that would appear if the error at the code reading did not occur. From the direct feedback equation
\[ y(n) = y(n-1) + 0.5c(n) - c(n-1) \]
that follows that the first formed bit will be wrong. Therefore, after the first shift of the contents of register \( Y \), \( Y = (y(n-1), \ldots, y(0)) \)
during the following \( n - 1 \) shifts, bit \( y(0) \) will lead to the formation of one more wrong bit, because at least one of the coefficients \( c(n-1), \ldots, c(1) \) must have value 1.

Conclusions: The new code reading method presented in this Letter provides continuity of the pseudorandom sequence and in many applications the addition of one more code reading head (two heads instead of one) is a minor drawback in comparison with the importance of the achieved continuity in forming the \( n \)-tuples. The positional information is not lost after the change of direction and consequently, not even for possible oscillation of the movable system in the direction of movement. The applied head arrangement for code reading also eliminates the systematic errors, considered in Reference 4, thus simplifying the system realisation. At the same time, this method enables a simple realisation of permanent checking of code reading correctness which is particularly important when high reliability of the measurement system is required.

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M. Arsić and D. Dimić (Faculty of Electronic Engineering, University of Niš, 18000 Niš, Yugoslavia)

References


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SELF-STARTING FEMTOSECOND
TI: SAPPHIRE LASER WITH INTRACAVITY
MULTIQUANTUM WELL ABSORBER


A titanium-doped sapphire laser has been mode-locked using an intracavity multiquantum well absorber. Stable transform-limited pulses as short as 136 fs have been generated.

Titanium-doped sapphire (Ti: Al₂O₃) lasers can routinely generate femtosecond pulses and recently, pulse durations below 20 fs have been achieved [1-4]. The process of Kerr lens mode-locking (KLM) [2], which is used in these systems, is generally not self-starting and so some additional amplitude modulation is required to initiate the pulse formation, e.g. synchronous pumping [3], passive mode-locking with a 'fast' saturable absorber dye [4], resonant passive mode-locking (RPM) with an extracavity semiconductor saturable absorber [5] or active mode-locking with an acousto-optic modulator [6]. Recently, in a unidirectional Ti: Al₂O₃ ring laser, picosecond pulses have been obtained with self-starting operation [7] but the requirement for an intracavity Faraday rotator is inconvenient because it increases both the intracavity loss and group velocity dispersion (GVD). For practical, user-friendly, femtosecond laser systems, it is often desirable to have some convenient means to maintain self-starting operation of femtosecond Ti: Al₂O₃ lasers. Synchronous pumping places demanding requirements on the pump source and, like active loss modulation, necessitates some form of cavity length matching. Passive mode-locking leaves the pulse repetition rate as an adjustable parameter but an intracavity dye stream is mechanically complex and can lead to instability due to fluctuations in the jet stream. A solid-state saturable absorber is clearly desirable and we describe here a femtosecond Ti: Al₂O₃ laser with an intracavity MQW saturable absorber. We note that the use of a semiconductor-doped glass is an alternative approach [8].

In the work reported here we employ an MQW absorber originally developed for mode-locking external cavity semiconductor diode lasers [9]. In an earlier experiment, we have used this absorber, intracavity and extracavity, with a Cr: LiSAF laser to generate pulses as short as 93 fs. The MQW absorber consisted of 100 periods of 70 Å-thick GaAs wells with 100 Å-thick AlGaAs barriers. Proton implantation was used to reduce the carrier lifetime to ~150 ps. The excitonic absorption peak was at 822 nm at room temperature. The surface of the absorber had a single layer antireflection coating and it was put on to a copper block which was water-cooled and maintained at a temperature of ~5°C. The small signal reflectivity of the MQW absorber structure was measured to be ~12% at the exciton peak. A more detailed discussion of the MQW absorber is given in Reference 9.

