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OPTI 511L
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Active Modelocking of a Helium-Neon Laser

The generation of short optical pulses is important for a wide variety of applications, from time-resolved measurements utilizing the short pulse durations to nonlinear optics utilizing the high peak intensity of the pulses. In this experiment we explore the ideas behind active laser modelocking. We will implement a technique to modelock a long cavity Helium-Neon laser by injecting frequency shifted light from each longitudinal mode of the laser into an adjacent mode. Frequency shifting is accomplished with an acousto-optic modulator (AOM); we explore the operation of the AOM in the first part of the lab.

Part I Operation of the Acousto-Optic Modulator

A. Aligning for maximum deflection efficiency
B. Properties of deflected light

Part II Modelocking the laser

A. AOM alignment
B. Electrical Spectrum Analyzer (ESA)
C. Time domain measurements
D. Optimization

Part I Operation of the Acousto-Optic Modulator

Simple analysis of Acousto-Optic Deflection:

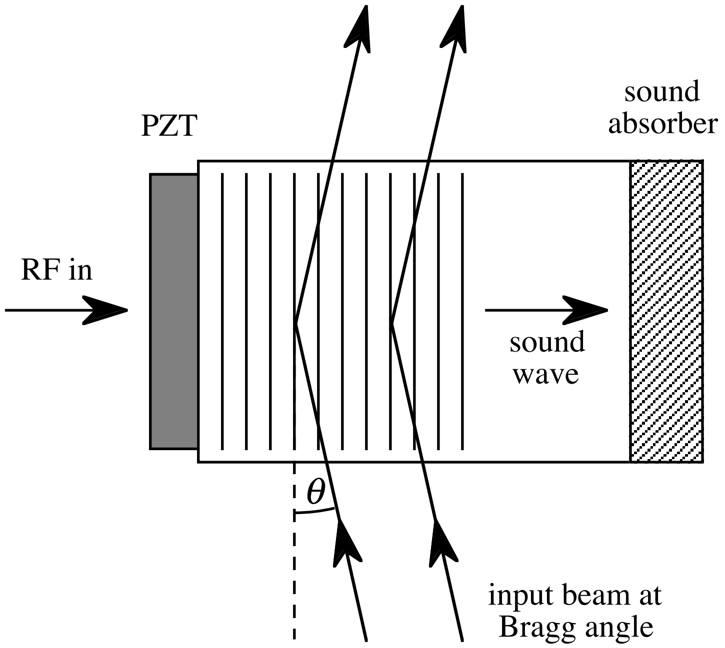
An AOM consists of a piezo-electric transducer (PZT) bonded to an optical medium (glass or crystalline). Applying a radio-frequency electrical drive to the PZT launches a high-frequency traveling sound wave in the medium. The pressure modulation in the sound wave is accompanied by a modulation in the index of refraction of the material; this index grating moves at the speed of the sound wave and can Bragg reflect an incident laser beam. The index variation can be small, but scattering efficiency can be high.

For a sound wave frequency at frequency ω_s we have

$$k_s = \omega_s / v_s = 2\pi / \lambda_s , \qquad \text{or} \qquad \lambda_s = v_s / \nu_s .$$

To efficiently diffract incident laser light, the ***Bragg scattering condition*** must be met:

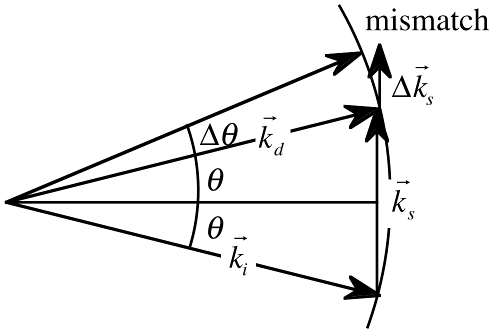
$$m\frac{\lambda}{n} = 2\lambda_s \sin\theta \;\Rightarrow\; \theta = m\frac{\lambda}{2n\lambda_s}$$



