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Numerical model of Kerr-lens mode-locking

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In recent years, there has been a great deal of interest in Kerr-lens mode-locking (KLM) in view of its implications for femtosecond pulse generation in solid-state lasers. Simple criteria for determining the cavity parameters that maximize the nonlinear amplitude modulation and promote self-starting have been sought,[1,2] with attention centered on the parameter δ defined as the relative change of beam size w with power P at one of the cavity mirrors ($\delta = ((1/w)\partial w/\partial P)_{P\to 0}$). Optimal KLM operation occurs when δ exhibits its most negative value.

A simple formula for calculating $\delta(x, z)$ was developed by Cerullo *et al.*,[1] where z is the separation of the two central mirrors in a Z-folded cavity and x is the distance of one of them from the gain medium. The aim of the work presented here has been to develop a general numerical model to calculate values of δ in both the tangential and sagittal planes, taking into consideration astigmatism introduced by off-axis spherical mirrors and Brewster-angled surfaces, nonlinear coupling of the beam sizes between the two planes of polarization,[3] self-focusing and gain-guiding.[4] The way in which contour plots of $\delta(x, z)$ change with the introduction of each of the above effects into the model and the effect on the optimum region for KLM have been studied.

Figure 1 shows contour maps of $\delta(x, z)$ in four different cases: Fig. 1(a) was generated for a symmetric Z-type cavity, based on the formula by Cerullo *et al.*;[1] Fig. 1(b) shows results of our numerical simulation for the same cavity in the absence of both astigmatism and gain-guiding; Fig. 1(c) takes astigmatism into account, while Fig. 1(d) also includes the effects of gain-guiding (results are for the tangential plane in both cases). The region of optimal operation is seen to shift significantly and lose its symmetry when gain-guiding is taken into account. This may be due to the fact that gain-guiding acts as a kind of soft-aperture inside the cavity, changing the beam sizes differently in the forward and backward-propagating directions. It should be understood that the form of these contour maps depends critically on the precise adjustment of the laser cavity.

We are currently applying our numerical model to the novel KLM cavities proposed by Ramaswamy-Paye *et al.*[5] and Bouma *et al.*[6] We will also analyze the effect of nonradially symmetric pump beams such as those from semiconductor diode lasers. Comparison with experimental results will be discussed.

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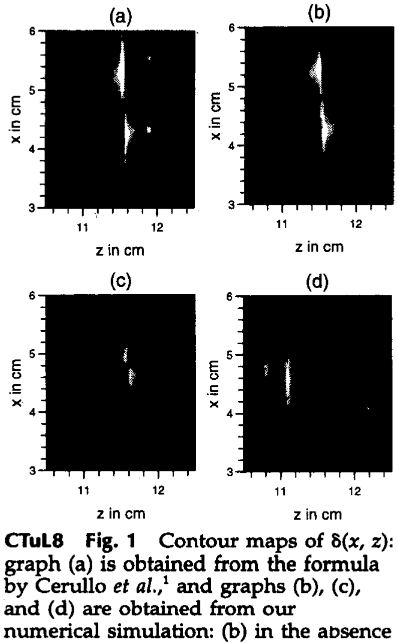

CTuL8 Fig. 1 Contour maps of $\delta(x, z)$: graph (a) is obtained from the formula by Cerullo *et al.*,[1] and graphs (b), (c), and (d) are obtained from our numerical simulation: (b) in the absence of astigmatism and gain-guiding, (c) when astigmatism is considered, and (d) when gain-guiding is also considered—(c) and (d) are taken in the tangential plane.

CTuL9

Ultrafast switching in highly birefringent fiber via soliton collision

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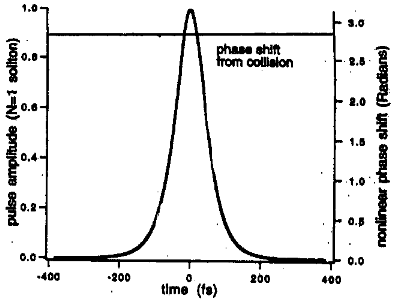
As bitrates in communications and computing systems continue to increase, switching components necessary for demultiplexing must operate at ultrafast speeds. Much research has recently concentrated on interferometric fiber-optic switching, and many such devices have been demonstrated as demultiplexers of ultrafast optical pulses with high switching contrasts.[1-3] The $\chi^{(3)}$ nonlinearity of fibers is extremely weak, and although the low propagation loss permits long interaction lengths, these long lengths have been a source of severe latency that is unacceptable for systems implementation.

