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# An efficient acousto-optic mode-locker with low insertion loss

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The requirements imposed on an for acousto-optic standing-wave modulator to perform as a laser mode-locker are discussed. A home-made acousto-optic mode-locker was built, with low both active and passive losses. The obtained modulation parameter ($\delta \cong 0.4$) is comparable with the typical, standard modulators, commercially available. Nevertheless, even for this moderate value of modulation depth, the low losses of the developed modulator allow the generation of very short pulses by active mode-locking, as demonstrated in a Nd:YLF laser. Pulses with ~50 ps duration, with good short and long term stability, were obtained.

As características necessárias para moduladores acusto-ópticos de onda estacionária utilizados para o acoplamento de modos de lasers são discutidas. Um modulador acusto-óptico desse tipo foi desenvolvido, com a principal característica de possuir baixas perdas, tanto passiva como ativa. O parâmetro de modulação obtido ($\delta \cong 0.4$) é comparável àquele encontrado em moduladores comerciais. Apesar desse valor moderado de profundidade de modulação, as baixas perdas do modulador desenvolvido permitiram a geração eficiente de pulsos ultracurtos em um laser de Nd:YLF. Pulsos com duração temporal de 50 ps foram obtidos, com boa estabilidade de longo e curto termo.

Acousto-optic active modulation of the net gain in c.w. Lasers is a conventional technique to obtain short optical pulses. Three main techniques are commonly used to this aim: *Q-switching, cavity dumping,* and *mode-locking*, each one providing different final pulse characteristics. The active mode-locking is based in the modulation of either the laser amplitude (AM) or the phase (FM), synchronously with the cavity round-trip time, leading to the generation, and phase coupling, of a large number of longitudinal modes. The time characteristics of the laser field are given by the Fourier transform of these laser modes complex amplitudes, that, due to the phase coupling, lead to the generation of an optical pulse train with typical pulsewidths within the range of hundreds of ps down to tens of fs. In turn, the Q-switching technique consists in prevent the laser action, such that the population inversion reaches a value far in excess of the threshold population. By a sudden opening of the modulator transmission, the laser will have a gain that greatly exceeds the losses, and the stored energy will be released as a short and intense light pulse. Normally, this procedure is performed repetitively, and a pulse train, with pulsewidths of nanoseconds and peak powers of the order of megawatts, is obtained. Besides, the cavity dumping technique allows the energy contained in the steady-state laser field to be coupled out the cavity in a time equal to the cavity round-trip time. In particular, when used combined with the mode-locking technique, the repetitive cavity dumping allows one to obtain a train of ultrashort laser pulses of much lower repetition rate and much higher peak power than those obtained

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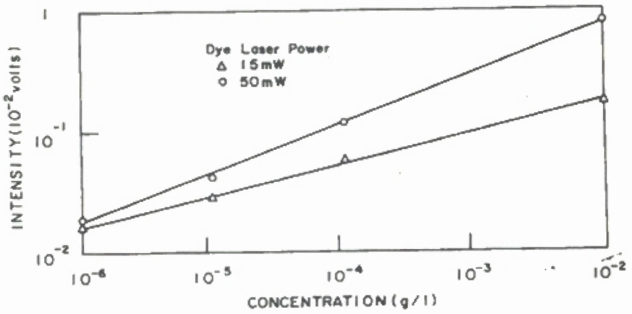

Figure 3. The optogalvanic signals versus solution concentrations relative to the sodium line 5890Å, for the 1 5mw and 50mw power of the dye laser.

The optogalvanic signals versus solution concentrations relative to the sodium line 5890Å is shown in Figure 3, for the 15mw and 50mw power of the dye Laser with the waist of lmm of the Laser beam kept constant inside the flame. A linear behavior of the curves is observed in the range of concentrations considered, and they seem to be converging to a point, where it seems to exist optical saturation and the Optogalvanic Effect independence of the incident Laser power. The figure suggests that such a point has concentrations about 0.5$\mu$g/1. As it is believed that the Optogalvanic Effect is processed by collisions between of electronic excited species, at this point the electronic excitations are limited and the collisions may be monitored by changing the temperature. We believe that for this critical point and concentrations below $\sim 0.5\ \mu$g/l, the relation between optogalvanic signals and solution concentration, for any power density (w/cm$^2$) of the Laser radiation excitation, will be linear and decreasing.