When the Bragg condition is met, the light scattered from multiple planes of the "thick" density grating will coherently add together. The incident and diffracted optical waves and the sound wave must fulfill the following conditions:

$$\vec{k}_d = \vec{k}_i + \vec{k}_s \qquad \textit{momentum conservation,}$$
$$\omega_d = \omega_i \pm \omega_s \qquad \textit{energy conservation.}$$

Frequency tuning of the deflected optical wave can be accomplished by changing the frequency of the sound wave. Because $\omega_s << \omega_i, \omega_d$ we have $|\vec{k}_d| \approx |\vec{k}_i| \approx k$, i. e. the length of the optical wavevector remains constant. If we assume the AOM and incident beam is aligned to fulfill the Bragg condition at frequency ω_s, then there will be a wavevector mismatch at the new frequency $\omega_s + \Delta\omega_s$:



Deflection occurs in the direction where the mismatch is minimized, $\Delta\theta = \Delta\omega_s / kv_s$, though the deflection efficiency suffers as $\Delta\omega_s$ is increased. The angle of incidence can be tuned to the new Bragg condition, and the original deflection efficiency recovered. Because of impedance matching conditions the frequency at which one can drive the AOM usually has limited bandwidth, typically in the range 10-20 MHz.

A. Aligning for maximum deflection efficiency.

1. Connect the AOM to the RF source (function generator + RF amplifier) and select a drive frequency around 60 MHz (and amplitude of ~ -8 dBm fed into the RF amplifier). Direct the beam from the [1]HeNe laser through the AOM and observe the pattern of deflected spots. What happens as you change the angle of incidence?

2. Align the AOM in one of the orientations that fulfills the Bragg condition for the 1st order beam. Then change the RF drive frequency. Note what you observe. What happens to the power? Can you recover efficient deflection by rotating the AOM? Why? What percentage of the total power can you obtain in the 1st diffracted order? Plot the maximum diffraction efficiency of light in the 1st order as a function of RF frequency (~ 5 points will do). What happens to the beam position of the diffracted beams as you change the drive frequency? Are any properties of the 0th order beam affected?

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[1] In this part of the lab, use one of the shorter cavity HeNe lasers you used in the previous lab.

3. Find a good way to make a careful measurement of the angle of incidence (theta). (hint: a good approach is to measure the residual reflection from the front of the AOM at a long distance. At normal incidence this beam will overlap with the incoming beam. By carefully measuring the separation between incident and reflected beams one can estimate the angular separation.) Assuming an index of refraction at the laser wavelength n~1.7, and knowing the RF frequency and the wavelength of the HeNe, determine the wavelength of the sound wave in this modulator. What would happen to the efficiency of the AOM if you focus the beam down to less than this wavelength? If you are not sure, you can try by just loosely focusing the beam into the AOM and re-measuring the diffraction efficiency. Try a ~50cm lens and remeasure the optimum diffraction efficiency. Why would the beam size matter? (hint: think about Bragg reflection)

B. Properties of deflected light: frequency shift.

3. Align both the 1st order diffracted beam and 0th order beam from the AOM into the 1.5 GHz FSR FPI using a lens and observe the HeNe spectrum (this requires a well thought out beam layout and alignment procedure). Arrange your layout so you can look at either the 1st order or 0th order independently, or both *simultaneously*. Describe what you see. Use the known AOM RF driving frequency and the FPI FSR to accurately verify and the frequency shift of the light in the 1st order.

Part II Active Mode-locking with the AOM

In an inhomogeneously broadened laser, such as the HeNe laser, oscillation in various cavity modes occurs independently. When the spectrum is measured with an FPI, one sees lasing in many longitudinal modes, each fluctuating independently in frequency and amplitude due to mirror vibrations, mode pulling and other effects. These independent laser oscillations can become locked, or coordinated, if means are found to impress some common physical restriction on all the modes simultaneously. One way is to inject light from each mode into the others such that a common phase relationship between longitudinal modes is obtained.

