Polarization effects and nonlinear switching in fiber figure-eight lasers

Andrew J. Stentz and Robert W. Boyd

The Institute of Optics, University of Rochester, Rochester, New York 14627

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We have developed a novel experimental procedure that allows us to quantify how polarization effects determine the passive mode locking of an optical fiber figure-eight laser. Based on our measurements, we have performed numerical simulations demonstrating that the nonlinear switching within this laser operates in a manner contrary to that described by the conventional theory of passive mode locking with a fast saturable absorber.

Fiber figure-eight lasers are the subject of intense research because of their potential to generate transform-limited ultrashort pulses at high repetition rates.[1–3] However, the stability, output pulse widths, and self-starting conditions of this laser are critically sensitive to optical anisotropies in the laser cavity.[4] We present here what we believe to be the first experimental characterization of the role of polarization effects in fiber figure-eight lasers. We also present the results of a numerical simulation of the laser based on experimentally determined operating parameters, demonstrating that the laser operates in a manner contrary to that described by the conventional theory of passive mode locking with a fast saturable absorber.

A schematic of the fiber figure-eight laser is shown in Fig. 1. The central 50:50 coupler and the right-hand side of the laser form a nonlinear Sagnac interferometer known as a nonlinear amplifying loop mirror[5] (NALM). In the absence of birefringence and in the low-intensity limit, light incident upon this device at port A is retroreflected. Part of this light leaves the laser at port C, and the rest is absorbed by the isolator. For an input pulse of the proper intensity the asymmetrically located amplifier induces a relative nonlinear phase shift between the pulses within the loop mirror such that, when the pulses interfere at the central 50:50 coupler, more of the light leaves at port B and less is absorbed by the isolator. In this way, the combination of the NALM and the isolator acts as an artificial saturable absorber.

However, the switching characteristics of the NALM depend in general not only on the relative nonlinear phase shift but also on the incident polarization and on the birefringence in the loop mirror.[6] These dependences were previously investigated in the context of fiber gyroscopes[7] and loop mirrors.[6,8] The fraction T of the total energy that is switched to port B by the loop mirror is of the general form

$$T = \frac{1}{2} + \frac{1}{2}\,\alpha\,\cos(\Delta\phi + \phi_B)\,, \qquad (1)$$

where $\Delta\phi$ is the relative nonlinear phase shift and the contrast factor α ($0 \leq \alpha \leq 1$) and the phase bias ϕ_B are functions of the input polarization and birefringence within the loop mirror.[7] Experimentally, the polarization controllers within the laser are adjusted by trial and error until the laser produces pulses, without any knowledge of the contrast factor or phase bias. Although this technique has proved to be effective in exploration of the various operating regimes of the laser, it provides little detailed knowledge of the operating conditions of the laser.

Characterization of the effects of birefringence in the laser is complicated by the capricious nature of stress-induced birefringence in non-polarization-preserving fiber. If we were to assemble the laser by fusion splicing all its components together, it would be impossible to measure accurately the birefringence within the laser since stress-induced birefringence is sensitive to even small mechanical disturbances, much less to the shock of breaking, mounting, and probing the birefringence at various points throughout the laser cavity. The technique illustrated in Fig. 2 can be employed to overcome these difficulties. Angled physical connectors are spliced into the laser at strategic locations, and their mating sleeves are rigidly mounted to an optical table. The equivalent retarder and rotator of the birefringence in the section of fiber shown in Fig. 2(a) are then measured by using bulk optical components to couple linearly polarized light of various orientations into one end of the fiber while measuring the output polarization at the other end. The rest of the laser is then assembled, as shown in Fig. 2(b); care is taken not to disturb the section of fiber whose birefringence has already been measured. The polarization controllers of the laser are adjusted by trial and error until a regime is found in which a small mechanical kick causes the laser to mode lock. In both the continuous-wave and pulsed modes of operation the polarization of the output light is measured, and the parameter T is determined by measurement of the relative optical powers at ports C and D (as defined in Fig. 1). The laser is then disassembled, and the birefringence in its components is measured, as illustrated in Figs. 2(c)–2(e). In this way, sections of fiber are moved only after their birefringence has been probed and does not need to be measured again. We checked the accuracy of this measurement procedure by comparing the output polarization and the value of T for continuous-wave

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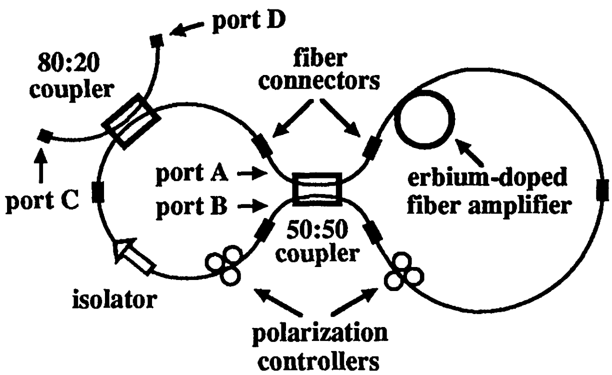

Fig. 1. Schematic of the fiber figure-eight laser.

operation that were directly measured in Fig. 2(b) with those calculated from the birefringence measurements shown in Fig. 2(a) and 2(c)–2(e), assuming a nonlinear phase shift of zero. These values agreed with one another to within a few percent. Because of length limitations, the details of this analysis cannot be presented here.

