Active mode locking of lasers by piezoelectrically induced diffraction modulation

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A new amplitude-modulation mode-locking technique is presented. Acoustic waves are generated directly on the faces of a resonant photoelastic medium. The created standing waves cause a highly efficient diffraction modulation of light. The modulation depth of standing-wave mode lockers is related to material and drive parameters and a figure of merit is introduced. With a lithium niobate crystal modulation depths over 10 are achieved at 1.054 μm and 1 W of radio frequency power. Using this device for the active mode locking of a continuous-wave Nd:glass laser pulses as short as 3.8 ps are produced at a repetition rate of 66 MHz. Limitations of amplitude-modulation mode locking by standing acoustic waves are discussed.

Active mode locking has been used for a long time to produce ultrashort pulses in solid-state lasers. The highly stable output of these picosecond light sources allows reproducible pulse compression outside the laser resonator. Additionally, solid-state laser materials are optimum media for optical pulse amplification. Owing to these features solid-state laser systems based on continuous-wave (cw) actively mode-locked oscillators offer an attractive alternative for high-intensity femtosecond pulse generation.[1,2] The same master oscillators are employed in synchronously pumped tunable dye laser systems.[3] The duration of the pulses delivered by the solid-state oscillator greatly determines the ultimate system performance in both cases. In this letter we present a new amplitude-modulation (AM) mode-locking technique for efficient ultrashort pulse generation in actively mode-locked lasers.

In general, the modulator transmission experienced by a short pulse in an actively mode-locked laser may be cast in the form $\exp[-\delta(2\pi\nu_m t)^2]$, where δ and ν_m are the modulation index and frequency, respectively.[4] Increasing either of them gives rise to a reduction of the steady-state pulse width in continuous-wave mode-locked lasers.[4] Recently, short pulses around 10 ps were obtained at high modulation frequencies.[5–7] However, the high repetition rate reduces the pulse energy in cw lasers and makes single pulse selection for regenerative amplification difficult. Therefore, the master oscillators in the laser systems mentioned above are operated at moderate repetition rates,[1–3] and increasing δ provides the only means for pulse shortening. In AM mode locking $\delta \sim P$, where P is the modulator drive power. By contrast, $\delta \sim \sqrt{P}$ in frequency-modulation (FM) mode locking, hence, much higher modulation indices can be obtained by AM than FM.

AM mode locking is usually performed with standing-wave acousto-optic modulators. In these devices the acoustic waves are generated in a piezoelectric transducer and coupled into a resonant photoelastic medium. We improved this concept in a rather straightforward way. Selecting a piezoelectric material which also possesses large strain-optic coefficients a refractive index grating can efficiently be created in the bulk piezoelectric transducer itself when driven at a harmonic resonance. As a result, the piezoelectrically induced strain-optic (PESO) effect may directly give rise to diffraction modulation of light. The purpose of this letter is to report that piezoelectrically induced light diffraction in a laser cavity provides an excellent means for efficient ultrashort pulse generation by AM mode locking at repetition rates variable from tens to hundreds of MHz.

Recently, a unified treatment of standing-wave acousto-optic phase gratings was developed.[8] The theory based on simple energy considerations applies to both PESO and conventional standing-wave devices. As a result of these calculations, the magnitude of the phase grating (also referred to as modulation depth) can be written as

$$\Theta_m = \frac{2\pi}{\lambda}\left(\frac{M_2}{\alpha_{\mathrm{eff}}}\eta P \frac{L}{A}\right)^{1/2}, \qquad (1)$$

where λ is the wavelength of light, η is the ratio of the acoustically dissipated power to the total absorbed power P. η is generally less than one because of some electric power dissipation and takes its maximum value η_0 on the resonance peak. L represents the interaction length, A is the cross section of the modulator aperture, M_2 is the acousto-optic figure of merit,[9] and

$$\alpha_{\mathrm{eff}} = \alpha_0 + \beta\nu_m^2 \qquad (2)$$

is the effective attenuation coefficient for the acoustic intensity in the resonator. The second term on the right-hand side describes the intrinsic acoustic attenuation of the resonant medium,[10] whereas α_0 comprises the extrinsic resonator losses. A similar expression to (1) was recently derived also by other authors.[7]

The modulation index δ is proportional to Θ_m^2, and the steady-state pulse duration in the AM mode-locked laser is given by[4]

$$\tau_p = \gamma(\sqrt{g}/\Delta\nu)^{1/2}(\Theta_m\nu_m)^{-1/2}, \qquad (3)$$

where $\gamma = 0.53$ for Bragg deflection and $\gamma = 0.45$ for Raman–Nath modulation, g is the saturated round trip amplitude gain, and $\Delta\nu$ is the fluorescence linewidth. The higher the product $\Theta_m\nu_m$ is the shorter pulses can be generated. For frequencies $\nu_m \ll \nu_0$, where $\nu_0 = \sqrt{\alpha_0/\beta}$, Θ_m appears to be nearly independent of the drive frequency and $\Theta_m\nu_m$ in-

