Electro-optic phase modulator as a starting mechanism in Ti:sapphire

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An electro-optic phase modulator in a regenerative mode-locker configuration is demonstrated as the starting mechanism for a Kerr-lens mode-locked Ti:sapphire laser. Mode locking is initiated automatically, and the system is capable of pulses as short as 21 fs.

The Kerr-lens effect in Ti:sapphire is widely used as a mechanism for passive mode locking in ultrashort-pulse lasers. Although Kerr-lens mode locking can be self-sustaining, it is, unfortunately, typically not self-starting. Exceptions to this rule can be found in recent reports of self-starting in which the resonator is carefully designed and aligned for self-starting. This method has the drawback that the best cavity configuration for self-starting is not necessarily the best configuration for self-sustained operation. This is characteristic of any design in which a single element plays important roles in both starting and pulse shortening. A desirable alternative is one in which these functions are carried out by different cavity elements. A number of methods have been employed to start mode-locked operation, including a coupled external cavity, a saturable absorber, acousto-optic modulation, and a moving mirror. Similar techniques have been used to start the operation. This is characteristic of any design in which a single element plays important roles in both starting and pulse shortening. A desirable alternative is one in which these functions are carried out by different cavity elements. A number of methods have been employed to start mode-locked operation, including a coupled external cavity, a saturable absorber, acousto-optic modulation, and a moving mirror. Similar techniques have been used in diode-pumped Cr\textsuperscript{3+}-LiSrAlF\textsubscript{6} lasers, in which mode locking is typically more difficult. In this Letter we demonstrate regeneratively initiated self-mode-locked operation in Ti:sapphire in which an electro-optic phase modulator is used as a starter. Of the various schemes for initiating Kerr-lens mode locking, this method is most similar to acousto-optic amplitude modulation. The phase modulator has the potential advantage, though, that it may be used for pulse timing jitter stabilization. This is possible because the phase modulator directly alters the cavity length by changing the refractive index of the electro-optic crystal. Moreover, the Q factor of the phase modulator is not particularly high, permitting compensation of cavity length fluctuations over a larger bandwidth.

The insertion of a phase modulator into an ultrafast laser necessarily introduces additional material dispersion. For better compensation of this additional dispersion, our laser design follows that of the four-prism laser used by Proctor and Wise. The modifications include a shorter rod (1 cm) and the placement of a phase modulator near the output coupler. Aperture losses and reflections at the crystal surfaces lead to an additional 2% cavity loss, causing the laser to be less stable. We remedied this by increasing the reflectivity of the output coupler from 94.5% to 96.5%. The dispersive arm of the cavity is composed of two pairs of quartz prisms. An alternative prism set consisting of two LaKL\textsubscript{21} prisms was also used but resulted in somewhat longer pulses. A photodiode monitoring a reflection from one of the intracavity prisms serves as the source of the rf signal for the phase modulator. The signal is then filtered, and the fundamental is amplified and inductively coupled into the phase modulator crystal via an LC tank circuit with a variable tuning capacitor. An electronic delay is also included to permit adjustments to the timing of the feedback signal.

Two different Brewster-cut crystals were used for the phase modulator itself—potassium titanyl phosphate (KTP) and deuterated potassium dihydrogen phosphate (KD\textsuperscript{3+}P). The length of each of the crystals was chosen to be 2 mm, representing a compromise between minimizing the material dispersion and maximizing the amount of phase modulation for a given applied voltage. The orientations of the optical path, the polarization vector, the rf field vector, and the crystal axes are shown schematically in Fig. 1. The optical field is polarized parallel to the table, and the electrodes are placed so that the rf field lines are perpendicular to the optical field, running vertically through the phase modulator (perpendicular to the page). The electro-optic coefficients coupling the two fields are \( r_{23} \) for KTP and \( r_{63} \) for KD\textsuperscript{3+}P. In the case of KTP, it was impractical to use the largest coefficient, \( r_{33} \). The reason for this is that \( r_{33} \) couples the optical and rf fields when they are parallel. In most applications, this is easily achieved. But in a very short crystal the rf field lines tend to run parallel to the crystal surface, which is not parallel to the optical field. Making use of the \( r_{23} \) coefficient permits us to orient the rf field so that it is perpendicular to the optical field, thus eliminating this problem. In addition, because of the Brewster cut, the horizontal dimension of the crystal must be made larger than the vertical dimension. So
Fig. 1. Schematic of the crystals used in the phase modulator. The beam path and the polarization vectors are represented by the dashed line and the small arrows, respectively. The electrodes are placed above and below the crystal (parallel to the page) and are separated by 2.2 mm. Accordingly, the rf field lines run perpendicular to the page. The orientations of the crystal axes are also shown.

using the $r_{23}$ coefficient permits closer spacing of the electrodes, thus increasing the rf field strength for a given applied voltage.

