

# Operation of a Nonlinear Loop Mirror In a Laser Cavity

I. N. Duling, III, C.-J. Chen, P. K. A. Wai, and C. R. Menyuk

**Abstract**— A nonlinear loop mirror can be used as a solid state saturable loss element. The transmission characteristics of the different embodiments of this mirror are shown to change significantly when it is used in the soliton-forming wavelength range. The implications for its use in a laser cavity are discussed.

## I. INTRODUCTION

THE nonlinear fiber loop mirror has received great attention of late as a fast optical switch for signal processing and communications [1]–[3]. In addition, it has been used as a fast saturable absorber to passively modelock laser oscillators and to reshape optical pulses [4]–[6]. When optimizing these lasers, it is necessary to know the operational characteristics of the nonlinear fiber loop mirror.

There are two general types of nonlinear loop mirror shown in Fig. 1, the nonlinear optical loop mirror [1] or NOLM [Fig. 1(a)], and the nonlinear amplifying loop mirror [7] or NALM [Fig. 1(b)]. Both of these devices operate on the same general principle: A Sagnac interferometer is constructed from a fiber coupler whose output ports have been spliced together, and the counterpropagating intensities are made unequal by either a coupler splitting not equal to 50% (NOLM) or by the inclusion of an in-line fiber amplifier close to one end of the loop (NALM). The optical trains with unequal intensities acquire a differential phase shift, due to the nonlinear index of the glass, causing light that at low power would be reflected to be transmitted by the mirror. Increasing transmission with incident intensity can be used to passively modelock a laser. Assuming this to be the case (that the laser is modelocked) the laser will tend toward the state in which loss is lowest, which in this case is when its peak power equals a transmission maximum of the mirror.<sup>1</sup>

A number of lasers have been built with nonlinear loop mirrors. The construction of two of these lasers is shown in

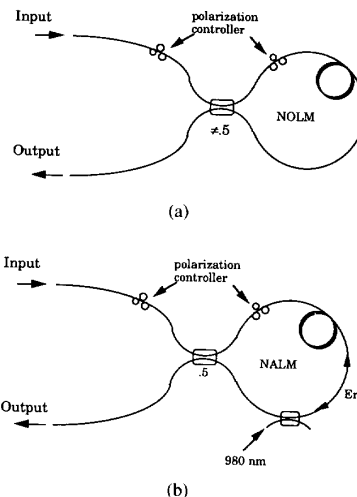


Fig. 1. Experimental layout of the nonlinear loop mirror. The NOLM incorporates an unequal coupling ratio to create a counterpropagating intensity mismatch (a), while the NALM uses an in line fiber amplifier to accomplish the same purpose (b).

Fig. 2. The first laser to incorporate a nonlinear loop mirror was a linear Er:fiber laser with a NOLM as the end mirror [Figure 1(a)]. This laser produced pulses of 300-ps duration and required a phase bias in the loop mirror [8]. The second laser incorporates a NALM used in transmission. This figure-eight laser has produced pulses as short as 100 fs and should, in principle, operate without any phase bias in the loop.

Previous analysis [1] showed that the behavior of the NOLM is significantly different in the negative dispersion regime, due to nonlinear propagation and the formation of solitons. In Section II, we show that with a careful choice of the operating conditions, it is possible to switch nearly all the pulse energy, but we also show that under most conditions the switching characteristics are more complicated, leading to wings and even multiple peaks in the output pulse. In Section III, we examine the operation of the NALM in the soliton propagation regime, and we extrapolate its effect on a laser cavity.

## II. NONLINEAR OPTICAL LOOP MIRROR

The counterpropagating light in a NOLM is mismatched in intensity by an unequal splitting in the coupler. If the light is sufficiently intense, a significant differential phase shift will accumulate between the counterpropagating fields, due to the nonlinear index of the fiber. When a  $\pi$  phase shift is attained,

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<sup>1</sup>The principle of mode competition, with the mode of least loss dominating, applies to different temporal operating states as well as different spacial or frequency modes of the laser. In this case the laser is constructed such that a pulsed operating mode has less total cavity loss than a CW oscillation.

