Appendix B

Electro-Optic Modulators

B.1 Intro

This chapter is a guide to building resonant electro-optic phase modulators in the frequency range 1-100 MHz. These techniques were developed to produce cheap, reliable modulators for SrF laser slowing and laser cooling. Currently, the experiment uses 12 EOMs of this design for addressing multiple spin-rotation/hyperfine levels with a single laser and for broadening lasers for white light slowing. I have also helped other groups make EOMs of this design for laser cooling [180], addressing multiple transition with a single laser [11] and locking lasers (PDH lock [10] and beat lock [16]).

B.2 Theory of Operation

An electo-optic phase modulator is a device which converts an electronic signal (typically at RF frequency) into modulation of the phase of an optical frequency. This can be achieved by sending linearly polarized light along the extraordinary axis a nonlinear crystal while modulating the crystal's extraordinary index of refraction n_{e}. For an applied voltage V, the phase shift $\Delta\phi$ is

$$\Delta\phi = (n_{\mathrm{e}}^3 r_{33}) \frac{\pi}{\lambda} \frac{V\ell}{d}, \tag{B.1}$$

where r_{33} is an electro-optic tensor element that depends upon the crystal material, λ is the wavelength, d is the distance between RF electrodes on the crystal, and ℓ is the crystal length.

Often, EOMs are characterized by the voltage that results in a phase shift of π

$$V_\pi = \frac{\lambda d}{\ell n_{\mathrm{e}}^3 r_{33}}. \tag{B.2}$$

Considering the crystal as a capacitance C, with perfect power coupling (e.g. by using an impedance-matching transformer as done below), the RF voltage we may apply is related to the