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creases linearly with ν_m. However, for $\nu_m > \nu_0$, $\Theta_m \nu_m$ stops increasing, and can be written as

$$\Theta_m \nu_m \approx \frac{2\pi}{\lambda}\left(MP\frac{L}{A}\right)^{1/2}, \tag{4}$$

where $M = (M_2/\beta)\eta$ is a figure of merit for standing-wave acousto-optic mode lockers. In conventional standing-wave modulators M_2/β is a characteristic of the photoelastic medium and η is that of the piezoelectric transducer, whereas in PESO devices all parameters comprised in M refer to the interaction medium. The most important result of these investigations is that the pulse duration in acousto-optic mode locking turns out to be independent of the modulator frequency, once $\nu_m > \nu_0$. In general, PESO mode lockers are expected to have lower ν_0 than conventional acousto-optic modulators owing to their lower extrinsic acoustic losses.

We chose a lithium niobate ($LiNbO_3$) sample for our experiments because of its favorable piezoelectric and photoelastic properties. Computer-aided theoretical investigations for optic-axis light propagation in lithium niobate showed that maximum diffraction occurs when the acoustic wave propagates along the y axis.[8] The acoustic resonator faces normal to the y axis were polished optically flat and parallel to within 5 seconds of arc to ensure a high quality factor of the acoustic cavity. A single quarter-wave layer of silica reduced the 16% reflection loss of the aperture faces to about 1% resulting in a single-pass insertion loss of 2%. The sample dimensions along the x, y, and z axes were $w = 4$ mm, $d = 3$ mm, and $L = 24$ mm, respectively. The crystal was mounted between copper electrodes forming a high-frequency package.

Impedance matching to a 50 Ω transmission line was achieved by inductive rf signal coupling to minimize electrical reflection losses.[8] The modulator was driven at the 31st harmonic of the extensional acoustic mode by applying the electric field parallel to the crystal's y axis at $\nu_m \approx 33$ MHz. The light propagating along the z axis of the sample was subjected to diffraction loss modulation at a frequency of ≈ 66 MHz. The above conditions involved light diffraction close to the Raman–Nath regime at $\lambda \approx 1\ \mu$m.[9] For light polarization parallel to the x axis $M_2 = 1.23 \times 10^{-15}$ in SI units. $\alpha_{\rm eff}$ and η_0 may be evaluated from electrical measurements. For the assembly investigated we obtained the peak acoustic efficiency $\eta_0 = 0.88$ and the quality factor $Q = 1.1 \times 10^5$. The acoustic quality factor can be expressed as $Q = 2\pi\nu_m/\alpha_{\rm eff} v_s$, where v_s is the sound velocity. With $\nu_m = 33$ MHz and $v_s = 6870$ m/s, $\alpha_{\rm eff} = 0.27\ {\rm m}^{-1}$ resulting in a round trip resonator loss of 1.6%. As the intrinsic loss is an order of magnitude lower at this frequency, $\alpha_{\rm eff} \approx \alpha_0$ under our conditions. Clamping the crystal along its yz faces should significantly reduce α_0. Using these numbers (1) predicts $\Theta_m = 16.4\sqrt{P}$, where P is given in watts.

Diffraction measurements yielded for the modulation depth $\Theta_m = 11.2\sqrt{P}$. The discrepancy may be attributed to the fact that stable operation is not possible on the resonance peak because of the nonzero temperature coefficient of the resonance frequency, $\partial\nu_r/\partial T = -3.7$ kHz/°C. However, self-stabilization occurs on the positive side of the resonance curve by the negative value of $\partial\nu_r/\partial T$ allowing stable long-term operation using a simple temperature control. Considering the very sharp resonance of $\Delta\nu_r = 0.9$ kHz (following from the high Q) this indicates a highly effective self-stabilization mechanism.

As a result of these investigations we may conclude that 100% amplitude modulation ($\Theta \approx 2.4$) is obtained with driving powers of a few tens of milliwatts at $\lambda = 1.054\ \mu$m. Increasing the rf power sharp transmission peaks are created as shown by the oscilloscope trace in Fig. 1. The Raman–Nath diffraction pattern of a He-Ne laser beam ($\lambda = 633$ nm) at a driving power of 1 W is shown in Fig. 2. Due to the low intrinsic attenuation $\nu_0 > 100$ MHz for our assembly. Consequently, Θ_m is nearly independent of the drive frequency below 100 MHz.