In order to obtain simple analytical results, let's assume the oscillation bandwidth is spanned by N longitudinal modes, each with equal amplitude. A straightforward derivation then shows that

(i) Pulses are produced with a period of $2L/c$.

(ii) The peak power of the pulses is ~N times the average power.

(iii) Pulse widths will be bandwidth limited, equal to approximately the inverse oscillation (ie gain) bandwidth.

More realistic situations, with e.g. unequal mode amplitudes, are easily dealt with by numerical summation of the appropriate Fourier series. For a simple estimate, taking (i)-(iii) into account, ***please answer the following in your lab notebook***:

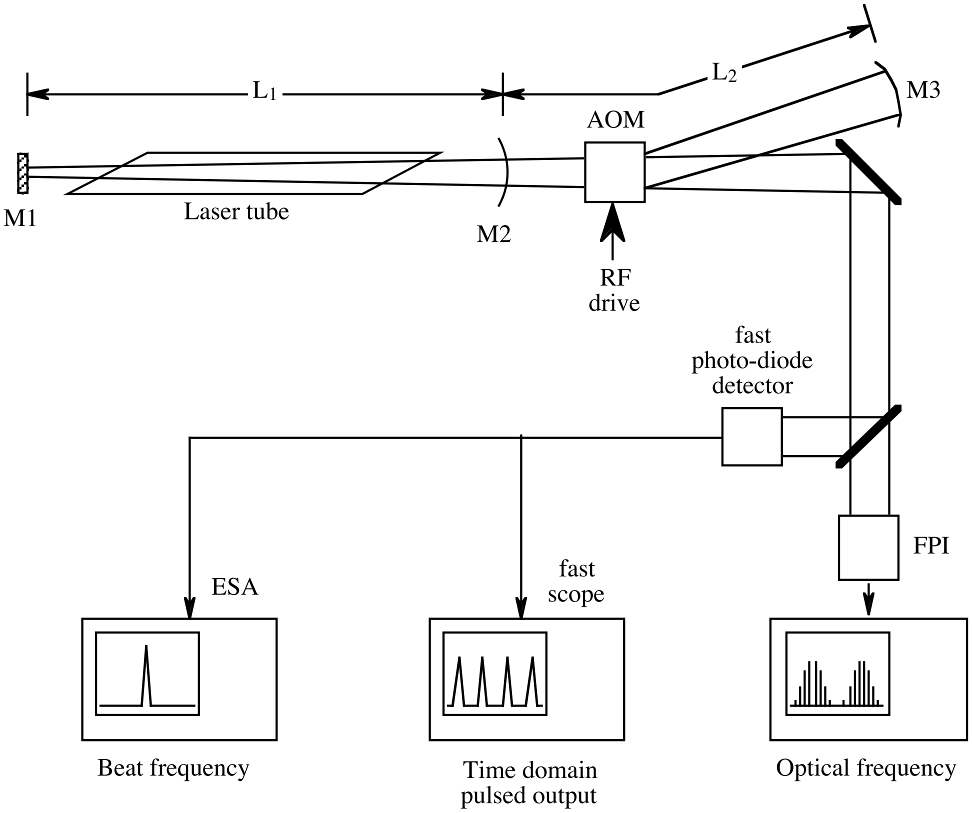
Q: If there are 40 modes and the oscillation bandwidth is 1.5 GHz, what would be the shortest pulse width possible? If the average power is 10 mW, what would be the peak pulse power?

A. Alignment

1. Set up the AOM modulator as shown on the following page. To assure high frequency stability, use the frequency synthesizer to drive the AOM. In positioning mirror M3 it is important that its distance from the output mirror M2 be the same as the laser length L_1. **Why?** (think of what is happening in the time domain) In positioning M3, allowance should be made for the index of refraction of the AOM. Estimate this correction assuming n=~1.7 for the AOM.