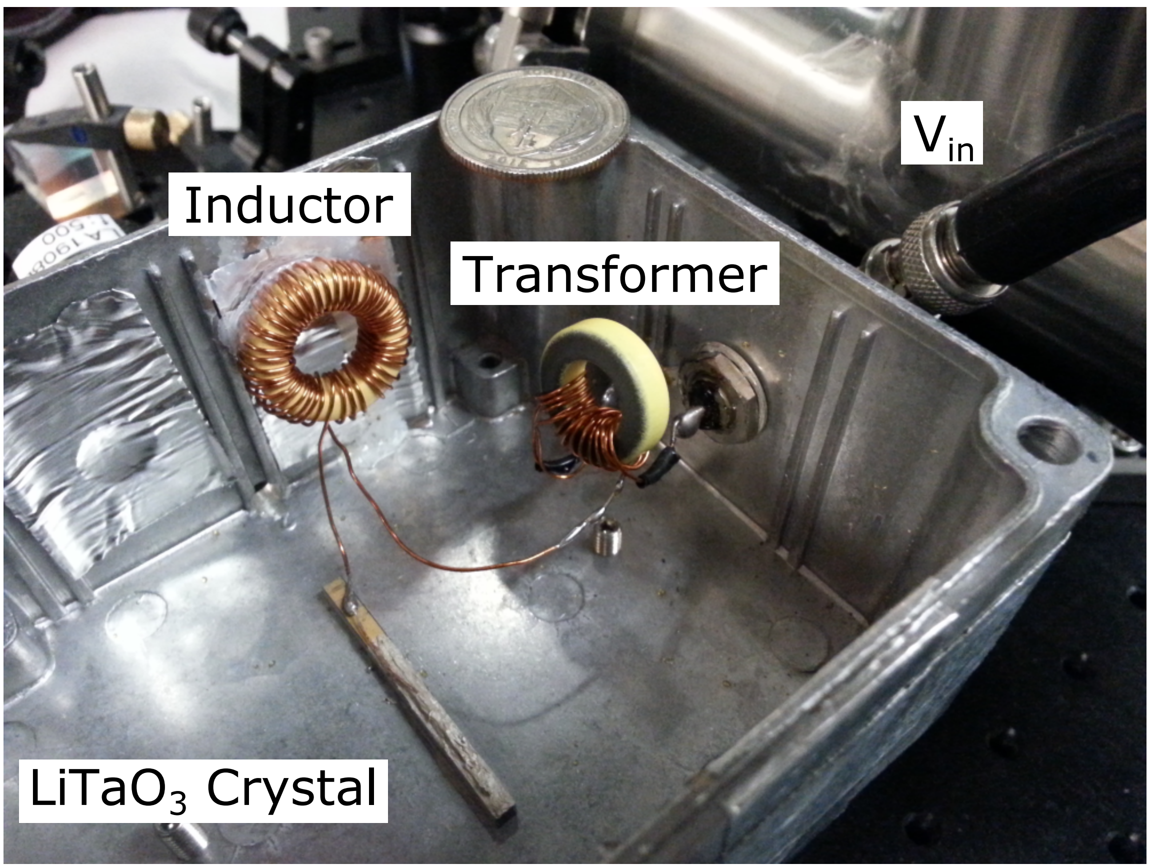

Figure B.1: A home-built resonant EOM circuit used in the experiment, with labeled components. The Al box acts as ground for the primary and secondary sides of the transformer. Note that the box pictured is much larger than our usual 2" × 2" box.

available RF power P by

$$V = \sqrt{P/\omega C}, \tag{B.3}$$

In crystals (e.g. $LiTaO_3$) for free space alignment ($d \approx 3$ mm), $V_\pi \approx 300$ V. Fast, high voltage amplifiers may be built if arbitrary modulation is required [181], but often sinusoidal modulation of carrier frequency ω_c within a narrow band around frequency ω_m is sufficient. In this case, it is straightforward to build a resonant LC series tank circuit (described below, see Fig. B.2) to increase the applied voltage [94].

For sinusoidal modulation, the time dependence of the light is transformed from

$$\mathcal{E}(t) = \mathcal{E}_0(t)e^{i\omega_c t} \tag{B.4}$$

prior to the crystal to

$$\mathcal{E}(t) = \mathcal{E}_0(t)e^{i\omega_c t + i\Delta\phi \sin(\omega_m t)} \tag{B.5}$$

after the crystal. Using the Jacobi-Anger expansion, Eq. B.5 may be written in a more intuitive form

$$\mathcal{E}(t) = \mathcal{E}_0(t)e^{i\omega_c t}[J_0(\Delta\phi) + \sum_{k=1}^{\infty} J_k(\Delta\phi)e^{ik\omega_m t} + \sum_{k=1}^{\infty}(-1)^k J_k(\Delta\phi)e^{-ik\omega_m t}] \tag{B.6}$$

where $J_k(\theta)$ is the Bessel function of order k. Thus, the effect of the sinusoidal modulation is to transfer optical power from the carrier frequency ω_c into sidebands of frequency $\omega_c \pm k\omega_m$, where k is an integer. The amount of power in each sideband is determined by the phase modulation $\Delta\phi$, or equivalently, by the applied RF voltage V.

The resonance frequency is given by

$$\omega = \sqrt{\frac{1}{L_{\text{total}}C}}, \tag{B.7}$$

where $L_{\text{total}} = L + L_t$ is the total inductance of the circuit. In a resonant series LC tank circuit, the voltage across the capacitor is $Q\times$ larger than the input voltage, where Q is the quality factor of the circuit. For a circuit with total resistance R,

$$Q = \sqrt{\frac{L}{C}}\frac{1}{R} = \frac{Z_0}{R}, \tag{B.8}$$

where $Z_0 = \sqrt{\frac{L}{C}}$ is the characteristic impedance of the circuit [94]. While we never deliberately add resistance to the circuit, losses from the capacitor and inductors lead to a typical effective resistance $R \sim 3\,\mathrm{Ohm}$. Actual capacitors and inductors have loss characterized by quality factors Q_C and Q_L, respectively (see Chapter 4.5.3). While Q_C is typically much higher than Q, for inductors at high frequencies, turn-to-turn and turn-to-core capacitive losses may be be large enough for the circuit Q_{LC} to be limited by Q_L. A number of Q curves for iron powder toroid inductors (which show measured values of Q_L for different toroid size, wire size, and number of turns) are available to as a guide to the optimum core and winding number for making low-loss inductors at the operating frequency.