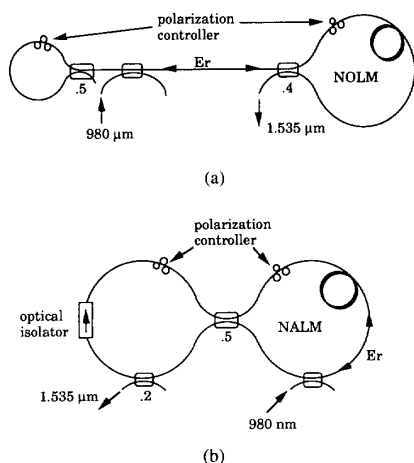


Fig. 2. Two examples of fiber lasers containing nonlinear loop mirrors. The linear laser with a NOLM used in reflection requires a phase bias in the loop (a), while the figure eight laser with a NALM (b) used in transmission does not.

the normally reflecting loop mirror will have become totally transmissive. This nonlinear transmission can be used to do pulse shaping and switching [6].

After [1], if dispersion is ignored, the transmission of a NOLM is given by

$$|E_2|^2 = |E_{in}|^2 (1 - 2\alpha(1 - \alpha) \cdot \{1 + \cos[(1 - 2\alpha)|E_{in}|^2 2\pi n_2 L / \lambda]\}) \quad (1)$$

where  $\alpha$  is the splitting ratio of the NOLM,  $n_2$  is the nonlinear index,  $L$  is the length of the loop,  $\lambda$  is the operating wavelength,  $E_{in}$  is the input field, and  $E_2$  is the transmitted field [1].

The nonlinear switching characteristic for CW light is presented in Fig. 3. The lower bound of the oscillating curve is determined by the intensity mismatch of the counterpropagating beams, while the upper bound corresponds to complete transmission. The increase of transmission with intensity is similar to the action of a fast saturable absorber, except that if a phase shift greater than  $\pi$  is generated, the transmission will decrease to its former minimum value. For pulses injected into the NOLM with a peak intensity less than the first maximum of transmission, the peak of the pulse will be transmitted more readily than the wings. As the peak intensity increases beyond the first maximum, a phase shift greater than  $\pi$  will be created, and less of the peak intensity will be transmitted. This results in broadening and, at high enough intensities, a double peaked pulse.

In pulsed light, as opposed to CW light, the intensity varies as a function of time; hence, the transmission also varies as a function of time. Thus, if one increases the energy of the pulses, keeping the shape fixed, one finds a curve for the transmitted energy similar to [1] but with a reduced contrast ratio. Experiments illustrating the pulse shaping that can occur have been conducted and are described in [6]. When negative dispersion is included and solitons are formed, regimes can be found where the entire pulse energy will be transmitted with no change in the FWHM of the pulse, in contrast to the

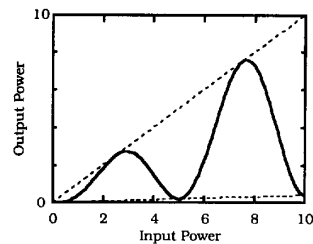


Fig. 3. Transmission characteristic of the NOLM (solid line). The curve is bounded on the top by 100% transmission, and on the bottom by leakage due to the intensity mismatch of the counterpropagating beams when they recombine.

positive or low dispersion case just described. It is with this behavior in mind that the NOLM has been referred to as a “soliton filter” [1]. The reason for this behavior is that the soliton will tend to acquire a uniform phase shift across the entire duration of the pulse that enables transmission to occur as a whole without significant reshaping!

A plot of the transmission of a NOLM in the soliton forming regime, is shown in Fig. 4 for a number of loop lengths. The plot is in soliton units. Dispersion and nonlinearity are the same in a fundamental soliton; so, the scale lengths associated with both are equal. The loop is measured in units of  $z_0 = 0.322\pi^2 c\tau^2 / \lambda|D|$  (the characteristic dispersive or nonlinear scale length, where  $c$  is the speed of light in vacuum,  $\tau$  is the pulse width, and  $D$  is the fiber dispersion) and the input energy is in units of the fundamental soliton energy ( $E_0 = 1.135\tau c P_1$ , where  $P_1$  is the soliton peak power given by  $P_1 = 0.776\lambda^3 |D| A_{eff} / \pi c n_2 \tau^2$ , where  $A_{eff}$  is the effective area of the propagating mode). As the loop length is increased, the energy required for peak transmission decreases. Since  $z_0$  and  $E_0$  depend on the pulse duration, it is important to interpret the curves in Figs. 3–8 and 10–12 properly. The quantities  $z_0$  and  $E_0$  depend on pulse duration, and hence the normalized length and energy can be varied by changing the pulse duration rather than the physical loop length. We note that although the curves shown in Fig. 4 always have a transmission maximum, that maximum does not always correspond to complete transmission, which will have consequences when the loop is used in a laser, as will be discussed later in this section. The plot for  $5z_0$  is a near reproduction of the soliton transmission curve (Fig. 3) of [1]. Doran and Wood do not, however, indicate what happens at other relative loop lengths, or what happens to the pulse width at operating points other than the peak transmission.

