EVALUATION OF THE MODULATION INDEX OF THE STANDING WAVE RAMAN–NATH MODE-LOCKING DEVICE ☆

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The performance of an acoustooptic standing wave Raman–Nath deflector as active mode-locking switch is evaluated and compared with theory. The time averaged intensities of the diffracted beam up to the eight order are calculated for acoustic phase shifts up to $\Delta\varphi = 4$. With fused quartz the highest attainable value of δ_m was 6.4 at 633 nm. In the theory describing the pulse width of homogeneously broadened AM mode-locked laser oscillators the modulation index δ_m is a parameter, given by $\delta_m = 2\Delta\varphi$.

1. Introduction

The pulse width of an acoustooptic mode-locked laser oscillator can be calculated by the well-known Siegmann-Kuizenga theory. Among other data it requires the knowledge of the so-called modulation index, otherwise called modulation depth δ_m, which controls the temporal width (fwhm) of the transmission of a light modulator. Previous experiments dealing with acoustooptic mode-locking of lasers involved only the standing wave Bragg modulator [1–3]. In this case, the temporal single pass transmission function for the light intensity of a probe-beam is

$$I(t) = \cos^2(\delta_m \sin 2\pi\nu_m t), \quad (1)$$

where ν_m is the modulation frequency. The modulation index can be determined by comparing the average power of the zeroth order with the single deflected beam of first order, for instance with an HeNe laser [3]. However, this is only possible in the case of Bragg deflection because of the equal temporal modulation functions of the zeroth and first order beam. Unfortunately, the highest available modulation index may be about $\pi/2$. With increasing $\delta_m > \pi/2$ the modulator will open twice or more per cycle, which is undesirable for good mode-locking. Otherwise, the modulator can be used as in the Raman–Nath case [4,5]. The intensities of the various diffracted laser beams transmitted by a Raman–Nath modulator are

$$I_n(t) = J_n^2(\delta_m \sin 2\pi\nu_m t), \quad (2)$$

where J_n is the Bessel function of first kind and nth order. Here one finds that in principle greater modulation indices must be possible because the maximum transmission amplitude of the zeroth order beam will decrease with increasing δ_m and mode-locking only occurs at the main maximum, where the argument of J_0 is zero. The determination of δ_m, however, is not as trivial as in the Bragg case and therefore this work was initiated because of the lack of detailed experimental investigations.

From eq. (2) one observes that the temporal transmission functions of the various orders of diffraction are unequal. Therefore, one must calculate the temporal average power of each diffraction order and then the modulation index can be determined by comparing the measured cw intensities of the aberrated beams with theory.

For such an experiment one only needs photomultipliers or photodiodes and time integrating electronics. Another way is the time resolved detection of the trans-

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mission function with fast photodetectors and oscilloscopes. In this work the two ways are followed and compared with each other.

2. Theory and experimental results

There are many review papers dealing with elastooptic or acoustooptic phenomena, [e.g. 4,5]. Here only the most interesting formulas are presented and the reader may refer to [4,5] for more details. Hargrove [6,7] published some theoretical considerations dealing with standing wave Raman–Nath modulators. The quality of the acoustic resonator is defined by the amplitude ratio a of the incident wave to the reflected wave. This means the standing wave is best when $a = 1$, whereas the acoustic wave propagates more and more if $a > 1$. The temporal light intensity function was found to be [6]

$$I_n(t) = J_n^2[\Delta\varphi(1+1/a^2 - (2/a)\cos 4\pi\nu_m t)^{1/2}]. \qquad (3)$$

$\Delta\varphi$ is a phase excursion of the incident light at wavelength λ caused by a change of refractive index Δn over the propagation length L of the light beam within the acoustic field:

$$\Delta\varphi = (2\pi L\,\Delta n)/\lambda. \qquad (4)$$

Furthermore, the phase shift $\Delta\varphi$ may be expressed by means of parameters which depend on the figure of merit, M_2 of the individual material, on the acoustic power dissipated in the ultrasonic field, P_{ac}, and on the cross-section of the acoustic field $L \cdot H$:

$$\Delta\varphi = \pi\left(\frac{2L}{\lambda^2 H} M_2 P_{ac}\right)^{1/2}. \qquad (5)$$