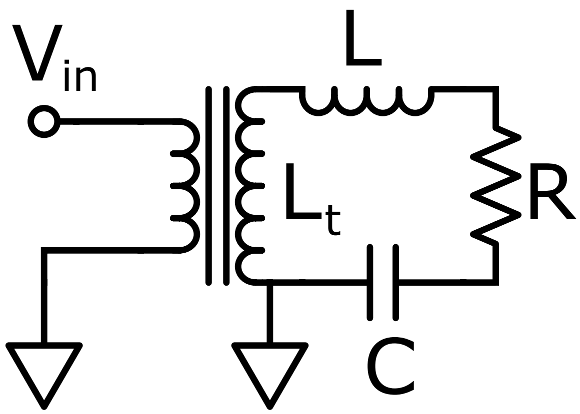

Figure B.2: Resonant EOM circuit diagram. Power is coupled in using a transformer with secondary inductance L_t. This is placed in series with an inductor (inductance L) and the EOM crystal (capacitance C). The circuit has total effective resistance R.

Manufacturer	Part Number	Description
Almaz Optics	Y cut $LiTaO_3$	$3.0 \times 3.0 \times 40.0$ mm
Hammond	1590LB	2" × 2" × 1.2" Al box
Amphenol	31-221-RFX	Uninsulated BNC Bulkhead
SPI	05063-AB	Silver Paste
Amidon	(various)	Iron Powder Toroid
McMaster	8546K31	1/8" diameter Teflon rod
RFMW	XFA-0101-16UH	16:1 Transformer

Table B.1: Parts list for resonant EOM construction.

B.3 Assembly Instructions

B.3.1 Parts List

Table B.1 lists the components used to make resonant EOMs. The Y cut Lithium Tantalate crystal is from Almaz Optics, AR coated from 600-1100 nm, with 20/10 scratch/dig $\lambda/4$ optical surfaces and Cr+Au electrodes on the two Z sides of the crystal for attaching leads. Other crystal materials may be optimal for other wavelengths.

B.3.2 Assembly

B.3.2.1 Prepare the Box

Use a 2" × 2" box to house the crystal and electronics. Drill a #8 tapped hole in the center of the bottom of the box to facilitate mounting to an optics post. Drill a hole for an insulated BNC 0.7" from the left and 0.3" from the top of one side of the box. On the two adjacent sides, drill a 3/16" hole for optical access to the EOM crystal.

B.3.2.2 Make the Inductor

The EOM circuit is essentially a series LC Circuit. The crystal acts like a ≈ 15 pF capacitor, and the solenoid/toroid acts like an inductor and a resistor. The resonant frequency of the circuit is given by $\omega = \sqrt{1/LC}$. Thus, the inductor must be made to match the desired frequency. For higher frequencies ($\gtrsim$ 40 MHz) a solenoid is ideal because it is easier to adjust the turn spacings to get the desired frequencies. However, for lower frequencies, more turns will be required. By using an iron powder toroid, you can reduce the number of turns necessary by a factor of the permeability of the material (usually $\sim$ 5). Use this handy calculator to find a toroid in the right frequency range and to calculate the number of turns (use 15 pF for C to estimate the required number of turns) . If possible, use a solenoid/toroid large enough to wind all turns in a single layer; stacking turns will increase the parasitic capacitance of the inductor dramatically, lowering the value of Q_{L}. Leave some wire for extra turns when winding; this can be shortened later.

B.3.2.3 Put in the Crystal

The aluminum box acts as a ground plane for both the tank circuit as well as the primary of the transformer. In this step, the crystal is electrically contacted and physically secured to the bottom of the box using silver paste (SPI 05063-AB). Wear gloves while handling the crystal. Do not touch the faces of the crystal. First, put $\sim$ 1 mL of paste on a sheet of paper. Use the wooden dowel of a cotton swab to apply a thin line of paste on the inside of the box between the 3/16" optical access holes. Press the crystal onto the paste. Rotate the crystal so that it is straight. Silver paste a thin magnet wire (>34 AWG, so that it is not "springy" when bent) with $\approx$ 1" of insulation removed to the top electrode, and then solder the thin wire to the inductor. Give the paste an hour to dry completely.

As an aside, the crystals were previously silver pasted to an FR4 circuit board, as in Fig. B.1. However, we found that changing the RF power dropped across the crystal, either by changing the input power or the drive frequency, lead to the temperature-dependant pointing of the beam. The aluminum box acts as a good heat sink for the crystal to dissipate the $\sim$ 1 W of power, and beam pointing effects are not significant enough to be detected against typical beam alignment drift with this design.

