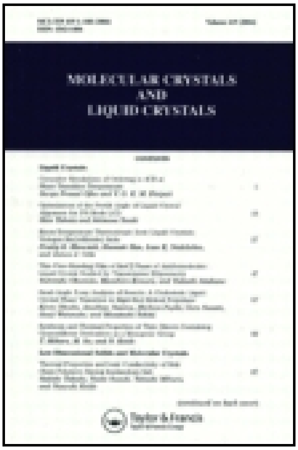

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H. J. Eichler [a], D. Grebe [a], I. Iryanto [a] [b] & R. Macdonald [a]

[a] Optical Institute, Technical University Berlin, Strasse des 17. Juni, 10623, Berlin, Germany

[b] Trisakti University, Jln. Kyai Tapa-Grogol, Jakarta Barat, Indonesia

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ACTIVE Q-SWITCHING OF A SOLID STATE LASER USING NEMATIC LIQUID CRYSTAL MODULATORS

H. J. EICHLER, D. GREBE, I. IRYANTO* and R. MACDONALD
Optical Institute, Technical University Berlin - Strasse des 17.Juni 10623 Berlin, Germany.
**on leave of Trisakti University, Jln.Kyai Tapa-Grogol - Jakarta Barat - Indonesia*

Abstract Fast electro-optical switching with planar nematic liquid crystals in multipass and also Fabry-Pérot modulators has been realized. By using short driving pulses of 150V, we achieved microsecond switching times for nematic planar cells (NPC) and even sub micro-second switching in case of nematic Fabry-Pérot modulators (NFPM), which have been applied as active Q-switches in Nd:YAG solid state lasers. Four different resonator configurations have been investigated. Typically, giant pulses of 35-70 ns duration (FWHM) with energies between 10-25 mJ are emitted. A rather plain Q-switch resonator design consists of only two optical components: a cholesteric liquid crystal polarizing mirror and a reflecting nematic liquid crystal modulator.

Keywords: Liquid Crystal, electro-optic, Q-switch Laser.

INTRODUCTION

Today's most common applications of liquid crystals are electro-optic displays. Nevertheless, several approaches have been done for the realization of passive linear optical devices for lasers, where liquid crystals serve as large aperture optical elements like waveplates and laser mirrors with low losses and high damage thresholds [1,2]. The observation of the giant optical nonlinear properties of liquid crystalline materials in the early eighties started the investigation of liquid crystals for optical switches [3] and optical data processing.

A mode of laser operation extensively employed for the generation of high pulse power is known as active Q-switching. It has been designated so because the quality factor of the optical resonator is altered by an active electro-optical or acousto-optical element [4]. As long as the low quality factor take place, the energy is stored and then converted into a powerful laser output in a very short time as the Q factor is switched on. By this way, a so-called giant laser pulse is generated. The most commonly used devices to achieve active Q-switching of lasers are presently a Pockels-cell modulators comprising inorganic crystals which exhibit a strong linear electro-optic effect, like e.g. KH_2PO_4 (KD*P) or $LiNbO_3$. These modulators are rather fast (few nanoseconds) but require high driving voltages of typically several kilovolts. Recently, fast electro-optical switching with planar nematic liquid crystals using multipass and also Fabry-Pérot modulators has been also reported [5,6]. By using short driving pulses of only 150V, we achieved microsecond switching times for nematic planar cells (NPC) and even sub-microsecond switching in case of nematic Fabry-Pérot modulators (NFPM). In the present paper we report on results of using these fast nematic modulators as active Q-switches in Nd:YAG (Neodymium doped Yttrium Aluminum Granat) solid state lasers. Four different resonator configurations have been investigated for this purpose.

FAST LIQUID CRYSTAL MODULATORS FOR LASER SWITCHING

Fast transient electro-optical switching has been realized in nematic planar cells and nematic Fabry-Pérot modulators. In both devices the light modulation results from electro-optically induced phase modulations, which are then converted into amplitude modulations by placing the liquid crystal between crossed polarizer for the nematic planar cell, respectively by interference effects for the nematic Fabry-Pérot cell. In our previous work [5,6], the optical phase modulation of a biased (1-5 Volt) planar cell driven by a short pulsed voltage (< 10 μs, 150 V) was running on the micro-second time scale with a contrast about 90 %. In the case of nematic Fabry-Pérot modulators, submicrosecond switching was achieved with a high finesse cavity, but at the same time the maximum transmission was reduced due to finite optical losses. The FP modulator works also in the reflection mode with the same speed but lower contrast.