At all input energies, we find that the pulse duration changes during the pulse’s propagation through the loop. In fact, for input energies less than one, the pulse inside the loop mirror has much less energy than a fundamental soliton, and it will always broaden. By contrast, when there is no significant dispersion, pulses with peak intensity less than that of the first transmission maximum will always shorten. A typical plot of the transmission curve and the relative output pulse duration is shown in Fig. 5. We plot the ratio of the output pulse duration to the input pulse duration, so that values less than one correspond to pulse shortening. It can be seen that

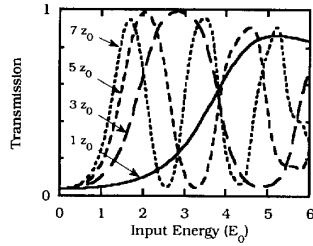


Fig. 4. Transmission of the NOLM for different loop lengths measured in units of the soliton period ( $z_0$ ) versus input energy measured in units of the fundamental soliton energy ( $E_0$ ). Note, as discussed in the text, that length and energy measured in these units depend on the pulse duration, as well as the physical length and energy.

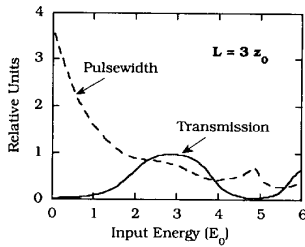


Fig. 5. Transmission and pulse width relative to the input to the NOLM vs. increasing input energy.

when dispersion is important, pulse shortening only occurs above a certain minimum energy for a given loop length.

Since the NOLM has increasing transmission with intensity below the first transmission peak, one might expect that if a NOLM is placed in a laser cavity, passive modelocking will occur. This expectation is correct and has been confirmed in a number of experiments [9]. Our description of the transmission characteristics of the NOLM provides insight into the operation of a laser incorporating a NOLM.

The first transmission peak of the NOLM is a function of both the loop length and the input energy. Figure 6 is a plot of the locus of the first three transmission peaks. The points are the maxima extracted from numerical simulations similar to Fig. 4. The lines are a fit to the points by a simple power law. The parameters for the fits are shown in Table I. Since lasers tend to minimize their loss, and the laser will start from spontaneous noise, it is reasonable to assume that the laser will operate at the first transmission peak. Once this assumption is made, the transmission and output pulse duration at the first transmission peak must be examined to determine if there is a preferred operating point and, therefore, a preferred pulse duration for a given loop length.

The transmission value at the first maximum is plotted in Fig. 7. To minimize the loss inside the cavity, the laser will run not only somewhere along the line of the first transmission peak, but will try to operate at a pulse duration that corresponds to a loop length of  $4-5z_0$ , as that is the point of maximum transmission.

In addition to the transmission value, the relative output pulse length is also plotted in Fig. 7. This figure indicates that

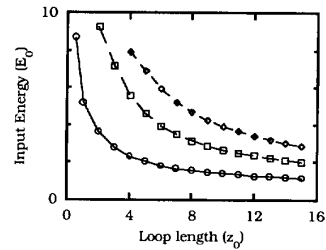


Fig. 6. Loci of the first three local transmission maxima for the NOLM vs. loop length and input energy.

TABLE I  
TRANSMISSION PEAKS

$y = a \cdot x^b$	$a$	$b$	$R$
Peak #1	5.393	-.58702	.99765
Peak #2	16.22	-.78033	.99861
Peak #3	24.23	-.79019	.99932

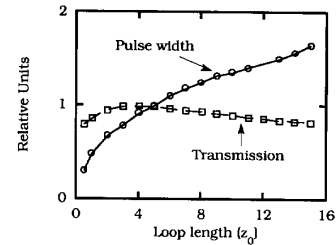


Fig. 7. The relative pulse width and transmission at the first local maximum vs. of loop length.

long-duration pulses, for which the loop length is smaller than  $4-5z_0$ , shorten on transmission, increasing the number of  $z_0$  on the next pass through the loop mirror, while short duration pulses, for which the loop length is larger than  $4-5z_0$  in length, broaden on transmission, decreasing the number of  $z_0$  on the next pass. Thus, the pulse duration evolution as well as the tendency to minimize loss tends to push the pulse duration toward  $4-5z_0$ .

