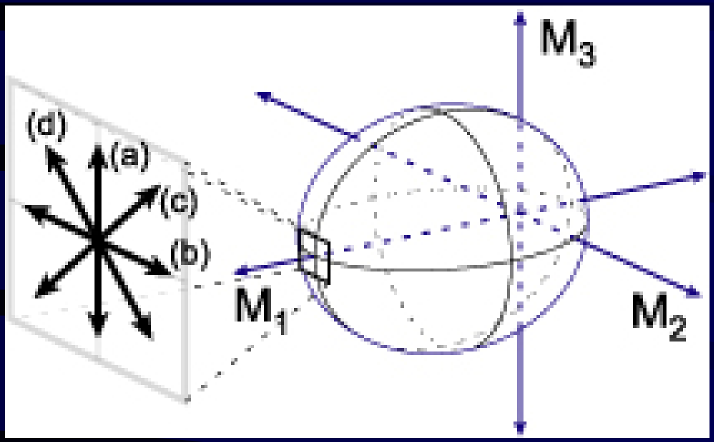


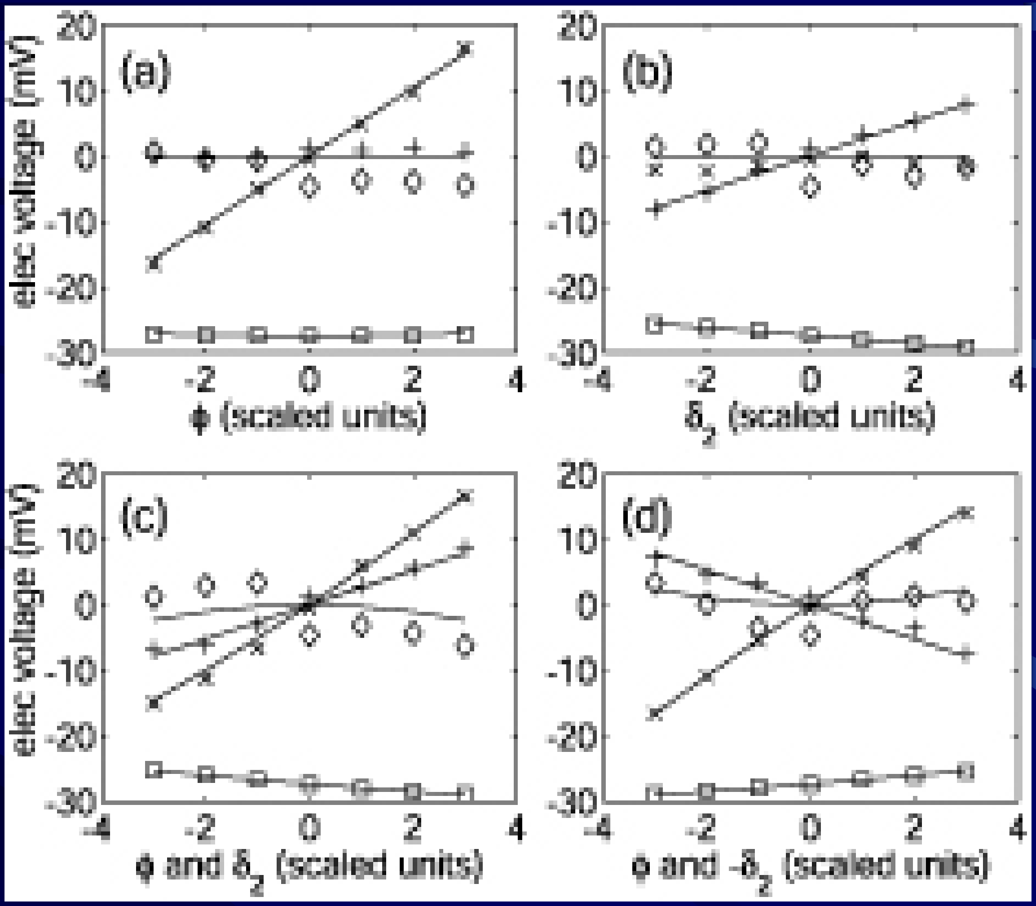
Variability: sweep around sphere





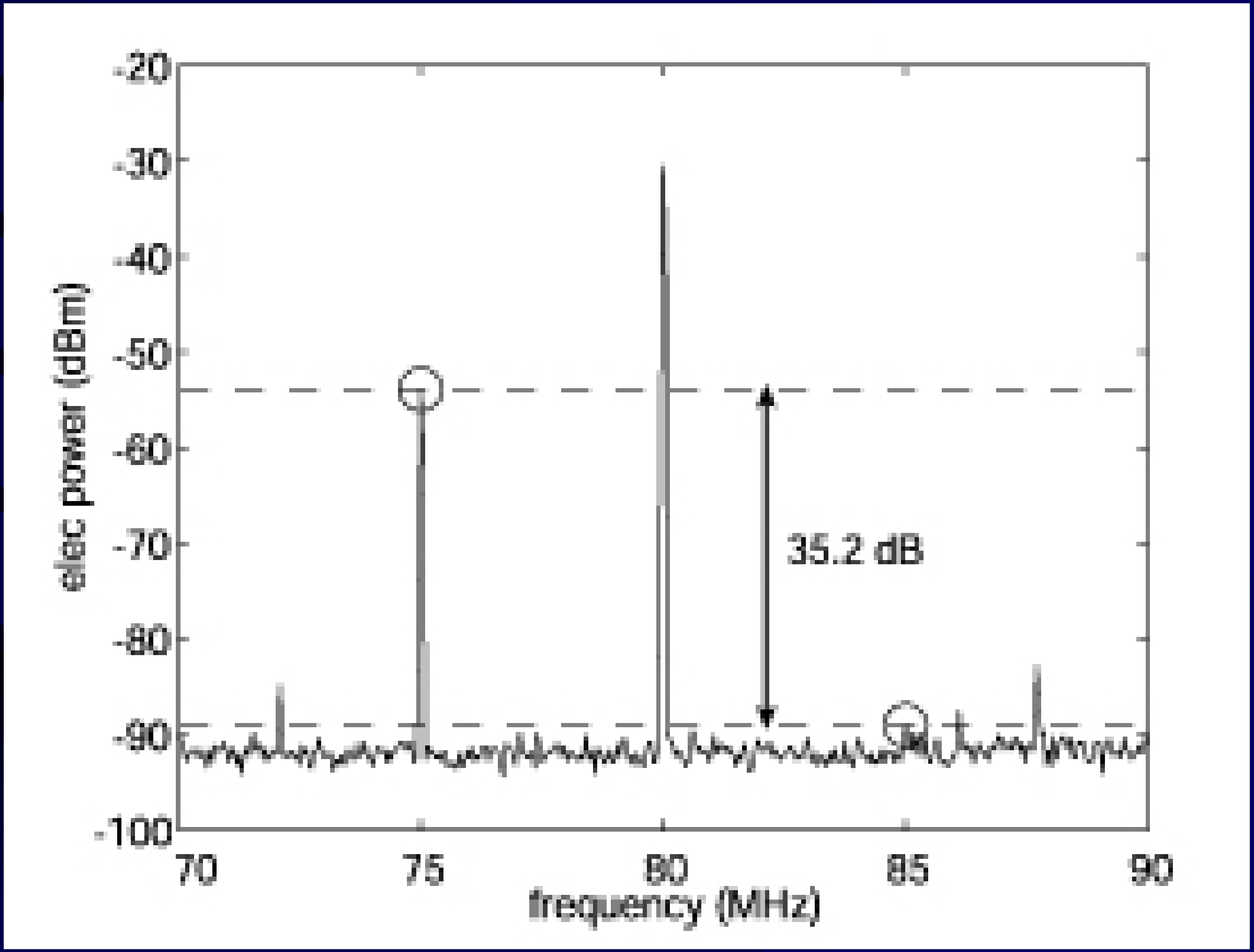
Variability: PM locality





- PM area important for offset locking
- Main PM (squares) scaled down by factor of 10 to fit