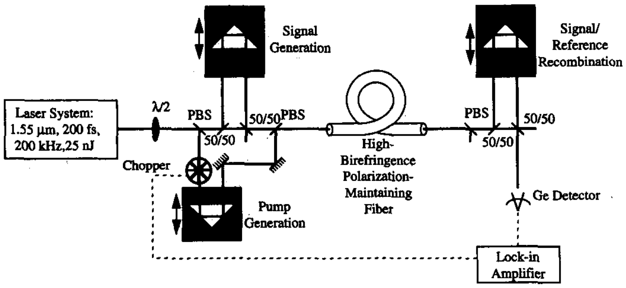


CTuL9 Fig. 1 Instantaneous pulse amplitude and phase shift of an $N = 1$ signal soliton after collision in highly birefringent fiber with a copropagating $N = 3$ pump soliton. The signal pulse closely maintains its original shape and experiences a phase shift of almost π.

We present theoretical and experimental results of the nonlinear phase shift obtained through a collision between two orthogonally-polarized soliton pulses in a highly birefringent polarization-maintaining (PM) optical fiber. The pulses are not strictly solitons since they are described by the coupled nonlinear Schrodinger equations. Prior numerical and experimental studies have shown that when two orthogonally-polarized solitary waves interact on a highly birefringent fiber, the pulse shapes do not change significantly if the exchanged phase shift is small compared with π.[4,5] Through further numerical studies we recently found that when a high-energy pump pulse collides with a lower energy signal pulse in PM fiber, the exchanged phase shift for one collision can be on the order of π without significantly affecting the pulse shape of the signal pulse.

We modeled the collision between a pump pulse of $N = 3$ soliton energy and a signal pulse of $N = 1$ soliton energy in PM optical fiber a birefringence (Δn) of approximately 5×10^{-4}. The interaction length of the collision is approximately 20 cm. In Fig. 1 we show the final amplitude and phase of the signal pulse in our numerical simulation. The pulse shape was nearly unaffected by this collision, and it acquired a nonlinear phase shift of nearly π.

Figure 2 shows the experimental setup used to observe the phase shift induced by the collision. An optical parametric amplifier producing 200-fs pulses at an idler wavelength of 1.55 μm is split into pump, signal, and reference beams, with the pump polarization orthogonal to the signal and reference polarizations. The pump is chopped (200 Hz), the signal and pump are delayed with respect to the reference, and all of the pulses are launched into 2 m of highly birefringent PM fiber. The amplitudes of the three pulses are set such that the pump forms an $N = 3$ soliton and the signal forms an $N = 1$ soliton. The effect of the pump on the signal as the pulses collide in the fiber was measured by a polarization interferometer. We found that the signal pulse obtained a phase shift of approximately π, as predicted by the numerical simulations (Fig. 1). We will discuss these ex-



CTuL9 Fig. 2 Experimental setup for soliton collision in a birefringent fiber and measurement of the resulting phase shift of the signal pulse. PBS indicates a polarizing (100%) beamsplitter, 50/50 indicates a nonpolarizing 50% beamsplitter, λ/2 indicates a half-wave plate. The pulse source is an optical parametric amplifie. pumped by a mode-locked Ti:sapphire laser and regenerative amplifier, producing 200-fs (FWHM) idler pulses at a 200-kHz repetition rate and a wavelength of 1.55 μm. The pump beam is chopped at a frequency of 200 Hz and eliminated after the fiber with a PBS. The interference of the final signal and reference beams is measured by a Ge photodiode.

periments and their applications to the development of a fiber-optic ultrafast demultiplexer with relatively short latency.