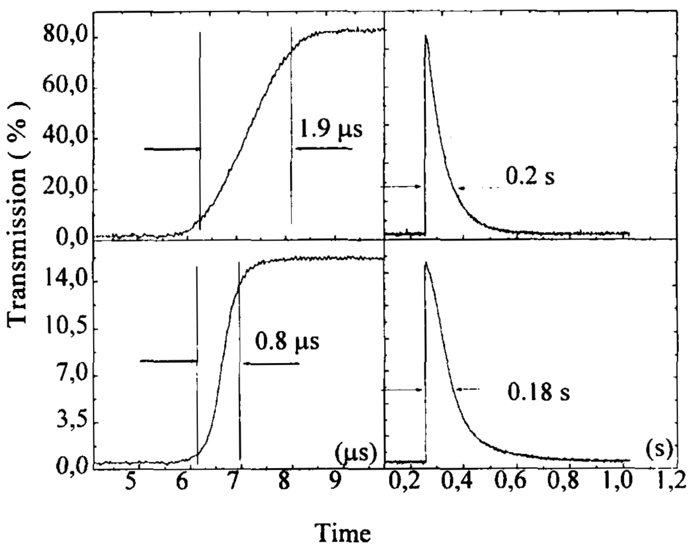

FIGURE 1: Typical temporal transmissions characteristic of the nematic planar modulator with the thickness of 13 μm (upper) and those of the nematic Fabry-Pérot modulator (lower) with the thickness of 23 μm and R=92 %.

However, the minimum optical losses are reduced, compared with the transmission mode. For a 5CB Fabry-Pérot modulator with mirror reflectivities $R_1 = R_2 = 90$ % and a thickness of 23 μm, the transmission switching time is 0.8 μs from 0.5 % to 16 %. In the reflection mode, it is switched from 90 % to 70 % with the same switching speed. Figure 1 displays typical temporal transmissions characteristic for both types of modulators.

Another important point is to minimize the electrical time constant of the cell which was shown to set a lower limit for the switching speed [5]. In the present work a new ITO transparent electrode configuration has been developed for this purpose (Fig.2).

Butterfly shaped electrodes are mounted perpendicular to each other to minimize the resistance and capacitance in the overlap region which is used as modulator. Results shown in Fig.1 have been obtained with such ITO configuration. The active area is 6 mm x 6 mm and the electrical time constant $\tau = RC = 50$ ns for a $d = 7$ μm thick sample, whereas full area electrodes of e.g. 16 mm x 16 mm result in RC=1 μs.

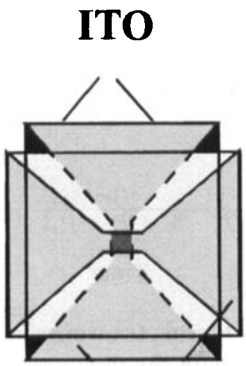

FIGURE 2: The design of the LC cell with butterfly ITO layer.

PREPARATION OF THE MODULATORS

Three kinds of modulators have been prepared for the present experiments. Firstly, a nematic planar cell for the transmission mode, secondly a similar one for the reflection mode and thirdly a nematic Fabry-Pérot cell. As an example, the design of the reflecting nematic planar cell is shown in Fig.3.

The nematic liquid crystal 5CB was placed between two glass flats coated with antireflection layer (AR) outside and a stack of transparent ITO electrodes in butterfly configuration, and a dielectric HR layer on one side. In the case of the FP modulator, instead of single side HR layer we used two mirrors of R= 90 % on both sides. The next layer is obliquely (about 80 degree) evaporated SiO_2 at the inner surface as an alignment layer. For the transmitting nematic planar cell, the HR mirror between alignment and ITO layer was omitted. All cells have a thickness of 7 μm. It must be noted that all dielectric layers were fabricated to fit for the laser wavelength of λ=1064nm.

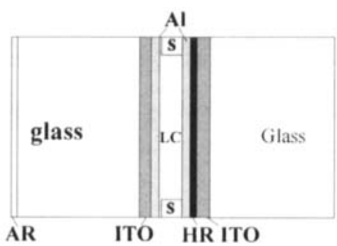

FIGURE 3: Design of the reflecting nematic planar modulator used. ITO: transparent electrode, Al: alignment layer, S: spacer, AR: antireflection layer, HR: high reflection layer and LC: liquid crystal.

ACTIVE Q-SWITCH APPLICATION

The schematic Q-switch laser set-up consists of a polarizing outcoupler, the laser medium and a reflecting phase modulator. Conventionally, the outcoupler and the HR-mirror are dielectric mirrors and the phase modulator is either an electro-optic modulator, for instance a Pockels cell, or an acousto-optic modulator. In our experiments we used the liquid crystal described above instead of a Pockels cell and have realized four different Q-switch resonator designs.

