Assignment n. 8 for Basic Laser Technique Laboratory (ZPLT) KFE, FJFI, ČVUT, Praha 2022

Acousto-optical modulator with traveling and standing acoustic wave

Acoustoo-optical modulators (AOM), sometimes also called Bragg cells, use the acousto-optical phenomenon to deflect or shift the frequency of optical radiation using sound waves (usually of frequencies of f the order of tens of MHz and wavelengths) $\Lambda \sim 10 - 100\ \mu\mathrm{m}$). In laser technology, they are used for modulation of the quality factor Q of the optical resonator either for Q-switching (AO Q-switch, which is most often **AOM with a traveling acoustic wave**) or mode synchronization (AO Mode-locker, which is most often **AOM with standing acoustic wave)**. The difference between them is that in AOQS the acoustic wave is dampened after one passage through the environment and is not reflected, while the standing wave in the AOML is achieved by the reflection of the sound wave on the second parallel face and the interaction between the opposing sound waves. AOML thus represents a resonator for a sound wave with **its own resonant frequencies spaced apart by the value:**

$$\Delta f = \frac{v_{ak}}{2L} \tag{1}$$

where v_{ak} is the speed of the ultrasonic wave in the modulator environment and L is the transverse dimension of the modulator. In telecommunications, AOMs are used as amplitude modulators, in spectroscopy to control the frequency of radiation. AOM **consists of a piezoelectric transducer** connected to the modulator's own transparent optical material, such as glass or quartz. The high-frequency electrical signal causes vibrations of the transducer, which excite a sound wave in the modulator material. This can be thought of as moving areas of compression and stretching of the material. Through a photoelastic effect that binds mechanical stress and refractive index of the material, sound waves create periodic modulation of the refractive index and the material thus behaves like an optical phase grating. The resulting phase grating has a period equal to the wavelength of the acoustic wave Λ and an amplitude proportional to the sound amplitude.

The incident optical wave is scattered on the resulting grating similarly to the Brillouin scattering and the resulting diffraction effect is similar to Bragg diffraction.

If an optical beam is incident upon this grating, a portion of its intensity will be diffracted out of the beam into one or more discrete directions. By properly choosing the parameters, the diffracted beam can be deflected out of the laser resonator cavity and thus cause a loss of energy, which is sufficient to effectively reduce the quality factor of the resonator Q for Q-switching. When the control voltage to the transducer is switched off, the laser resonator returns to the state with a high-quality factor Q. Without propagating ultrasonic waves inside, the fused silica block again has a high optical transmittance and a Q-switched pulse is emitted.

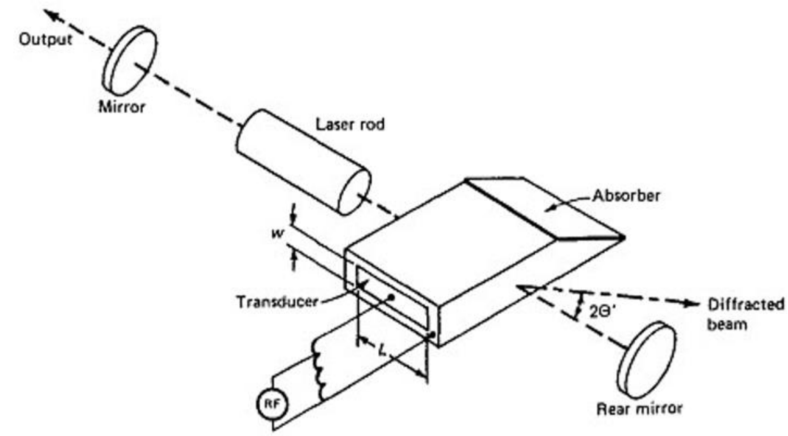

Figure 1:Acoustooptic Q-switch employed in a cw-pumped Nd:YAG laser. The major components of the Q-switch are a very thin quartz crystal transducer having a thickness of a half acoustic wavelength, a fused silica block to which the transducer is epoxy-bonded, an inductive impedance-matching network, an acoustical absorber at the side opposite to the transducer, a water-cooling jacket system to conduct away generated heat, a thermal interlock which automatically turns off the rf power if the temperature in the modulator rises beyond allowable limits, a Bragg angle adjustment, a 50 MHz rf driver containing a pulse generator, and logic which allows adjustment of the repetition rate from 0 to 50 kHz

It is possible to observe two different diffraction effects depending on the optical and acoustic wavelength λ and Λ, and distance L through which the light interacts with the acoustic beam. These are either so-called Raman-Nath or Bragg scattering, depending on whether the condition (2) or (6) is met.