B.3.2.4 Impedance Match

When impedance matching, it is very helpful to measure the complex impedance using the Smith chart on a network analyzer. Without impedance matching, the real part of the impedance on resonance R will typically be a few Ohms. With perfect matching, the input impedance should be $R_0 = 50 + 0j\,\Omega$. To match, we set the transformer turns ratio

$$\frac{\text{primary turns}}{\text{secondary turns}} = \sqrt{\frac{R}{R_0}} \tag{B.9}$$

We may either construct a transformer with the necessary turn ratio on a toroid, or use a chip transformer such as XFA-0101-16UH.

Note that if you are winding your own transformer, you will need at least 5 turns on the primary and secondary to get good coupling, but the secondary turns contribute to the inductance of the tank circuit. To account for the inductance of the transformer secondary L_t, you may need to remove a few turns from the inductor L to remain at the desired resonant frequency.

B.3.2.5 Fine Tuning

Once you have a resonance near your desired frequency with about $50\,\Omega$ impedance, some fine tuning may be required to obtain the desired resonant frequency to within a few percent. Coarse frequency adjustments can be made by adding or removing a turn from the inductor; fine adjustments can be made by increasing or decreasing the turn spacing. The impedance can adjusted by making the same changes to the transformer. If using a chip transformer, moving the lead wires of the inductor closer together can make the circuit slightly more capacitive (decrease reactance); looping the leads or moving them further apart can make the circuit more inductive (increase reactance).

A well-made circuit will have a power reflection coefficient of -20 to -25 dB at resonance (this should be checked after the silver paste has dried, as the resonance may shift from when the paste is wet). My personal best is -41 dB, but a high Q value of the circuit comes at the expense of decreased bandwidth. Once all wires are adjusted to make the desired resonance, it is a good idea to lock them in place. The may be accomplished using Q-dop, which is essentially a liquid Styrofoam that will hold the wires in place without changing their electrical properties.

B.4 Testing and Performance

Use a stable high frequency source to drive the EOM circuit. A good choice is the Novatech 409B, which outputs 4 dBm at frequencies from DC to 171 MHz. This should be amplified to ≈ 1 W