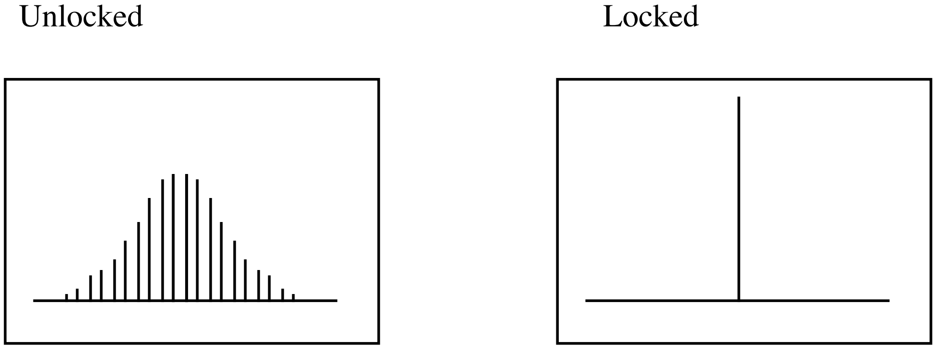
2: Note that when the AOM is double-passed it shifts the frequency of the light by $2\omega_s$. With a laser cavity mode spacing $c/2L_1$, what is the appropriate AOM drive frequency? Think about how precisely you need to set the frequency (within a MHz? kHz? Why?)

Experimental setup for modelocking:



B. Electric Spectrum Analyzer (ESA).

In order to modelock effectively it is important to find and maintain a modulation frequency equal to the average longitudinal mode spacing of the laser cavity. An excellent indicator for the best frequency is the collection of nearly identical beat frequencies between the laser modes (see figure).



The radio-frequency spectrum analyzer displays the power per unit bandwidth (determined by the Resolution Bandwidth, RBW) as a function of frequency. The power can be displayed in dBm (log scale) or Watts (linear scale). The frequency range of a typical ESA is from near DC up to several GHz. Therefore, this instrument can be used to see the beating between optical frequencies that occurs at RF frequencies (at about the free spectral range of the laser), but not the optical frequencies themselves.

1) Use the ESA to observe the incoherent *laser mode beating* at $c/2L_1$ directly from the laser without optical feedback. What is the approximate bandwidth of the RF beat spectrum? ***What accounts for this bandwidth?***

2) Apply optical feedback, and slowly tune the modulation frequency of the AOM. When the laser locks, you should see the background distribution of different beats coalesce into a single frequency (see figure). This indicates that the feedback from the AOM into the laser cavity has injection-locked the modes such that all the laser frequencies are equally spaced by c/2L and in phase with respect to each other.

C. Optimization.

11. After everything is working satisfactorily, you should optimize the system to obtain the strongest modelocking. The parameters which affect this most strongly are:
    (i) Positioning of mirror M3.
    (ii) Alignment of the retro-reflected beam into the laser.
    (ii) Tuning of the AOM frequency.

Monitor the longitudinal modes as seen on the scanning FPI and describe the difference in their behavior when the feedback from the AOM is optimized vs. blocked.

When the longitudinal modes of the laser are locked together, you should be able to measure directly these short pulses on the oscilloscope. What time duration do you measure? How does this compare to their theoretical duration? What determines the actual pulse width you are measuring?

Be sure to measure/record at least the following:

- Over what RF bandwidth (ie detuning AOM frequency) can you maintain good modelocking? How does this compare to the "cold cavity" linewidth of the laser? You can estimate this if you assume an output coupler transmission of ~1% and the other mirror with R=100%.
- Over what approximate range of external cavity lengths can you still obtain good modelocking? What physically accounts for the limited locking range?
- Record (sketch and description) the **RF** spectrum with vs. without optical feedback
- Record the **optical** spectrum with vs. without optical feedback.
- Try and measure the temporal pulse width on the oscilloscope. Compare this with a theoretical estimate. What accounts for the difference if any?
- Compare the average cw power with the peak power. (you'll need a fast DC coupled photodiode) Is this what you expected?

If time permits, try again with an external cavity length of L/2. You should be able to generate a pulse train with 2 pulses in the cavity (twice the repetition rate). Would other external cavity lengths will work?