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CTuL10

Pulse-shape characterization of colliding pulse mode-locked laser diodes

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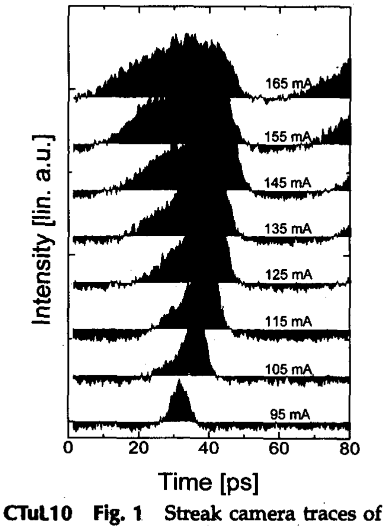
Monolithic colliding pulse mode-locked (CPM) lasers have recently attracted attention as a possible pulse source for optical time-division multiplexed (OTDM) communication systems.[1,2] For proper operation in these systems, the pulse width, chirp must be controlled by tuning of the biasing parameters. In this paper we present first measurements of the pulse width and chirp dependence on the biasing parameters. The CPM device used for investigation is a 5-mm-long InGaAsP based multiple quantum well (MQW) device with a ridge waveguide structure and three electrode layout.

Shown in Fig. 1 is the pulse shape as the forward gain current is varied from 95 mA to 165 mA in each of two electrodes, keeping the negative absorber bias constant at −0.25 V. The RF synchronization signal is held constant at the frequency 16.692 GHz corresponding to the period of twice the cavity round trip time. We observe asymmetric pulses building up slowly and ending with a sharp edge. A significant pulse broadening (5 times) is seen when the gain current is increased while the pulse peak power is almost constant. At the same time, the extinction of light between the pulses is almost 100%. The optimum combination between narrow pulse and high peak power is seen for around two times 105 mA, the threshold being approximately two times 85 mA. Beyond the 105 mA the pulses broaden significantly and even though the average power is increasing, the pulses are unuseful for system applications. This pulse broadening is explained on the basis of our numerical model[3] as a consequence of instantaneous gain suppression in the long gain sections.

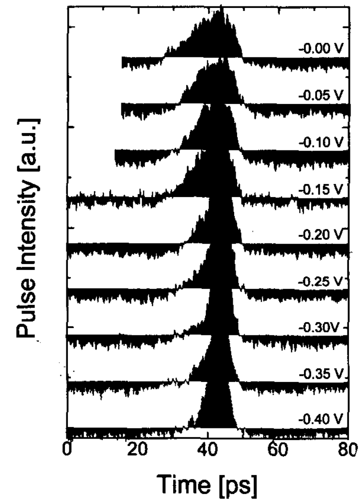


CTuL10 Fig. 1 Streak camera traces of the pulse for varying gain current. The absorber voltage is fixed at −0.25 V and the RF synchronization signal at 16.695 GHz. The gain current is indicated at each trace.

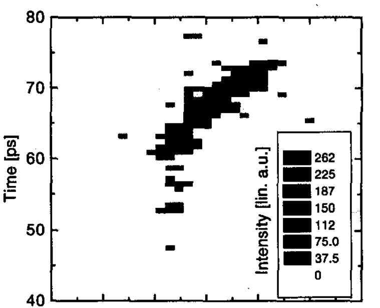
Figure 2 shows the pulse-shape development for increasing reverse absorber voltage, documenting significant pulse narrowing. However, exceeding approximately −0.3 V the laser goes into the self-pulsation regime[4,5] and it is only emitting bursts of pulses. This change in pulse shape is also explained by our model.[3]

The pulse width as a function of RF frequency is also discussed in the paper. Optimum tuning of the forward gain current, the reverse absorber bias and the RF leads to a minimum pulse width of 7.5 ps and a maximum peak power corresponding to around 1 mW coupled into the fiber.

Finally, the chirp of the pulses is investigated by adding spectral resolution to the temporal streak camera measurements. As an example, Fig. 3 shows the chirp near optimum performance of the



CTuL10 Fig. 2 Streak camera traces of the pulse for varying absorber voltage. The gain current is fixed at 2 × 105 mA and the RF at 16.695 GHz. The absorber voltage is indicated at each trace.



CTuL10 Fig. 3 Chirp for varying gain current obtained from spectrally resolved streak camera measurements. The gain current is 2 × 115 mA, the absorber voltage −0.25 V and the RF is 16.695 GHz. The grading shows the intensity.