Purity: single-sideband state



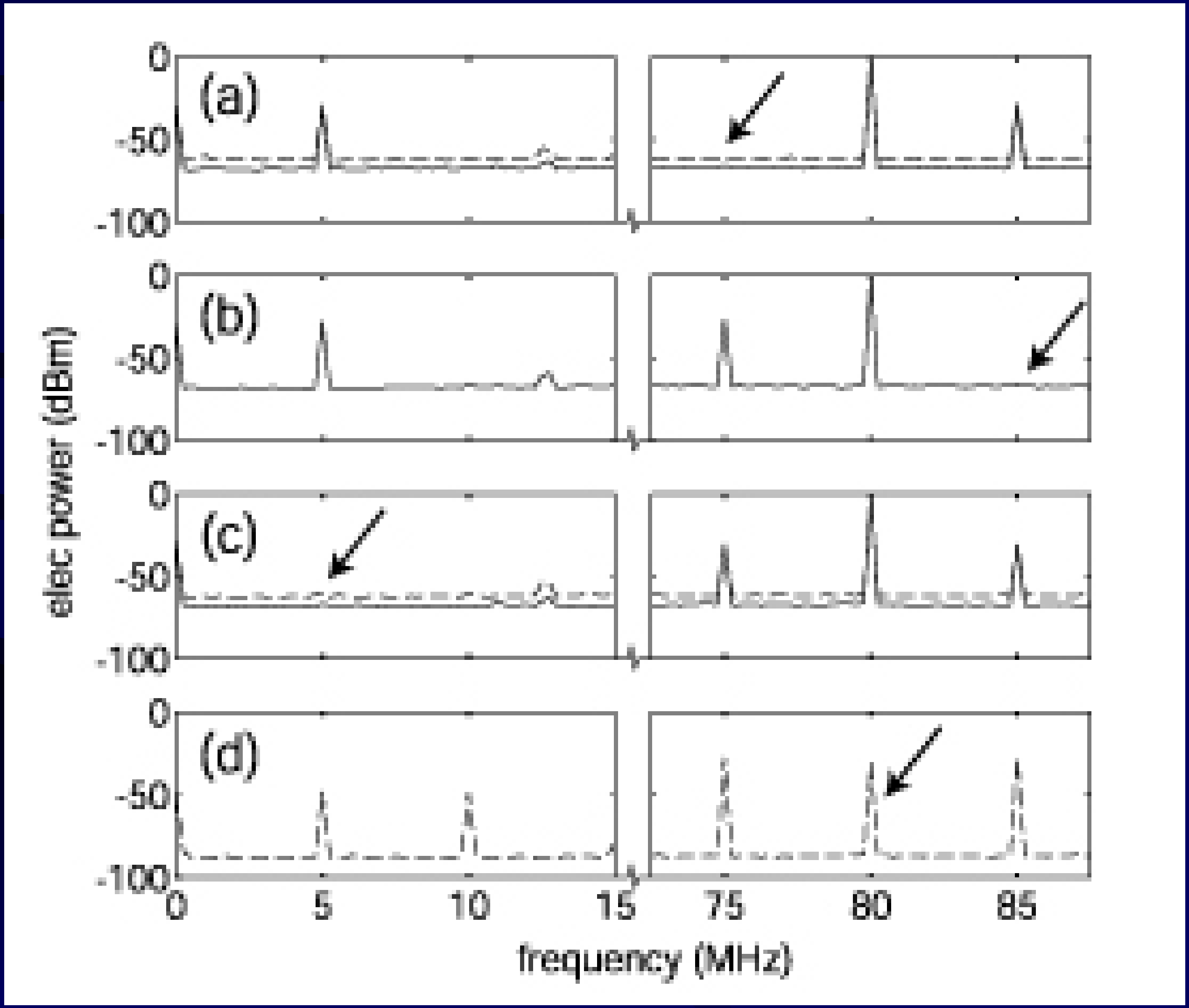
Purity: other operating points

SSB (upper) — 34.9 dBm

SSB (lower) — 39.5 dBm

Pure PM — ~38 dBm

Suppressed Carrier (σ = 180) — ~30 dBm



A few difficulties …

- UTM birefringence limits purity
  - spatial modes produced at tap off: ~ 1% power
- Optical path length drift due to crystal temp
  - dual crystal design helps; long τ locking loop?
- Electrical impedances not well matched
- Nor modulation impedances (xtal spatial fx)
  - needs careful alignment and electrical filters where very high performance required

Summary

- Universally Tunable Modulator tested
- Heterodyne / double demodulation scheme
- Prototype *variability* & *purity* demonstrated
- Phasor description and geometric phase description (modulation sphere) developed
- Potential for GW detector control scheme
  - – tune frequency response with rf locking