The diffraction effect in Raman Nath scattering has the character of multiple diffraction maxima symmetrical with respect to the zero maximum. It occurs when either the interaction path L is very short, or when the ultrasonic frequency $f = 1/\Lambda$ is very low:

$$L\lambda \ll \Lambda^2 \tag{2}$$

Maximum light scattering is observed if the light beam and the ultrasonic wave are perpendicular with respect to each other.

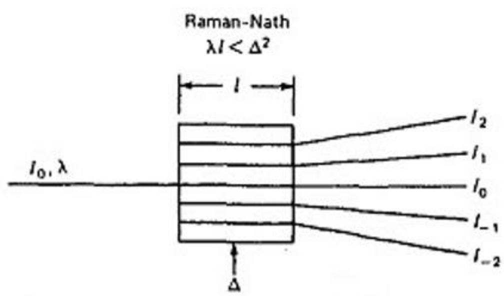

Figure 2: Diffraction in the case of Raman-Nath scattering.

The intensity of individual maxima orders is given by the relation:

$$\frac{I_n}{I_0} = J_n^2(\Delta\phi) \tag{3}$$

where I_n is the intensity of the nth order, I_0 is the intensity of the incident light, J_n is a Bessel function of the nth order, and $\Delta\phi = \pi\Delta n L/\lambda$ is the amplitude of the phase lattice. The advantage of this mode may be the possibility of resetting the zero diffraction order.

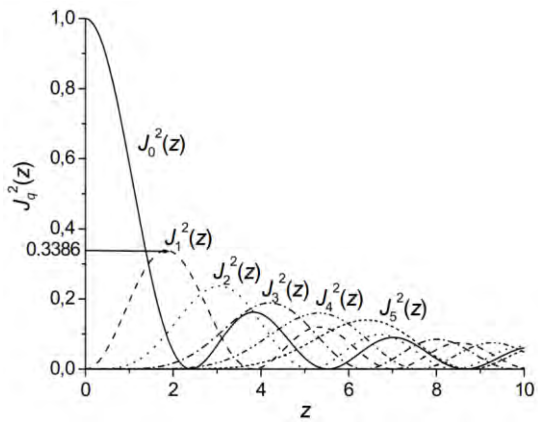

Figure 3: Behaviour of the Bessel functions $J_n^2(z)$.

It can be proved that the amplitude $\Delta\phi$ is

$$\Delta\phi = \pi\left(\frac{2}{\lambda_0^2}\frac{l}{w}M_2 P_{ac}\right)^{1/2} \tag{4}$$

where λ_0 is the optical wavelength, P_{ac} is the acoustic power, l and w are the dimensions of a flat rectangular transducer and M_2 includes a group of material parameters known as the acousto-optical figure of merit:

$$M_2 = \frac{n^6 p^2}{\varrho v^3} \tag{5}$$

where n is the refractive index, p is the appropriate photoelastic coefficient, ϱ is the density and v is the acoustic velocity. The higher the index of refraction n and photoelastic coefficient p of the material the better for its use in acoustic-optical applications. Such materials have outside of large densities ρ often other disadvantages, and therefore suitable material is not many.

In **Bragg mode,** higher-order diffraction maxima are eliminated and most of the energy is concentrated in only the zero and first order. This mode occurs when the frequency of the ultrasonic wave increases and the path of interaction is prolonged:

$$L\lambda \gg \Lambda^2 \tag{6}$$

Practically, this is fulfilled for $L\lambda \geq 10\,\Lambda^2$. In Bragg mode, optical and ultrasonic beams are slightly shifted from the perpendicular impact, to interact at Bragg angle Θ in the modulator medium:

$$\sin\Theta = \frac{\lambda}{2\Lambda} \tag{7}$$

Bragg mode settings are very sensitive to angle adjustment (~ minutes). When detuned, the efficiency drops very quickly. During interaction is therefore essential the ratio between **the wavelength of the optical wave λ and the wavelength of the acoustic wave Λ in modulator medium of the refractive index n**. I.e. $\lambda = \lambda_0/n,$ whereλ_0 is the optical wavelength in vacuum. Externally measured angle Θ' between incident light I_0 and the acoustic wave is $\Theta' = \mathrm{n}\Theta$ and the scattering angle is doubled:

$$2\Theta' = 2\mathrm{n}\Theta \approx \frac{\lambda_0}{2\Lambda} \tag{8}$$

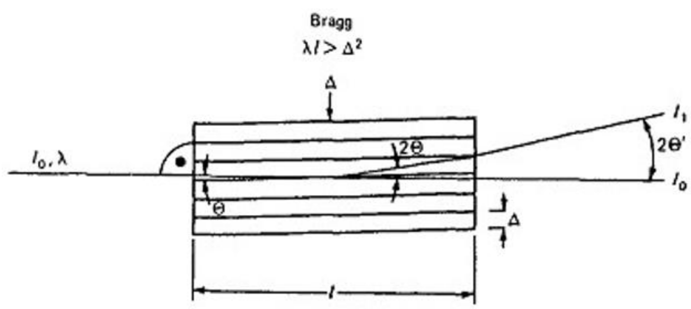

Figure 4: Diffraction in Bragg mode.

Intensity scattered into the first diffraction order I_1 is:

$$\frac{I_1}{I_0} = \sin^2\left(\frac{\Delta\phi}{2}\right) \tag{9}$$

The depth of modulation is called the percentage decrease in energy at zero maximum compared to the case without modulation. Reaches a value of about 1% per 1 W excitation electrical power for AOQS and values several times higher for AOML. From equations (3) - (9) it is clear, that the magnitude of the diffracted power depends on the material parameters expressed by M_2, the ratio of length to width of the interaction path, and the acoustic power P_{ac} . In a given material such as fused silica, the value of the photoelastic coefficient p in (5) is dependent on the plane of polarization of the light beam relative to the direction of propagation of the ultrasonic wave and also on its type,

i.e. longitudinal or shear wave. Typical efficiency of acoustic elements working in Bragg mode is usually 70–90 %, higher only rarely, as 100% efficiency requires 2.5 times more power than 70% efficiency.
With shear wave generation the particle motion is transverse to the direction of the acoustic wave propagation. In this case the dynamic optical loss is independent of polarization in isotropic materials such as fused quartz. Table 1 lists the pertinent material parameters for an acoustooptic Q-switch fabricated from fused silica. Since at a small depth of modulation the sine function in (8) can be taken equal to its argument, the diffracted power is proportional to the figure of merit M_2.

From Table 1 it follows, that in a Bragg angle device employing longitudinal-mode ultrasound, light polarized perpendicular to the acoustic wave vector is deflected five times stronger than light polarized parallel to this direction. The shear wave device, which operates independent of the light polarization, has a higher diffraction efficiency than parallel-polarized light in a longitudinal device, but a substantially lower efficiency compared to the perpendicular-polarized light in a longitudinal modulator.

Table 1: Material parameters of acustoo-optical Q-switches using fused silica.

Acoustic wave	Elasto-optical coefficient p	Polarization of the optical beam relative to the acoustic wave	Velocity of sound	Figure of merit M_2	Sound power for 1% deflection $(l/w = 10)$
			$\times 10^5 [cm/s]$	$\times 10^{-18} [s^3/g]$	$[W]$
Shear wave	$p_{44} = 0.075$	Independent	3.76	0.47	0.42
Longitudinal	$p_{11} = 0.121$	Parallel	5.95	0.30	0.67
Longitudinal	$p_{12} = 0.270$	Perpendicular	5.95	1.51	0.13

The goal is to measure the most important parameters of an acousto-optic modulator based on traveling acoustic wave (used as AOQS – Acousto-Optic Q-Switch) and of an acousto-optic modulator based on standing acoustic wave (used as AOML – Acousto-Optic Mode-Locker). The principal scheme of the measurement arrangement is shown in Fig. 5.