The NALM used in these experiments is constructed with a 15-m-long diode-pumped erbium-doped fiber amplifier and a 30-m length of standard communication fiber. The cold-cavity loss L of the laser is 65%, including the 20% output coupler and assuming a value of T of 100%. The average output power of the laser operating in the continuous-wave regime is 850 μW and increases to 900 μW when the laser mode locks, producing pulses of 1-ps duration.

To treat the effects of nonlinear polarization evolution, one would need to know the details of the distribution of the birefringence throughout the fiber laser and not simply the equivalent retarders and rotators measured by the method illustrated in Fig. 2. However, the effects of nonlinear polarization evolution are insignificant if the laser contains numerous, randomly oriented, birefringent elements of sufficient strength that their linear beat lengths are much shorter than the nonlinear beat lengths of the pulses within the laser cavity. These conditions apply for the laser we have constructed, and therefore we may assume that the pulses within the laser effectively experience scalar nonlinear phase shifts. In this case the measurements illustrated in Fig. 2 permit the complete characterization of the transmission characteristics of the loop mirror.

We performed a continuous-wave analysis of the laser under the assumption that the pulses underwent only a scalar nonlinear phase shift. The results of the polarization measurements were used in the analysis, and the results are depicted in Fig. 3(a). The energy transmission coefficient of the loop mirror was calculated as a function of the relative nonlinear phase shift for the eigenpolarizations of the laser. As one would expect, for small relative phase shifts the transmission of the loop mirror increases for increasing relative phase shift. This is the action of a conventional saturable absorber and makes the continuous-wave operation of the laser unstable.[9]

To study the temporal evolution of the pulses within the laser and to investigate our hypothesis of an effective scalar phase shift, we performed numerical simulations of the laser. Propagation of a pulse through the laser cavity was simulated by a numerical integration of a tensor nonlinear Schrödinger equation that included the effects of dispersion self- and cross-phase modulation and nonlinear ellipse rotation. Discrete randomly oriented birefringent elements were placed periodically throughout the laser cavity, simulating the random stress-induced birefringence present in the laser cavity as well as the equivalent retarders and rotators measured by the procedure illustrated in Fig. 2. A pulse was propagated through hundreds of round trips of the laser cavity until reaching a steady state. The time-averaged output polarization and the energy transmission coefficient of these simulations were compared with those values directly measured in Fig. 2(b) for picosecond operation and were found to agree to within a few percent. We find that both polarization components experience nearly identical nonlinear phase shifts within the first few pulse