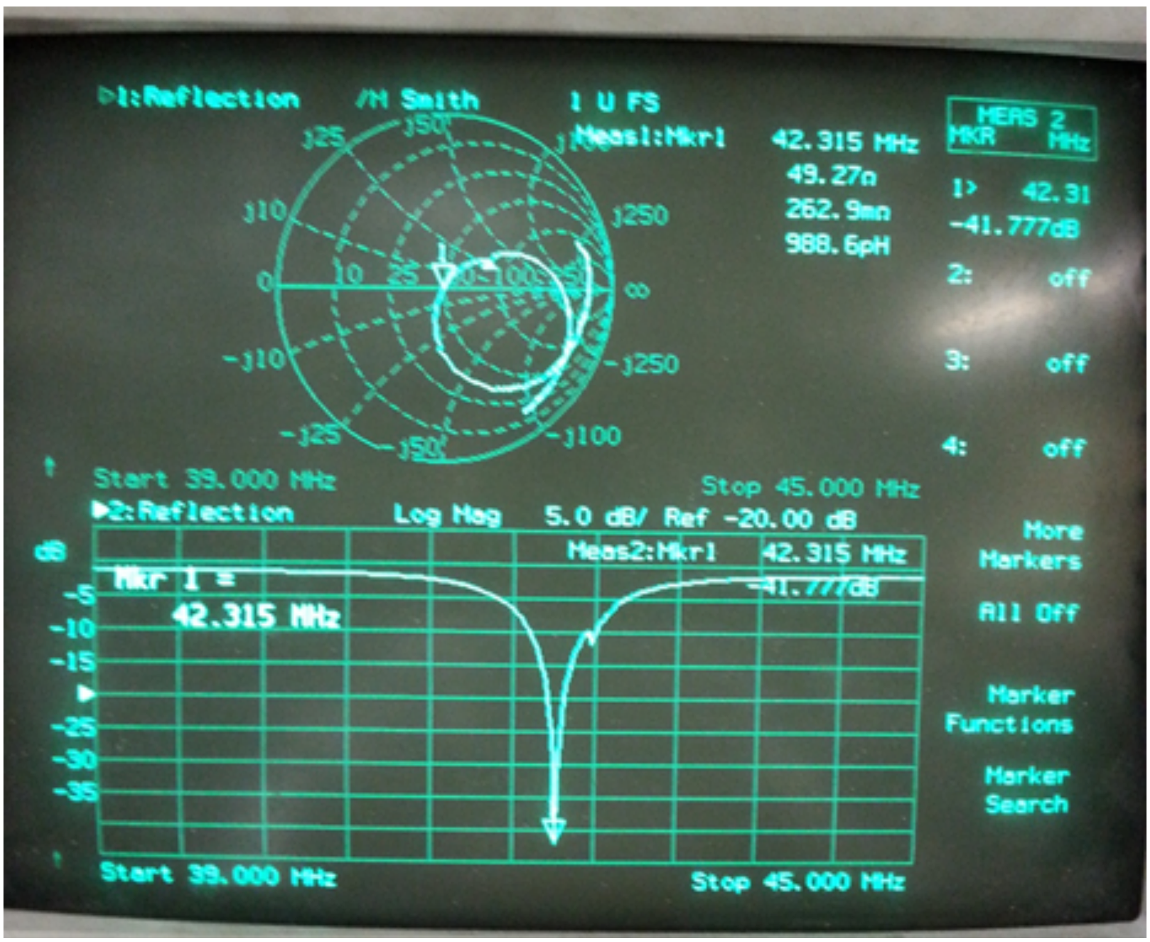

Figure B.3: Network analyzer scan of an EOM tuned to 42.3 MHz with 50 Ohm impedance.

with an appropriate amplifier to achieve high modulation depth. Minicircuits ZHL-3A, ZHL-6A, and ZHL-32A have been tested and found to perform adequately. With a laser aligned into a Fabry-Perot cavity, add the EOM to the optical path. Apply the full RF power to be most sensitive to noticing the sidebands appear. Then scan the RF to find the resonance. Finally, set the RF power to achieve the desired modulation. An example transmission profile of a phase modulated laser passing through a scanning Fabry-Perot cavity is shown in Fig. B.4.

Note that it is much easier to obtain a given modulation depth at lower frequencies. For example, with a 1 W amplifier, the best modulation depth I have achieved for 663 nm at 42 MHz is ≈ 3.1 rad. However, at 10 MHz with 1 W, modulation > 6 rad are routine. This behavior follows directly from Eq. B.3.

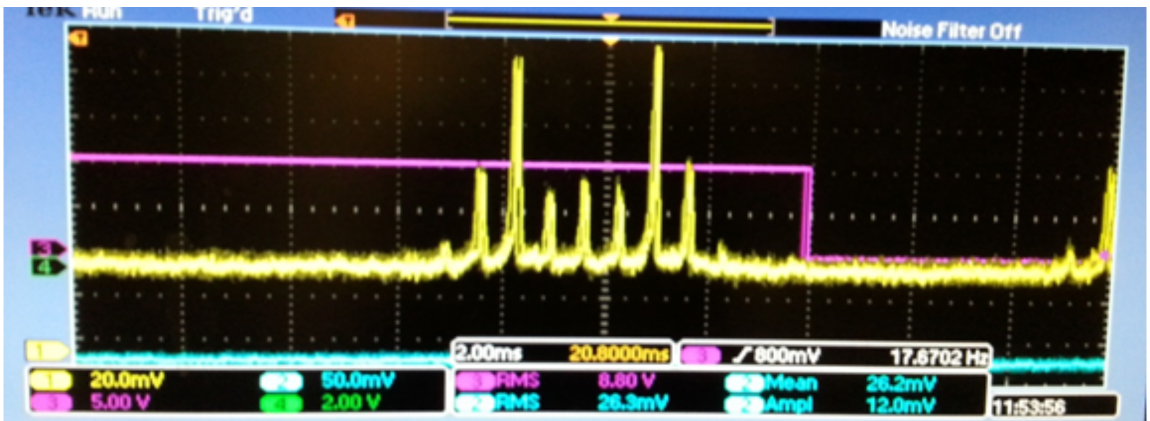

Figure B.4: A scan of a Fabry-Perot cavity showing a laser with 42.3 MHz sidebands. Modulation is $\Delta\phi \approx 3.1$ rad.