From eq. (3) one observes that only the case of $a \approx 1$ leads to temporal change of the intensity. For travelling waves mode-locking is impossible! Eq. (2) follows from $a = 1$ and the modulation index needed for the calculation of the pulse width becomes $\delta_m = 2\Delta\varphi$. It can be calculated if all parameters are known, which is usually the case, with the sole exception of P_{ac}. Mostly the electric output power of the RF equipment, but not the acoustic power of the field, is known. This depends on as different characteristics as: the coupling factor and the dielectric constant of the ultrasonic driver, the mechanical impedance matching of driver, glue and deflector, and the acoustic damping, which is, furthermore, frequency dependent [5]. Especially for standing waves one needs only a little fraction of that power P_{ac} necessary for travelling waves, commonly a few percent because of the acoustic resonator effect. This effective acoustic power will be determined according to [8] by the gain

$$g = \frac{2\,e^{\alpha D}}{2\alpha D + \frac{1}{2}\ln(1/R_1 R_2)} \sim 1/P_{ac}, \qquad (6)$$

where D is the acoustic resonator length, α the acoustic damping, R_1, R_2 the sound reflectivity of the acoustic resonator end faces. Commonly αD is very small and g is extremely sensitive to small changes of α; see [8]. Therefore, the only way to determine δ_m is by measurements. First the time integrated method will be discussed.

The time averaged intensities of Raman–Nath deflected light beams are [7]

$$\hat{I}_n = \sum_{p=-\infty}^{\infty} J_p^2(\Delta\varphi)\, J_{p-n}^2\left(\frac{\Delta\varphi}{a}\right). \qquad (7)$$

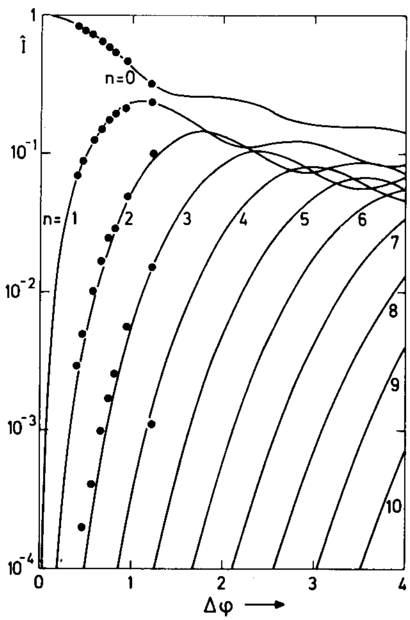

Fig. 1. Calculated time averaged intensities of a light beam deflected by a standing wave Raman–Nath modulator. Order n from zero to 10, acoustic phase shifts up to $\Delta\varphi = 4$. Experimental points for cw-RF power up to 600 mW, $\lambda = 633$ nm, $\nu_m = 30$ MHz.

where the transducer was glued with cyanacrylate on the quartz block. The acoustic damping of fused silica is 12 dB/cm GHz^2 [4] and at 30 MHz with D = 2 cm one gets $\alpha D = 2.5 \times 10^{-3}$ neper. With eq. (6) and assuming that $R_1 = R_2 = 1$, the highest standing wave acoustic resonator gain should be about 400. In the travelling wave case and with a figure of merit M_2 of 1.56×10^{-15} s^3 kg^{-1} [4] the acoustic power would be 20 watt. Since one must assume that the acoustic power is smaller than 0.6 watt, the real gain lies somewhere between 30 and 400. From eq. (5) it follows that more acoustic power delivers higher values of $\Delta\varphi$ for the same wavelength and material. Because of the great losses higher cw power inputs into the mode-locker cause temperature gradient disturbances or damage of the deflector system [9]. Therefore one commonly applies pulsed RF drivers with peak powers of ~20 watt during 100 μs at a few hundred Hz [10]. In this version the time average intensity of the central beam does not noticeably change because of the long switch-off time of the acoustic field at each cycle. Only the deflected beams carry the time averaged intensity information and can therefore be measured with an integrating DC light power meter. On the other hand, the time resolved intensities are accessible for all diffracted beams if the oscilloscope triggering is chosen in the right manner.