Mode locking by piezoelectrically induced diffraction modulation was performed in a cw Nd:glass laser, which was described in a recent paper.[11] A schematic diagram of the laser cavity is shown in Fig. 3. A 1-mm-thick plate of Nd:phosphate glass (LG 760) with 8% doping was placed at the focus of an astigmatically compensated cavity. The laser was longitudinally pumped by a krypton laser at 0.8 μm. The mode locker was positioned close to the output coupler and driven with 1 W of rf power at about 33 MHz by an ultrastable frequency synthesizer and a broadband rf power amplifier. Stable modulation was easily obtained by tuning the frequency synthesizer from higher frequencies to resonance. When doing so, the self-stabilization mechanism was immediately activated once the resonance was reached. Precise matching of the cavity length and the driving frequency was realized with piezocontrol of the resonator length.

With a 2.5% output coupler the threshold pump power and the slope efficiency were 50 mW and 10%, respectively. Precise adjustment of the cavity length was necessary to obtain the shortest pulse, the autocorrelation trace of which is shown in Fig. 4. For a Gaussian pulse shape, this indicates a pulse duration of (3.8 ± 0.4) ps, which is significantly shorter than those obtained in recent experiments.[12-14] To our knowledge, these are the shortest pulses generated by AM and FM mode locking to date.

The accuracy of the measurement is limited by the noise of the second-harmonic signal, which is attributed to small fluctuations of the resonator length. In fact, producing the shortest pulses mode locking was sensitive to a cavity length mismatch of less than 0.5 μm, which is a consequence of the large bandwidth of the gain material.[12] With $g = 0.05$ and $\Delta\nu = 6$ THz (3) gives $\tau_p = 4.6$ ps under the experimental conditions described above. The improved performance may be explained by additional frequency modulation due to self-

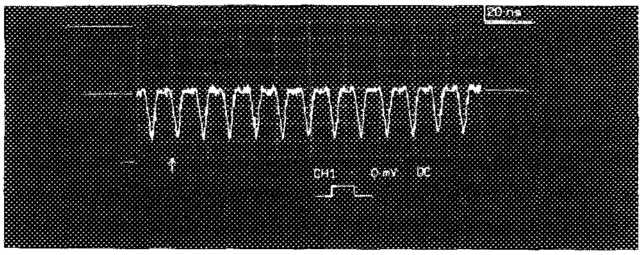

FIG. 1. Intensity of the zeroth-order (undeflected) light beam at 1.054 μm transmitted by the PESO modulator which is driven with a rf power of about 0.1 W at 33 MHz.

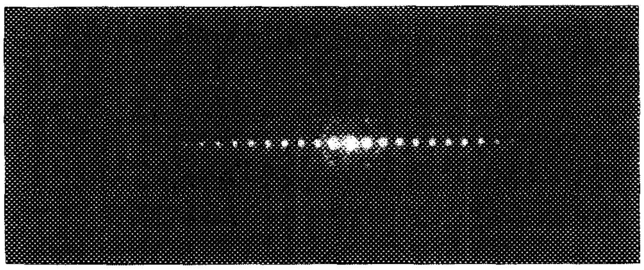

FIG. 2. Raman–Nath diffraction pattern of a He-Ne laser beam when the modulator is driven with 1 W of rf power at 33 MHz.

phase modulation in the active medium.[12] The reasonable agreement between experiment and the theory of pure AM mode locking suggests that the pulses are nearly bandwidth limited.

Equation (3) predicts further pulse shortening when either Θ_m or ν_m is raised. However, the increase of Θ_m or ν_m may encounter the limitation originating from the finite length of interaction between light and acoustic waves. Once the width of the double-pass intensity transmission of the modulator (determined by $\Theta_m \nu_m$) compares to the time taken by the laser pulse to pass twice through the modulator, (3) becomes incorrect.[15] To establish a region of validity for (3) the above criterion is quantified as follows:

$$(\Theta_m \nu_m)^{-1} \geqslant \kappa(2nL/c), \qquad (5)$$

with $\kappa \approx 3\pi$ for Raman–Nath and $\kappa \approx 2\pi$ for Bragg modulation. A significant increase of $\Theta_m \nu_m$ beyond the limit given by (5) considerably reduces both the peak transmission and the sharpness of modulation. Optimum mode locking performance with an actual modulator can be achieved when $\Theta_m \nu_m$ approximately satisfies the equality in (5). In our case $\kappa(2nL/c) = 3.5$ ns and $(\Theta_m \nu_m)^{-1} \approx 2.8$ ns, i.e., $\Theta_m \nu_m$ may not be further enhanced with our present modulator. A lengthening of L in (5) can be simulated by removing the mode locker from the output coupler. In fact, an effective increase of L by 20% led to significant pulse broadening and reduction of the output power confirming our considerations. We conclude that the interaction length of our PESO modulator has to be shortened for further improvement of mode locking.