In the first arrangement, a combination of a dielectric mirror as outcoupler and Glan-Taylor polarizer were used together with a transmitting nematic planar modulator and HR concave mirror as the reflecting phase modulator.

Secondly, we placed a reflecting nematic Fabry-Pérot modulator and afterwards a reflecting nematic planar modulator as a single component reflecting phase modulator together with a conventional polarizer and outcoupling mirror as in the first case.

Since it was also reported recently that in order to realize a Q-switch laser system, the dielectric out-coupler-mirror and polarizer combination could be replaced by a single cholesteric liquid crystal (CLC) mirror [7], the fourth set-up was realized by using a cholesteric liquid crystal mirror as polarizing outcoupler and a reflecting nematic planar modulator as reflecting phase modulator.

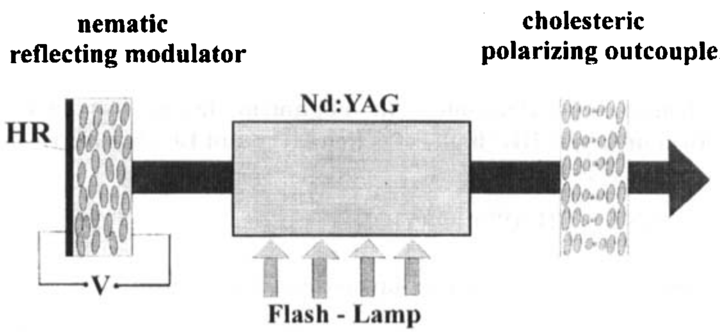

FIGURE 4: Schematic set-up of liquid crystals Q-switch solid state laser resonator.

The schematic set-up is shown in figure 4. It must be noted that we have only two optical components to realize a Q-switch laser cavity in the last case: a cholesteric liquid crystal mirror and a reflecting nematic liquid crystal modulator. The length of all resonators was 50 cm.

EXPERIMENTAL RESULTS

The laser performance depends on the bias voltage as well as the driving voltage of the liquid crystal modulator. The reason is that the bias voltage determine the initial condition of the transmission or reflection and hence the switching speed. Also the driving voltage determine the switching speed but also the contrast. The laser emits one single giant pulse per excitation cycle under optimized conditions of several variables such as the bias voltage and the driving voltage pulse length. In our experiments, these conditions were about 2.4 V of bias voltage and 2,3μs driving voltage pulse length. Otherwise, a low Q-switch condition took place and several Q-switch pulses were emitted during one excitation cycle.

As an example, the performance and results for an all liquid crystalline Q-switch resonator are shown in Fig.4 and will be discussed first. In this case, the polarization dependence of the reflectivity of a cholesteric liquid crystal is suited to work as the polarizing out-coupler.

In order to explain the Q-switch process in that arrangement, let us start with a left handed circular polarization wave starting from the out-coupler. With the bias voltage properly set but without driving voltage, the nematic film acts as a $\lambda/2$ plate, and hence the polarization state is reversed to right handed circular by reflection at the HR mirror and passing the liquid crystal twice. Consequently, the optical losses are very high because the cholesteric mirror does not reflect that polarization and the laser process can not start. If then however, a short pulse voltage is applied to the reflecting nematic modulator, the single pass retardation is decreased to λ/4 rapidly, and the total retardation is λ/2 for two passes. Thus, the reflecting modulator change the polarization state rapidly into left handed circular polarization and this is connected with an increase in reflectivity of the CLC mirror. Consequently a short intense laser pulse is emitted.

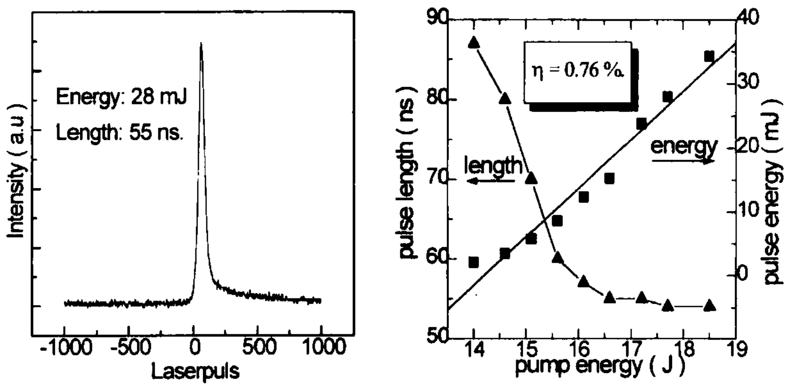

FIGURE 5: Q-switch pulse with reflecting nematic planar modulator and cholesteric outcoupler.