To achieve starting, we first align the cavity so that the laser self-mode locks with the phase modulator in place but not turned on. Once the laser is properly aligned, the feedback is turned on, and minor adjustments are made to the position of one of the focusing mirrors until starting occurs. The phase modulator is typically driven with 200–500 mW of rf power. This corresponds to a calculated peak phase delay of $\approx 0.3$ rad. Increasing the gain of the amplifier has little effect on the performance of the starter. With the phase modulator turned off, the laser remains mode locked for several minutes at a time. Once the modulator is turned on, however, we observe stable mode-locked operation without interruption. Self-mode-locked operation is not measurably affected by the regenerative feedback. That is, turning the phase modulator on and off does not change the characteristics of the output pulse train. But when the cavity is disturbed enough that mode locking stops, the phase modulator quickly starts it once again. The start-up time depends on all the system parameters and ranges from $\approx 20$ ms to as much as several seconds. The lower bound is similar to that reported for self-starting that uses no additional elements but is much longer than the start-up time attained with other techniques.\cite{6,15} The range over which the laser starts is a substantial portion of the self-mode-locking regime for which the cavity is aligned so that it is able to support either stable cw operation or stable mode-locked operation. It seems that a small amount of mode-beating noise is necessary for the modulator to initiate the transition to Kerr-lens mode-locked operation.

With no phase modulator in the cavity, we have measured pulses as short as 18.5 fs, though we suspect that this may represent the limit of our autocorrelator. With the phase modulator in place, the laser is capable of 31-fs pulses in the case of KTP and 21-fs pulses for KD*P. A typical interferometric autocorrelation for the KD*P laser output is shown in Fig. 2(a). Also plotted is the best fit to the autocorrelation envelope, with a sech$^2$ pulse shape assumed and adjustment for unequal reflectivities of the autocorrelator mirrors. The spectra have widths of 24 and 34 nm, respectively, and the KD*P laser spectrum is plotted in Fig. 2(b). The pulse duration–bandwidth products are 0.365 and 0.355, slightly larger than the transform-limited value of 0.315. The increased pulse duration associated with the KTP is attributed to its higher dispersion, which cannot be adequately compensated by the prism sequence. The Sellmeier coefficients\cite{16,17} give dispersion constants of

Fig. 2. (a) Typical autocorrelation with KD*P in the phase modulator. The dashed curves represent the calculated autocorrelation for a sech$^2$ pulse with duration of 21.3 fs. (b) Optical spectrum of the output of the same laser, with a FWHM of 34 nm.
The increased pulse durations are due, of course, to the insertion of an additional element into the laser cavity. This problem might be avoided by incorporation of the phase modulator into one of the existing cavity elements. For example, the dispersive arm of the cavity could be made up of two prisms cut from an electro-optic material. The prism nearest the end mirror could then be used as a phase modulator. This type of scheme may prove to be useful in diode-pumped lasers, in which power considerations prohibit the insertion of additional cavity elements. An acousto-optic modulator has been used as an AM mode locker in this configuration in a Cr$^{3+}$:LiSrAlF$_6$ laser. To assess the feasibility of such a scheme, we have calculated the second- and third-order dispersions of a pair of KD*P prisms at 800 nm. To compensate the second- and third-order dispersions of a pair of KD*P prisms at 800 nm, the phase modulator was increased from 28 to 47 cm for the KTP phase modulator and to 31 cm for the KD*P phase modulator. The difference in pulse durations and the fact that only a small phase modulation is necessary for starting suggest that material dispersion is more critical than the size of the electro-optic coefficients in the selection of materials suitable for this type of application.

In conclusion, we have demonstrated the use of an electro-optic phase modulator as a starting mechanism in a Ti:sapphire laser. The phase modulator provides stable operation and does not significantly degrade the performance of the laser. In addition, it holds the potential that the device can simultaneously be used for pulse timing jitter stabilization and for mode locking. In spite of the additional material dispersion of the phase modulator, pulse durations as short as 21 fs are possible. Although this research was carried out with a Ti:sapphire laser, this type of phase modulator should serve as a reliable starter in any type of ultrafast laser and may be particularly useful in diode-pumped schemes in which starting is more difficult.

References