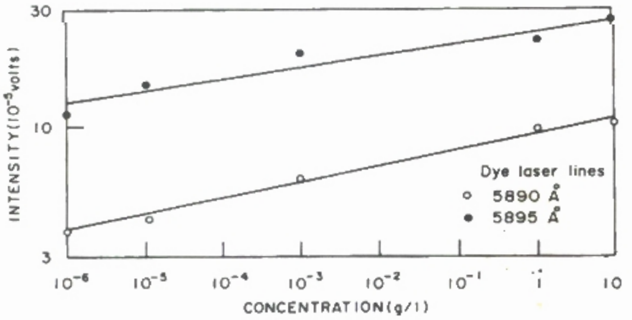

Figure 4. Intensity of the optogalvanic signal versus Sodium Chloride solution concentration for 15mw laser power ofthe lines 5890Å and 5895Å.

The transition probability for the sodium line $D_2$ is larger than for line $D_1$ and this seems to be reflected in Figure 4, where the intensity of the optogalvanic signal is shown as a function of the Sodium Cloride solution concentration for 15mw laser power for both lines. The large differences in the 5890 and 5895Å signals suggests that the cross-section differences for the transitions excited by Laser process are followed by the collisions, characteristic of the Optogalvanic Effect. This work shows that the large sensibility of the Optogalvanic Spectroscopic Technique and its very powerfull efficiency to detect very low concentrations of sodium in aqueous solutions, suggest that this technique can be used to study the mechanisms that make metals, alkali metals and alkaline earth metals inhibitors of soot formation. It also allows measuring the concentration rate of such metals in a vertical free flame as a function of height. The Optogalvanic Spectroscopy Technique, complemented with other techniques such as the extintion of a Laser bearn by the flame, for example, make it possible to analyse soot formation at each position above the reaction zone.

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by ordinary mode-locking.

In the case of active mode-locking, the final pulse characteristics have a critical dependence with the modulator maximum of transmission. As it is well known, from the Kuizenga and Siegman model of this regime[1], the final pulsewidth is given by:

$$\tau_P = \frac{\sqrt{\sqrt{2}\cdot\ln 2}}{\pi}\cdot\frac{\sqrt{\sqrt{L}/\delta}}{\sqrt{\Delta\nu_C\cdot\Delta\nu_L}} \tag{1}$$

where $\delta$ is the modulation parameter, as will be discussed later, $\Delta\nu_C$ is the cavity's longitudinal modes frequency separation, $\Delta\nu_L$ is the gain linewidth, and $L$ is the total cavity loss at maximum modulator transmission. The value of this last parameter must be minimized in order to obtain the minimum pulsewidth. $L$ is a sum of different contributions, as given by:

$$L = L_L + L_{\mathrm{Mod}} + L_{AO} \tag{2}$$

where $L_L$ is the double-pass linear cavity loss (scattering, absorption, output mirror transmission, etc.), $L_{\mathrm{Mod}}$ is the (double-pass) insertion loss of the acousto-optic modulator (purely passive), and $L_{AO}$ is the (double-pass) residual acousto-optic loss at the modulator maximum transmission.

In this paper, we describe the development of an acousto-optic modulator with minimal losses, and significant modulation depth. With this home-made modulator, we demonstrate the efficient mode-locked operation of a longitudinally pumped Nd:YLF laser.

## Basic description of acousto-optic mode-lockers

Acousto-optic amplitude modulators are based in the diffraction effect caused by the periodic perturbation of the refraction index, that is created by an acoustic wave[2-4]. The diffracted light intensity has a dependence on four main factors:[5,6] (1) the photo-elastic tensor, (2) the acoustic power, (3) the operation regime, and (4) the optical wavelength. In the case of a traveling acoustic wave, the switching time is limited mainly by the sound velocity and by the optical beam diameter. For fast modulation, in the nanosecond scale (the laser round-trip time), it is normally used standing acoustic wave modulators. In these devices, the modulation velocity is given only by the acoustic frequency.