Typical results for this configuration are shown in fig.5 displaying the temporal pulse evolution and the dependence of pulse duration and energy upon excitation energies.

The slope efficiency was found to range around 0.8 %. This value is lower than that for a conventional set-ups, where the Pockels cell together with a HR-mirror is used as a reflecting phase modulator and the dielectric outcoupler together with Glan-Taylor polarizer as polarizing outcoupler which served about 2-3 % slope efficiency [4]. The reasons are higher losses in nematic phase modulators compared with the Pockels cell. In our resonator, the internal cavity losses result mainly from absorption and scattering in the nematic liquid crystal and absorption in the ITO Layer. The overall losses in nematic modulators as measured in our previous experiments are around 20 % per one round trip. Typical losses in a commercially available Pockel cell are only around 1-2 % added by 0.5 % for dielectric outcoupler as used in a conventional design. That means that our resonator design have internal cavity losses that are eight times higher than conventional ones. Moreover, the 23 % outcoupler reflectivity of the cholesteric outcoupler used above is far from the optimum value, which was found around 50 %.

For comparison, the results obtained with the two other resonator designs described above are shown in Fig.6. In the case of a FP, we observed a single Q-switch pulse only for lower pump energies. For instance: with a 44 % outcoupler reflectivity, the pump energy must be less than 9 Joule. For higher energies we observed a small free running signal besides a Q-switch pulse because of imperfect suppression of oscillation. This disadvantage was not observed in the case of reflecting nematic planar modulator. Fig. 6 showed the dependence of the energy and pulse length on the pump energies of both cases. The minimum pulse length was about 35 ns with energy around 30 Joule by using the reflecting planar modulator, so far.

The differences in slope efficiency and also the threshold pump energy between Fig.5 and Fig.6 result again from the difference of the internal cavity losses and the outcoupler reflectivity of the resonator design. The first design, as shown in Fig.4, has only three components whereas the others contain four components, since instead of a single cholesteric polarizing outcoupler, a combination of dielectric mirror and a polarizer was used.

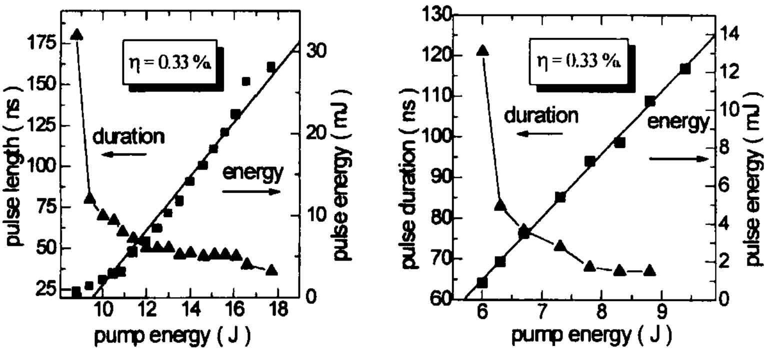

FIGURE 6: Reflecting nematic planar (left) and reflecting nematic Fabry-Pérot modulator (right) as HR-mirror with 44 % dielectric outcoupler in Nd:YAG Q-switch laser.

As a consequence, the losses of the last design are higher because of at the additional surfaces and losses in the polarizer. Although the outcoupler reflectivity of 44 % was near the optimum value, the influence of the low losses is stronger in reducing the slope efficiency. On the other hand, an increasing of the outcoupler reflectivity decreased the threshold pump energy. As a consequence, the threshold in the experiments shown in Fig.6 with R = 44 % is lower than that displayed in Fig.5 with R = 23 %.

CONCLUDING REMARKS

Active Q-switching of Nd:YAG solid state lasers using high speed nematic liquid crystal electro-optical modulators have been demonstrated and investigated for the first time. Best performance was obtained with rather compact modulator designs like the high back plane reflectivity double pass nematic retardation modulator or nematic Fabry-Pérot modulators. Electro-optical switching times of 1 μs or somewhat less have been achieved by applying driving voltages of only 150 V across the liquid crystal modulator, which allow for active Q-switch component and emission of giant laser pulses as short as 35 ns FWHM comprising energy of up to 30 mJ. Furthermore, a rather plain all-liquid crystalline Q-switch laser resonator comprising only two components, a cholesteric polarizing mirror and a high reflectivity nematic modulator, has been realized.

Advantages of thin film liquid crystalline electro-optical modulators and laser mirrors are the expected low fabrication costs, lower driving voltage and the opportunity to realize rather compact resonator design, which may be of interest in particular with miniaturized diode pumped solid state lasers.

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