Fig. 1 shows the laser cavity used in this experiment. The Ti: Al₂O₃ laser rod was pumped by an argon-ion laser using an antireflection-coated, 10 cm focal length lens (L₁). The astigmatically-compensated laser cavity consisted of two 10 cm radius of curvature folding mirrors (M₁ and M₂), a 1% output coupler (M₃), two Brewster-angled SF10 prism pairs and the MQW absorber at the focus of a 30 mm radius of curvature highly reflecting mirror (M₄).

With no MQW absorber in the cavity, the CW lasing threshold was 1.5 W of absorbed pump power. Introducing the MQW absorber assembly to form the high reflector at one end of the cavity increased the lasing threshold to 5 W. At above 6 W pump power, stable, self-starting, CW mode-locking was observed. An average output power of 10 mW was measured at 7 W pump power. This low output power is partly a reflection of our poor quality laser rod although the optimum alignment of the cavity for the intracavity MQW absorber did compromise the output power achievable.
After optimising the intracavity glass path, pulses as short as 200 fs duration (assuming a sech$^2$ pulse profile) were routinely achieved and these were within 10% of their transform limit. The shortest pulses obtained were of 130 fs duration and an autocorrelation profile of these pulses is shown in Fig. 2.

The pulse duration was not critically sensitive to the laser alignment and we did not need to employ any intracavity slit or aperture. The use of the intracavity MQW absorber to mode-lock the laser resulted in a shift of the laser spectrum to lower frequencies, which shows that the pulse duration increased slowly with increasing positive GVD and stable mode-locking rapidly terminated with increasing negative GVD. This is in contrast to what is normally seen with femtosecond laser systems dominated by positive frequency chirp arising from the optical Kerr effect. Fig. 3 suggests that the net intracavity frequency chirp was negative and therefore due to the time-dependent saturation of the absorption of the MQW absorber. This observation highlights the possible disadvantages of employing an intracavity MQW absorber whereby the minimum achievable pulse duration may be ultimately limited by its frequency response, i.e. by the bandwidth limitation of any etalon structure in the absorber, by the GVD it introduces and by nonlinear frequency chirp arising from the time-dependent saturation of the absorption. The inclusion of an intracavity MQW absorber can introduce undesirable frequency chirp, which may lead to complex behaviour of the laser as a function of intracavity GVD, as observed with passively mode-locked dye lasers.

In conclusion, we have used an MQW absorber inside a Ti:Al$_2$O$_3$ laser and have generated stable, self-starting pulses of $\leq$100 fs in duration. It may be possible to refine the laser further and initiate KLM using an intracavity MQW absorber to generate sub-100 fs pulses. To achieve the shortest possible pulse durations, it will be necessary to take the phase response of the MQW absorber into account when designing the laser cavity. Furthermore, a suitable alignment must be found which optimises the laser for KLM, minimum insertion loss due to the absorber and maximum output power.

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Fig. 1 Schematic diagram of Ti:Al$_2$O$_3$ laser with intracavity MQW absorber.

See text for details of the labelled components.

Fig. 2 Intensity autocorrelation of pulse from Ti:Al$_2$O$_3$ laser mode-locked with an intracavity MQW absorber.

The pulse duration was not critically sensitive to the laser alignment and we did not need to employ any intracavity slit or aperture. The use of the intracavity MQW absorber to mode-lock the laser resulted in a shift of the laser spectrum to $\sim$850 nm from its free-running wavelength of $\sim$780 nm. We attribute this operation, at a longer wavelength than the room-temperature excitonic absorption peak, to a decrease in the MQW absorber effective bandgap energy due to local heating of the absorber by the laser radiation. This laser was not readily tunable although small changes in alignment, or the translation of an intracavity slit in front of mirror $M_2$, could shift the centre wavelength from $\sim$840 to 854 nm.