Another way to look at the operating characteristics is to plot the energy above which the pulse will shorten and compare that to the energy at which the peak transmission occurs. This comparison is shown in Fig. 8. From this plot it can be seen that for long pulses, the required energy in soliton units to obtain pulse shortening is quite small compared to the energy at which maximum switching occurs. With each successive round trip, the pulse becomes shorter so that its loop length in soliton units is longer, moving the operating point closer to  $L = 4-5z_0$ . The assumption is made here that there is sufficient gain to compensate for the loss from both the NOLM and the cavity. If the pulse becomes too short, then as the laser stabilizes at the first transmission peak, the pulse will become broader with each round trip, and the operating point will again slide toward  $L = 4-5z_0$ .

What has not yet been addressed in this discussion is the shape of the pulses exiting from the NOLM. In fact,

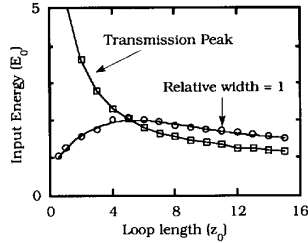


Fig. 8. Loci of the first transmission maximum and the point at which the output pulse is equal in width to the input pulse. Below this line, the output pulses are longer than the input pulses, and above the line they are shorter than the input pulse.

pulses of various shapes can be produced at different points along the switching curve. Figure 9 shows the output pulse shape for various input energies at a loop length of  $5z_0$ . The most pronounced feature are wings whose energy content depends sensitively on the initial conditions. In most cases, the amplitude of the wings are small and only indicate that the pulses do not have the ideal soliton shape, but in some cases, for example when the input energy is  $6.6E_0$ , the wings can be quite significant. This pulse was generated at the minimum of transmission and is therefore not likely to be a stable laser operating point.

Up to this point in the discussion, only loops with lengths of an integral number of  $z_0$  have been examined. It might be expected that since  $z_0$  is the distance over which a soliton recovers its initial shape, that this is a special case. In fact, the point of maximum transmission occurs for a differential phase shift of  $\pi$ , which for solitons of any order occurs prior to the pulse developing side lobes or multiple peaks. It is therefore not a special case to only examine integer values of  $z_0$ . This assertion was verified by additional numerical simulations at non-integral values of  $z_0$ .

### III. NONLINEAR AMPLIFYING LOOP MIRROR

In a NALM, the unbalanced coupler of the NOLM is replaced by a 50% coupler, and a fiber amplifier is spliced close to one end of the Sagnac loop [Fig. 1(b)]. The intensity imbalance in the loop mirror is thus proportional to the gain. The much larger mismatch that can be achieved compared to the NOLM lowers the switching threshold considerably. The off contrast of the mirror is also better, since the counter-propagating light beams are precisely the same intensity when they return to the coupler. One can show that the switching characteristics of the NALM in the positive dispersion regime saturate with the fiber amplifier, providing a constant pulse shortening as the pulse energy is increased [10].

One of the major differences between the NOLM and the NALM in the soliton forming regime is elucidated when the mirror response to a train of pulses is examined. Both communications applications and laser cavities use trains of pulses; so it is useful to examine this behavior. Because of the electronic nature of the nonlinear response, the response of the NOLM to one pulse of a train is identical to that of an isolated pulse. By contrast, the NALM relies on the

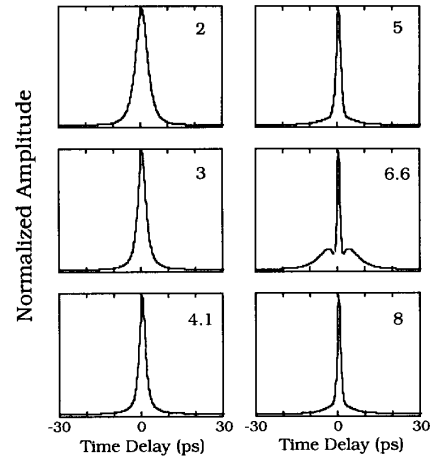


Fig. 9. Pulse shapes as they exit the NOLM for a loop length of  $5z_0$  at normalized input energies of 3, 4.1, 5, 6.6, 8 and 9.8 times  $E_0$ .