The usual structure of acousto-optic modulators and deflectors consists of a piezoelectric transducer, excited by a radio-frequency (RF) wave, coupled to an interaction medium, in which it irradiates energy in the form of acoustic waves. Usually, this acoustic wave is in the longitudinal mode of propagation. There are two important regimes of operation, the Raman-Nath[7,8] and the Bragg[9]. This last one occurs for the following condition: $(K^2d)/k \gg 1$, where $K$ and $k$ are the acoustic and optical wavenumbers, respectively, and $d$ is the interaction length. The Raman-Nath regime is established for: $(K^2d)/k \ll 1$. For the case of a standing-wave Bragg modulator, the amplitude transmission is given by[10,11]

$$a(t) = \cos[\delta\cdot\mathrm{sen}(\Omega t)] \tag{3}$$

where $\delta$ is the modulation parameter and $\Omega$ is the frequency of the acoustic wave. It can be readily verified that the amplitude modulation frequency is twice the frequency of the acoustic wave. The modulation parameter dependence on the optical wavelength is given by[12]: $\delta(\lambda_2) = [\lambda_1/\lambda_2]\delta(\lambda_1)$. For the use as mode-lockers for c.w. lasers, the usual required operation conditions are:

i. The acousto-optic medium must be highly transparent at the used wavelength, stress-free, polarization preserving, and with good thermal characteristics. The optical surfaces must be at Brewster angle or have anti-reflection coatings.

ii. The modulation depth, given by $\delta$, must be maximized. This can be accomplished by using materials with high acousto-optical figures of merit, maximizing the acoustic power or optimizing the modulator design.

As in any standing-wave device, a fraction of the circulating acoustic power is non-stationary (traveling wave). This acoustic component must be minimized, as it corresponds to a constant loss (c.w.) for the laser in the mode-locking regime ($L_{AO}$).

## Modulator development

We have developed an standing-wave acousto-optical modulator operating in a regime between the Bragg and the Raman-Nath (in the present case, $K^2d/k \cong 3$). Although the most efficient regime, regarding the modulation depth for a specified RF power, is the Bragg one, the Raman-Nath regime allows the fastest modulations when operating at high levels of acoustic power[11] (for low signal, the behavior is analogous to the Bragg case). In fact, the shortest pulses of an actively mode-locked Nd:YLF laser were obtained by using a Raman-Nath modulator[13].

The details and techniques used in the construction of the modulator follow closely those described in Ref.14. An analogous description can also be found in Ref.15 . The modulator is formed by a fused silica rectangular prism, with six faces of approximately $1 \times 1$ cm$^2$, being the (two) optical faces at Brewster angle. The acoustic faces have high degree of parallelism, thus giving a high $Q$ to the acoustic resonator. The used transducer is a $\sim (5 \times 7)$mm$^2$, 200$\mu$m-thick, plate of $LiNbO_3$ in the 36°Y-cut orientation. This transducer is resonant at the fundamental frequency $f_0 \cong 18.3$ MHz (3$^{rd}$ harmonic in $f_0 \cong 55$ MHz). The piezoelectric plate was bonded to the acousto-optic block, by using an epoxy resin, as shown in the general scheme of Figure 1. An impedance transformer inductor was used to match the impedance of the device and the RF driver (50Ω).

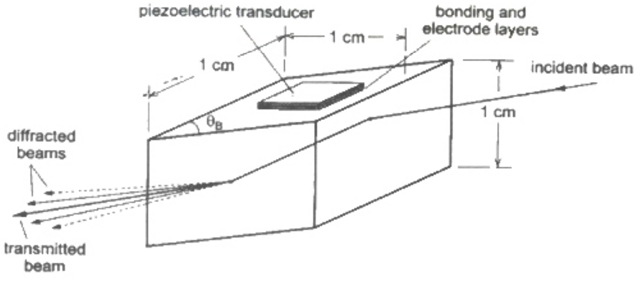

Figure 1: General design of the developed modulator. $\theta_B$ is the Brewster angle. Only two orders of diffraction are shown, but several orders can be generated.