The use of the MQW absorber intracavity in the laser configuration reported here did not appear to initiate Kerr lens mode-locking. For this system, the insensitivity of the femtosecond laser operation to the precise adjustment of the cavity focusing suggests that passive modelocking with the ultrafast excitonic resonant nonlinearities (i.e. a 'fast' saturable absorber) dominated the steady-state laser dynamics, rather than KLM which would be expected to yield pulses of less than 100 fs duration. This may have been due to a failure to align the laser cavity to both minimise the insertion loss of the MQW absorber and optimise the focusing for KLM. We believe this should be possible and continue to work towards this end.

Some pulse compression was achieved intracavity by the interaction of nonlinear frequency chirp and GVD. Fig. 3 shows a plot of pulse duration against intracavity glass path which shows that the pulse duration increased slowly with increasing positive GVD and stable mode-locking rapidly terminated with increasing negative GVD. This is in contrast to what is normally seen with femtosecond laser systems dominated by positive frequency chirp arising from the optical Kerr effect. Fig. 3 suggests that the net intracavity frequency chirp was negative and therefore due to the time-dependent saturation of the absorption of the MQW absorber. This observation highlights the possible disadvantages of employing an intracavity MQW absorber whereby the minimum achievable pulse duration may be ultimately limited by its frequency response, i.e. by the bandwidth limitation of any etalon structure in the absorber, by the GVD it introduces and by nonlinear frequency chirp arising from the time-dependent saturation of the absorption. The inclusion of an intracavity MQW absorber can introduce undesirable frequency chirp, which may lead to complex behaviour of the laser as a function of intracavity GVD, as observed with passively modelocked dye lasers.

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R. Mellish, P. M. W. French and J. R. Taylor (Femtosecond Optics Group, Department of Physics, Imperial College of Science and Technology, Prince Consort Road, London SW7 2BZ, United Kingdom)

P. J. Delfett and L. T. Flore (Bell Communications Research, Red Bank, NJ 07701, USA)

References


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A LINEAR CCD ARRAY

INTRODUCTION:

Recent publications have outlined the advantages of demonstrating tunable lasers and spectrometers [1] to the recent trends in coherence [2]. In this paper, we describe a novel form of low coherence interferometric sensor, which uses a CCD array to perform measurements. The sensor is based on a channelled spectrum dispersed on a linear CCD array, which can be used to measure the coherence properties of light. The channelled spectrum is generated using a receiving interferometer, which is tuned to the source spectrum with the transfer function of the interferometer. The number of peaks and their positions are determined with a precision of better than 0.5 nm. Accurate alignment of the interferometer is essential to prevent unwanted peaks on the CCD caused by Fizeau fringes. The correct alignment was checked by replacing the grating with a mirror and ensuring that no fringes appeared on the CCD signal. A small aperture was used to prevent the appearance of Fizeau fringes.

EXPERIMENT:

The setup, illustrated in Fig. 1, and currently in bulk optic form, incorporates a multimode laser diode mounted on a stepper motor driven translation stage of 1 µm resolution controllable via an RS 232 interface by an IBM compatible computer. The output from the Michelson interferometer is directed towards a diffraction grating (1200 lines/mm) and the reflected spectrum is directed towards a CCD with a resolution of 128 pixels. The signal is displayed on an oscilloscope and for extracting information on the path imbalance, either a spectrum analyser or a counter may be used.

By inducing an OPD in the interferometer using the computer controlled translation stage, a series of peaks is observed within the light shape of the source. The number of peaks and hence the frequency at which these peaks are read out of the CCD is directly proportional to the path balance of the interferometer. Accurate alignment of the interferometer mirrors is essential to prevent unwanted peaks on the CCD caused by Fizeau fringes. The correct alignment was checked by replacing the grating with a mirror and ensuring that no fringes appeared on the CCD signal. A small aperture was used to prevent the appearance of Fizeau fringes.

The spectrum and time evolution of the signal from the optical beam was used to prevent the appearance of Fizeau fringes.

Fig. 2 Spectrum (upper traces) and time evolution (lower traces) of CCD signal for different distances

a) 50 µm
b) 1 mm

128 pixels. The signal is displayed on an oscilloscope and for extracting information on the path imbalance, either a spectrum analyser or a counter may be used.