gain, which is a saturable phenomenon. Since the emission cross section of the Er ions is low, the gain saturation from a single pulse is negligible. A pulse train, however, can saturate the amplifier when the average power rises above a certain level. The NALM, then, is strongly affected by the presence of a pulse train since the effective amplitude imbalance changes as the gain is saturated. In addition, the transmission of the NALM can be much greater than one due to the gain of the amplifier. A typical switching characteristic is plotted in Fig. 10. The calculation was performed by solving the full nonlinear Schrödinger equation in the optical fibers and assuming an arbitrary saturation value for the Er-doped fiber amplifier. A fixed repetition rate was assumed for the plot so that the saturation could be observed. At low-input-pulse energy the gain is high, leading to a transmission significantly greater than one and a large amplitude mismatch in propagating around the ring. The large mismatch is made evident in the plot by the rate at which the transmission curve oscillates between maxima and minima as a function of input energy. It is clearly seen that when saturation occurs, the transmission decreases and the oscillation rate decreases. Also plotted in Fig. 10 are the FWHM and the rms (root-mean-squared) half widths as compared to the input pulse widths. The results have been replotted in Fig. 10(b) in order to see in detail the effects for low input energy. To interpret the curves, a smooth single-peaked pulse is produced when the FWHM is larger than the RMS half width by a factor of 1.7. As the ratio decreases, it indicates that the pulse is developing wings. The discontinuous jump in the FWHM indicates that the wings have grown to larger than half the height of the main pulse.

In the operation of the NOLM, variation of the pulse width was the same as varying the loop length in soliton units. As the pulse width is varied in the NALM, the energy scale will change due to the increased energy required for a fundamental soliton, the average power will increase for a fixed repetition rate, and the amplifier will saturate more. Saturation turns the analysis into a four-dimensional problem making a complete

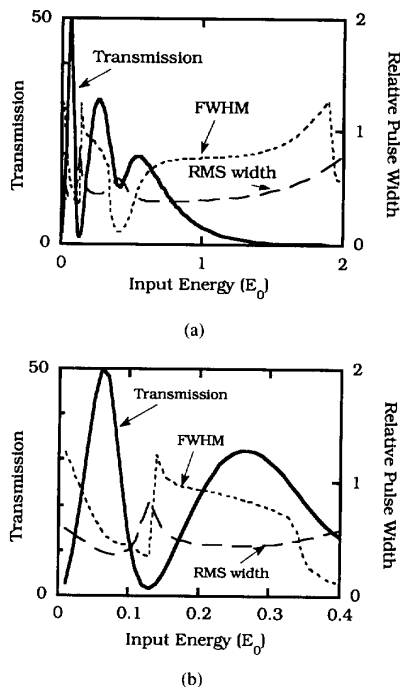


Fig. 10. Transmission (solid line), RMS pulse width (dashed line) and FWHM (dotted line) for the NALM. (a) Typical switching characteristic. (b) Same, replotted to show detail for low input energy.

analysis impossible, but some effects can be illustrated as in Fig. 10.

If we try to consider the situation where the NALM is included in a laser cavity [5], the overall length of the cavity will affect the repetition rate, and the losses in the cavity will affect the steady state gain of the amplifier. As a pulse evolves in its cavity toward steady state, the pulse width changes, changing the average power and the effective loop length. To track this evolution on the plots of the NALM response would be very difficult, but operating points may be found. In Fig. 11, physically meaningful values were used for the saturation. The functional form was taken to be

$$P_{out} = P_{in} \{1 + [A/(1 + BP_{in})]\} \quad (2)$$

where  $A$  and  $B$  are saturation parameters determined from a fit to the saturation plot of an existing Er fiber amplifier. Their values are  $A = 1764$ ,  $B = 0.2804$ . The pulse width for Fig. 9 was 0.3 ps, so that  $z_0$  is approximately 4 m for the fiber used here, and the repetition rate was chosen to be 30 MHz. It is clear from the figure that the amplifier quickly saturates. The output pulsewidth smoothly decreases without developing wings throughout the plot. It is interesting to note that around the point where the pulse is transmitted without change,  $3.5z_0$ , the gain is approximately 1.25, which would be appropriate to a laser with a 20% linear loss. The fact that the gain drops below 1 prior to reaching the desired operating point is an indication that the laser, if built with 20% linear loss, will be bistable and may not be self-starting. This straightforward interpretation ignores the fact that the pulse will not have maintained a constant pulse width during startup, but will