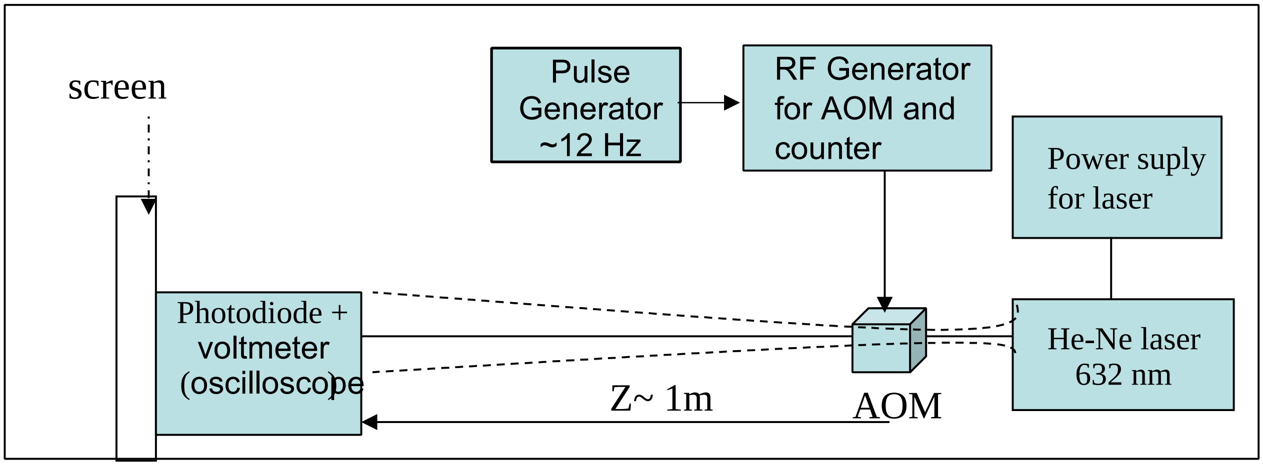

Figure 5: The schematic of a measurement setup. A distance between the AOM and the laser is about 20 cm and a distance between the AOM and the observation plane is about 1 m. He-Ne laser is working at its standart wavelength 632.8 nm.

Principle of diffraction measurement and AOM modulation depth: For measurements we use He-Ne laser as sources, the diffraction effect is observed on a screen at a distance of about 1 m. The depth of modulation is measured using a photodiode and a voltmeter (oscilloscope).

Used AOMs and generators:

a) Q-switch AOQS with RF generator 45 MHz, min. power 5 W, max. power 20 W.

b) Mode-locker AOML with RF generator 74.630 – 74.990 MHz, max. power 5 W.

Instructions:

Theoretical home preparation:

1. Consider an acoustic-optical fused quartz modulator with an interaction length of $L = 40\,mm$ and refractive index of $n = 1.46$. The speed of ultra-sound in fused silica is $v_{ak} = 6\,km/s$. Calculate the wavelength of the sound wave Λ for excitation frequencies 45 MHz and 75 MHz.
2. Calculate the product $L \cdot \lambda$ and compare it with square of the acoustic wavelength Λ^2 for both excitation frequencies. Determine whether the condition for Raman-Nath (2) or Bragg diffraction (6) is fulfilled.
3. Determine the frequency interval of two closest resonant frequencies for the AOML of the thickness of $L = 1\,cm$ according to the formula (1).
4. Calculate for both excitation frequencies the Bragg angle (in degrees and minutes) inside modulator of refraction index n and the angular deviation of the first diffraction maxima outside the modulator. Use relationships (7) and (8).

Measurement of modulator parameters

5. Operate the AOQS modulator only **quasi-continuously** using pulse generator, so that AOQS is turned on for less than 5 s. Permanent switching on in the absence of water cooling would lead to the destruction of the modulator. Set the AOQS modulator so that the diffraction pattern is visible on the screen with maximum intensity. Record its shape, for example, using the camera in your mobile phone, or draw.
6. Measure the angular distance of the diffraction maxims from the zero maximum.
7. Measure modulation depth (percentage of power diffracted from zero maximum) for minimum and maximum excitation power of the RF generator 45 MHz (only for maximum power in the case of AOML).
8. Measure what percentage of performance is contained in each higher order maxims.

9.-12. Repeat measurements 5-8 with AOML modulator and 75 MHz generator.

13. By changing the excitation frequency of the RF generator within 74.630 – 74.990 MHz, measure the frequency interval Δf between two adjacent frequency maxima of diffraction (disconnect the pulse generator for few seconds to read the frequency value on the counter, then immediately connect pulse generator again) and compare with the calculated value from point 3.
14. Measure the detailed shape (at least 10 points) and determine the width of one frequency peak Δf_{FWHM} at full width half maximum. From the measured values, calculate the finesse of the AOML acoustic resonator $\mathcal{F} = \Delta f / \Delta f_{FWHM}$. Decide what should be the frequency stability of a hf driver.

Required results in the measurement report:

1. All results of the theoretical home preparation.
2. Schematic of the measurement setup.
3. Images of observed diffraction patterns for both AOM.
4. Table with measured and calculated angular distances of adjacent diffraction maximums for both AOM.
5. Depth of modulation [%] and diffraction efficiency [%/W] of both AOM. For AOQS a pair (min and max), for AOML single values. The finesse of AOML.
6. Plot the measured dependence of depth of modulation of the AOML on driving frequency in range of 100 kHz around maximum.

Literature:

W. Koechner: Solid State laser Engineering
M. Vrbová: Lasery a moderní optika
B.E.A. Saleh, M.C. Teich: Základy fotoniky, sv. 4