This is shown in fig. 5. The mode-locker was driven by a pulsed RF power of ~25 watt (200 Hz with a duty cycle of 1 ms). The light beam intensities at 633 nm were detected by a fast photomultiplier (RCA: 1 P 21) and the oscilloscope was triggered directly by the RF driver. Comparison of these oscilloscope traces with the calculated intensity functions via eq. (2) show good qualitative agreement for $\delta_m = 6.4$. Note that the number of the extrema is correct, but the experimental traces are somewhat distorted. This may be due to the time response of the detection system and/or due to some irregularities of the acoustic field. Perhaps the theory may become invalid because of the high power input, which may affect the higher order intensities, a point which is noted in [11]. Fig. 6 shows both the time averaged and time resolved experimental results. In the case of high pulsed acoustic power one sees that the time integrated intensities, especially of the order 4 and higher, show deviations from the

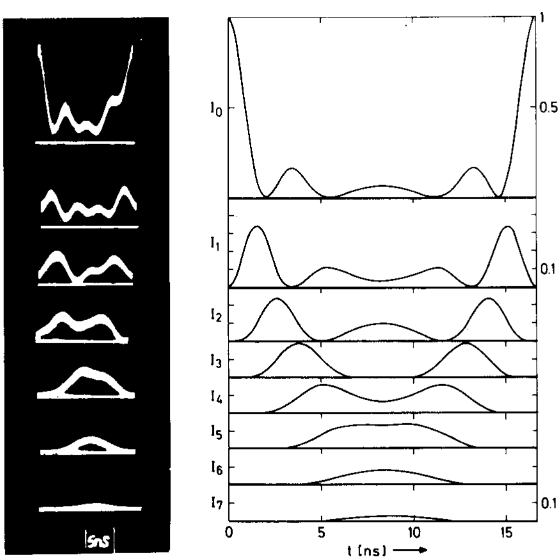

Fig. 5. Measured time resolved intensities of diffraction orders $n = 0 \ldots 6$ compared with theory (pulsed RF power). $\delta_m = 6.4$.

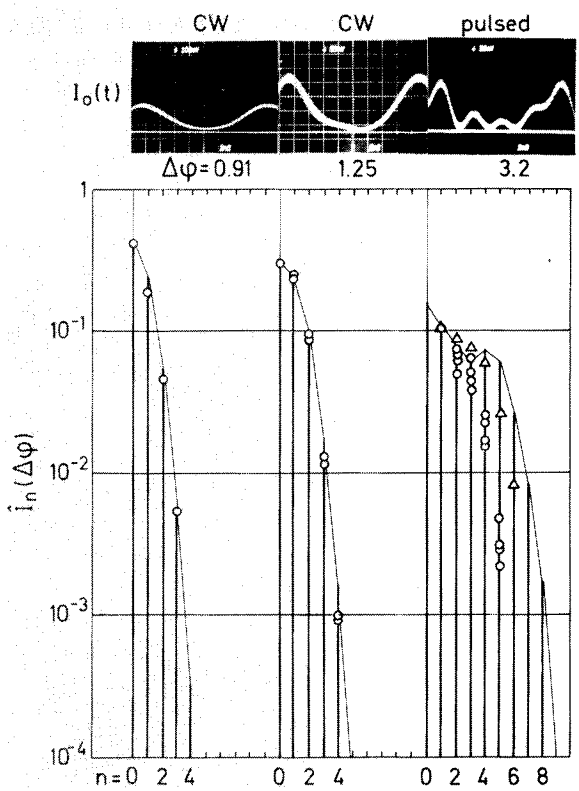

Fig. 6. Time averaged intensities up to $\delta_m = 6.4$ at λ = 633 nm. Circles correspond to direct DC measurements, triangles to graphically integrated oscilloscope traces.

theory with increasing order numbers up to more than one order of magnitude. Therefore, one can conclude that for high acoustic driving powers the time resolved method for determination of the modulation index seems more favorable. Nevertheless, it was found that a Raman–Nath mode-locker illuminated with a 4–8 mW HeNe laser can easily be controlled by the unaided eye. As a rule of thumb one can say: The modulation index at 633 nm is as high as the visible number of diffracted orders in one direction including the zeroth order.

3. Conclusion

With the knowledge of δ_m we were able to calculate the pulse width of our iodine laser-oscillator since the rest of the parameters in the theory of [3] are well known or easily measured. We found excellent agreement with the observed pulse width.

The modulation index of $\delta_m = 6.4$ seems to be an upper available limit with fused quartz as deflector material. Greater values may be reached with other materials, i.e. higher figures of merit M_2 in eq. (5). For the iodine laser at $\lambda = 1.3\ \mu m$ $LiNbO_3$ should be one of the favorites because of its greater M_2 and smaller acoustic damping.

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