In summary, we presented a unified characterization of conventional standing-wave acousto-optic mode lockers and PESO devices in which the acoustic waves are generated on the faces of the resonant medium. A figure of merit for these devices was introduced. We found that optimum mode-locking performance is achieved when the drive frequency is raised to ν_0 where the extrinsic and intrinsic acoustic losses are approximately equal. An increase of the modulation frequency beyond this value does not result in further pulse shortening. We demonstrated that the generation of acoustic waves on the faces of a resonant photoelastic medium may result in high-efficiency diffraction modulation of light which is well suited for ultrashort pulse generation in actively mode-locked lasers. Driving the bulk (piezoelectric) crystal sample directly makes quasi-continuous adjustment of the pulse repetition rate possible in a wide frequency region over several hundred MHz. Optimum performance can be obtained at comparatively low ν_0 frequencies. The monolithic construction greatly simplifies the fabrication and allows the PESO devices to be driven with higher rf powers than conventional acousto-optic mode lockers. The development of PESO mode lockers with high figure of merits and short interaction lengths will allow further advances in active mode locking of solid-state lasers.

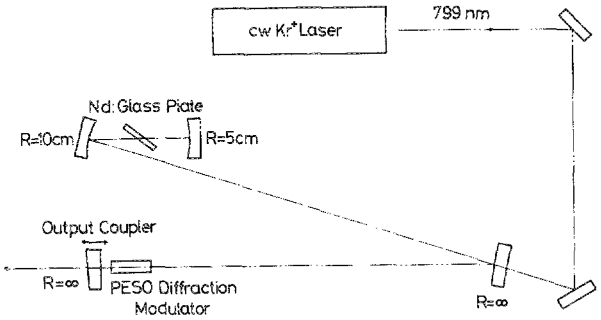

FIG. 3. Schematic illustration of the mode-locking experiment. The largest cavity dimension shown is about 120 cm.

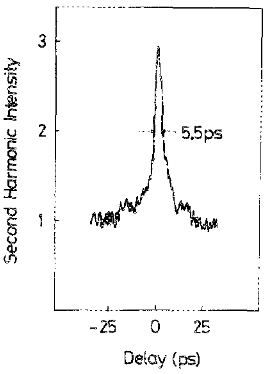

FIG. 4. Autocorrelation trace of the mode-locked pulse train. Assuming a Gaussian pulse shape the measurement yields a pulse width of 3.8 ps.

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[1] P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, IEEE J. Quantum Electron. **QE-24**, 398 (1988).
[2] L. Yan, P.-T. Ho, C. H. Lee, and G. L. Burdge, Appl. Phys. Lett. **54**, 690 (1989).
[3] T. Juhasz, J. Kuhl, and W. E. Bron, Opt. Lett. **13**, 577 (1988).
[4] D. J. Kuizenga and A. E. Siegman, IEEE J. Quantum Electron. **QE-6**, 694 (1970).
[5] G. T. Maker and A. I. Ferguson, Opt. Lett. **14**, 788 (1989).
[6] G. T. Maker and A. I. Ferguson, Electron. Lett. **25**, 1025 (1989).
[7] U. Keller, K. D. Li, P.T. Khuri-Yakub, D. M. Bloom, K. J. Weingarten, and D. C. Gerstenberger, Opt. Lett. **15**, 45 (1990).
[8] L. Turi, Cs. Kuti, and F. Krausz, IEEE J. Quantum Electron. (to be published).
[9] N. Uchida and N. Niizeki, Proc. IEEE **61**, 1073 (1973).
[10] B. A. Auld, *Acoustic Fields and Waves in Solids* (Wiley, New York, 1973).
[11] F. Krausz, E. Wintner, A. J. Schmidt, and A. Dienes, IEEE J. Quantum Electron. **QE-26**, 158 (1990).
[12] F. Krausz, T. Brabec, E. Wintner, and A. J. Schmidt, Appl. Phys. Lett. **55**, 2386 (1989).
[13] L. Yan, J.-D. Ling, P.-T. Ho, C. H. Lee, and G. L. Burdge, IEEE J. Quantum Electron. **QE-24**, 418 (1988).
[14] S. Basu and R. L. Byer, Opt. Lett. **13**, 458 (1988).

[15] We assumed the modulator to be close to one of the end mirrors in a linear resonator, and Θ_m to be not much less than unity.