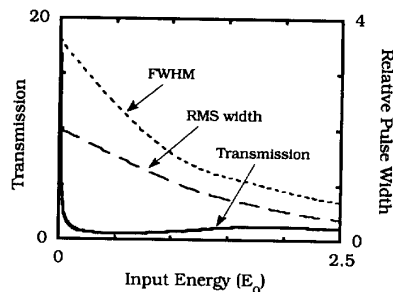


Fig. 11. Transmission (solid line), RMS pulse width (dashed line) and FWHM (dotted line) for the NALM with the realistic saturation parameters described in the text. The pulsewidth is 0.3 ps and the repetition rate is 30 MHz.

have arrived at this point from a plot with a different amount of saturation and a different loop length measured in soliton units.

The general pulse shape evolution seen in the NOLM, that the pulse is single peaked except at the minima of the transmission curve, is also true for the NALM. In all cases, the pulse shape at the transmission maximum is single peaked and the amplitude of the wings is minimal, ensuring that in a laser cavity the pulse will exit the nonlinear mirror as a single pulse, provided that it entered the nonlinear mirror as a single pulse. In practice, multiple peaked pulses have been observed from lasers modelocked by a NALM [5], and we conclude that they must be due to soliton reshaping in the feedback loop of the laser.

Since the pulse width will evolve as the laser starts, and the loop length as measured in soliton units will change length accordingly, it is instructive to plot the parameters for constant average power and changing loop length or pulse width. These conditions imply that the repetition rate or number of pulses in the cavity will change as the pulse width varies. Figure 12 shows a coarse plot of the variation of transmission and relative pulse width for these conditions. As can be seen in the figure, the quality of the pulse is greatest in the region where the relative width of the pulse is close to 1. This point is also close to the peak transmission of approximately 1.7. For this particular configuration then, a laser with a loss of 0.4 would support 0.3 ps pulses at a repetition rate of 30 MHz. The output power would be approximately 1 mW, and the pulse energy would be approximately 36 pJ. Although the transmission drops sharply for longer pulses corresponding to short loop lengths, the gain during startup is significantly higher than that in the steady state evaluated here. What this figure tells the laser designer is that for the laser parameters given above, a loop length of about  $2.5z_0$  is necessary. For 0.3 ps pulses,  $2.5z_0$  is approximately 9 m. These characteristic parameters are comparable to those which can be found in the experimental literature.

#### IV. CONCLUSIONS

The operation of the NALM and NOLM have been numerically investigated in the soliton-forming dispersion regime in order to understand their effect on a laser cavity. The analysis

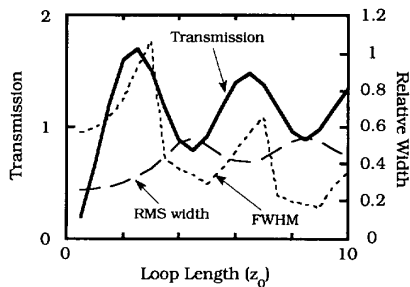


Fig. 12. Transmission (solid line), RMS pulse width (dashed line) and FWHM (dotted line) for the NALM as a function of loop length with a constant average power.

indicates that a laser that includes a NOLM will tend to operate at a pulse length corresponding to about  $4z_0$ , and that a laser incorporating a NALM will show a dynamic behavior which is sensitive to the repetition rate and the cavity loss. It has been found experimentally that these lasers tend to operate at a minimum pulse length corresponding to  $2-3z_0$  for the entire cavity length. This operation is a result of the periodic modulation of the soliton as it circulates in the cavity and the dispersive wave that is shed as a consequence of this perturbation [11] (these phenomena were not examined in our analysis). In the operating regimes examined experimentally the loop mirror is not the dominant element in limiting the pulse length. If a laser is constructed where this is not the limiting process it is expected that it will operate at a loop length of  $4-5z_0$ . In the case of the NALM, it is obvious that further analysis is necessary and may be best performed by fully modeling the laser using actual values for all parameters. The strong modelocking effect that the nonlinear loop mirror has on the laser by shortening its pulses will continue to make it one of the useful, passive fiber elements in the construction of short-pulse lasers.

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