The performance of the modulator, as a function of the RF frequency, was determined by measuring its temporal transmission at 1047 nm, outside the laser resonator, at an exciting RF power of 2W. The maximum transmission and the ratio of the peak to valley of the modulation are shown in Figure 2. The active continuous loss is given by: $L_{AO} = 1 - T_{\max}$.

The modulation parameter, as a function of the RF power, for the optimum excitation frequency (55.1 MHz), is shown in Figure 3. The modulator was mounted in a very compact mechanical assembly, specially designed to have high mechanical and thermal stability, besides minimum RF irradiation to the environment. Two metallic blocks are in contact with the lateral surfaces (non-optical, non-acoustic) of the acousto-optic prism, to dissipate the heat. These blocks are also water-cooled. In Figure 4 it is shown a picture of the modulator in its mechanical assembly.

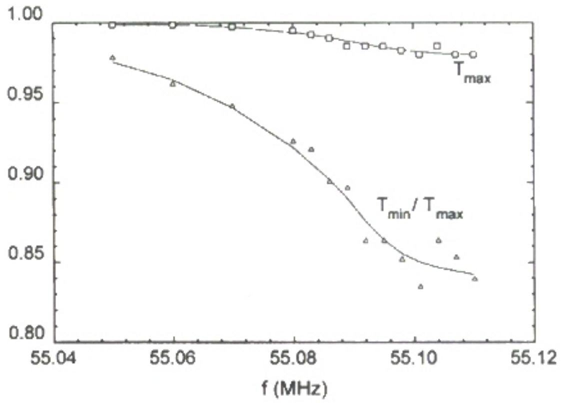

Figure 2: Peak transmission, $T_{\max}$, and normalized minimum transmission, $T_{\min}/T_{\max}$ of the developed modulator, as functions of the excitation frequency, and for a RF power of 2 W. The points correspond to experimental measurements. The solid lines are just a guide to the eye.

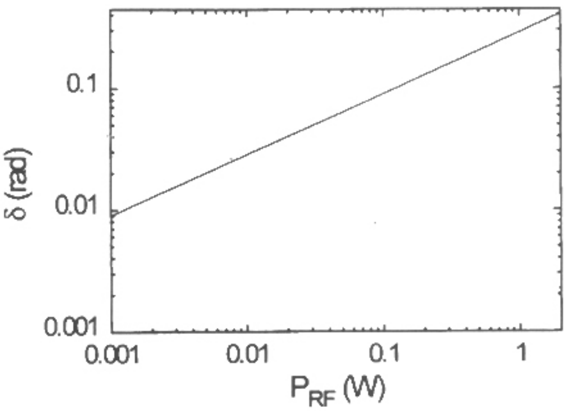

Figure 3: Modulation parameter of the developed modulator, as a function of the excitation power. The amplitude transmission is, for the present range of acoustic power, approximately given by: $T \cong cos^2[\delta.sen(\Omega t)]$.

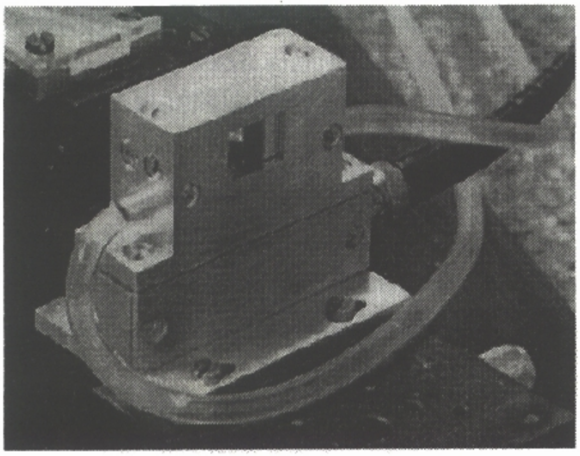

Figure 4: Picture of the developed acousto-optic modulator in its mechanical assembly.

## Mode-locking of a Nd: YLF laser

The modulator was inserted into the cavity of an argon laser pumped Nd:YLF laser[16], close to the output mirror, and excited with 2 W of RF power, near f=55.1 MHz. The laser cavity is formed by a concave end mirror ($M_1$), with radius of 5 cm, a concave folding mirror ($M_3$), with radius of 1 m, and a plane end mirror ($M_2$), with an output transmission of 2%, as shown in Figure 5. Due to the Brewster-angle geometry, and because the acousto-optic medium is isotropic, with minimum absorption and scattering losses, and without any mechanical stress (that can cause optical birefringence), the insertion of the modulator in the laser cavity does not affect the average output power. The estimated loss is approximately 1%, per double-pass.

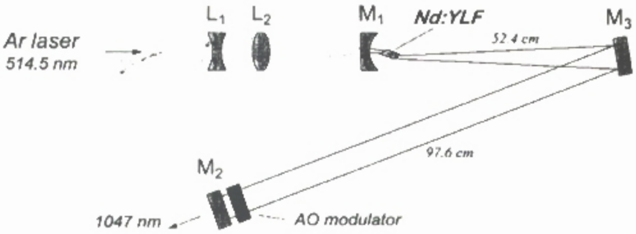

Figure 5: Experimental setup for the active mode-locking of the Nd:YLF laser.

Thus, according with the measured values of Figure 2, we have: $L = L_L + L_{\text{Mod}} + L_{AO} \cong 0.05+0.01+0.04 = 0.1$. For this RF power, the modulation parameter is: $\delta \cong 0.4$ (see Figure 3). By using expression (1), and considering $\Delta\nu_c \cong 110$ MHz and $\Delta\nu_L \cong 360$ GHz, the expected pulsewidth can be calculated as $\tau_P \cong (50\ \text{ps})\ L^{1/4}/\delta^{1/2} \cong 45$ ps.

The experimentally obtained pulse train was observed by using an electronic sampling system formed by an InGaAs ultra-fast detector (Opto-Electronics model PD50), with response time of 50ps, a high-performance sampling head (Tektronics SD-26 sampling head), with response time of 18 ps and sampling rate of 200 kHz, and a digital scope (Tektronics CSA 803). The total response time of the detection system is approximately 53 ps. The measured laser pulse is shown in Figure 6. The full-width at half maximum (FWHM) of this trace is ~75 ps, that corresponds to a FWHM of approximately 50 ps for the laser pulses. The pulse train presents an amplitude variation lower than 2%, as observed by using a silicon detector, with response time of 500 ps, and an analog scope (with maximum frequency of 100 MHz).

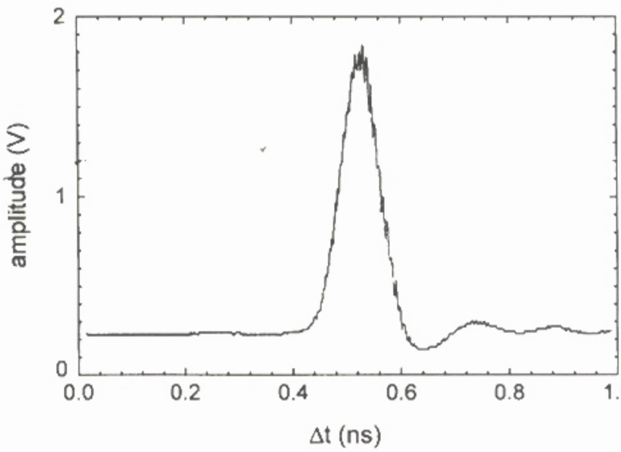

Figure 6: Oscilloscope trace obtained by using an ultra-fast photodetector and a sampling scope, for the mode-locked pulses of the Nd:YLF laser. The FWHM of this trace is 75ps, corresponding to a FWHM of 53 ps for the laser pulses.

## Conclusion

An standing-wave, home-made, acousto-optical modulator was designed and built to perform as a mode-locker. Great care was taken in its construction to minimize either the passive loss as well as the active one. Residual active losses as low as 2%, per single pass, were obtained for a modulation depth of ~15%. The performance of the modulator was demonstrated in a Nd:YLF laser. In the case of mode-locking with significative contribution of nonlinear modulation of parameters, the system characteristics have a critical dependence on the cavity loss[17]. Thus, the main features of the developed mode-locker are specially important, mostly when used with other modulation mechanisms, as for instance with passive techniques.

## Acknowledgments

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