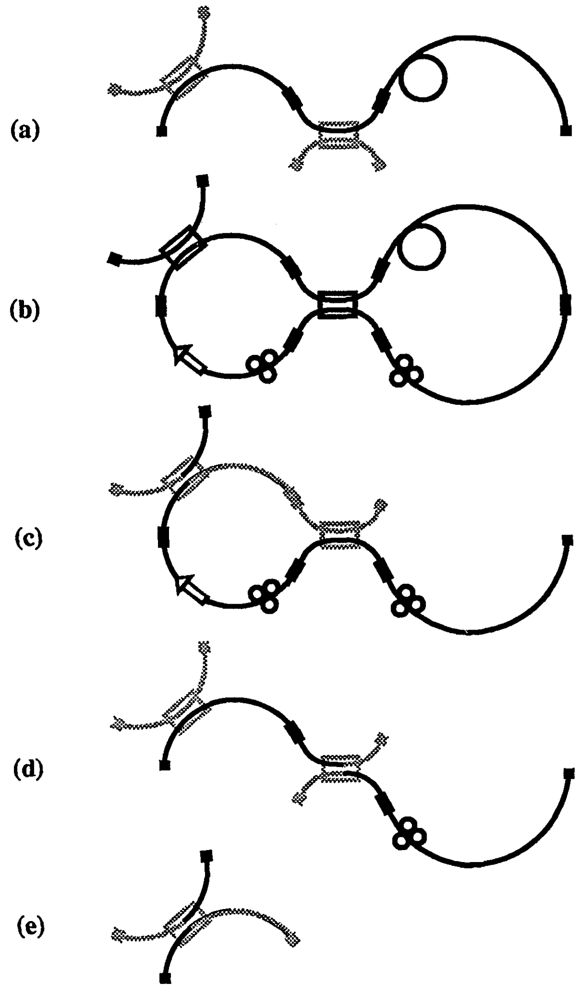

Fig. 2. Schematic of the experimental procedure for characterizing a figure-eight laser. (a) The birefringence in the bold section of the fiber is probed, (b) the laser is assembled and the average output powers and eigenpolarizations are measured for the characteristic modes of operation. (c)–(e) The birefringence in the bold sections of the fiber is measured as the laser is disassembled.

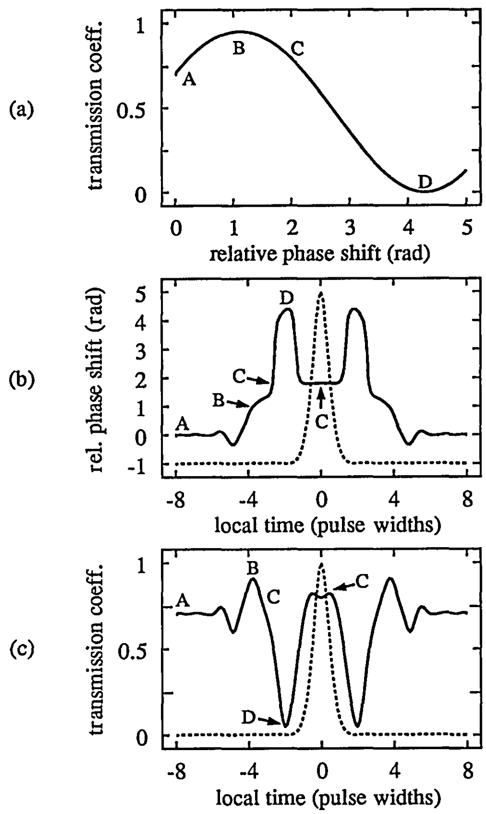

Fig. 3. Transmission coefficient of the nonlinear loop mirror as a function of the relative phase shift, as calculated from a scalar continuous-wave theory. (b) The relative phase shift and (c) the transmission coefficient of the nonlinear loop mirror as a functions of local time, as calculated numerically by use of a full tensor analysis. The pulse shape is shown by a dashed curve.

widths of the pulse center, indicating that nonlinear polarization evolution does not play an important role in the steady-state operation of the laser. Results from this numerical integration are shown in Figs. 3(b) and 3(c).

The plot of the relative phase shift as a function of local time shown in Fig. 3(b) reveals a few interesting features of the steady-state operation of the laser. First, near the center of the pulses the relative phase shift is constant, despite the rapidly varying intensity of the pulses. This is a consequence of the soliton-like nature of the pulses. Second, farther from the center of the pulses the relative phase shift increases as the intensity decreases. This effect is a result of the relative chirp of the two pulses in the loop mirror and occurs whenever the chirp of the clockwise-propagating pulse (as shown in Fig. 1) is less than the chirp of the counterclockwise-propagating pulse as the two pulses interfere at the central coupler. A plot of the transmission coefficient as a function of local time is displayed in Fig. 3(c). Notice that sharp transmission peaks are found in the wings of the pulse. These features are created when the relative nonlinear phase shift of the pulses passes through point B. Although the transmission at these points is much higher than at the pulse center, the pulse remains stable because these features are sufficiently narrow that a perturbation at this point spreads as a result of dispersion and is attenuated by the lossy feature at point D. However, these transmission peaks may be responsible for some of the instabilities observed in these lasers.

Within the conventional theory of passive mode locking with a fast saturable absorber, the transmission of the saturable absorber is assumed to be directly proportional to the intensity of the pulse.[9] In most laser systems this assumption is valid because the transmission of the saturable absorber is directly proportional to the nonlinear phase shift accumulated by the pulse, which is directly proportional to the intensity of the pulse. However, the results shown in Fig. 3 demonstrate that this laser operates in a regime in which an increase in the relative phase shift causes a decrease in the transmission of the loop mirror. However, since the maximum relative phase shift occurs in the wings of the pulse, the center of the pulse still experiences an effective saturable absorption. These conditions are exactly the opposite of the conventional conditions of saturable absorption.

In conclusion, we have performed an experimental and numerical study of polarization effects in a fiber figure-eight laser. We have characterized the operating conditions of the laser and find that the nonlinear switching within the laser operates by means of a mechanism contrary to that of conventional passive mode locking. In addition, we find that nonlinear polarization evolution does not play a major role in the steady-state operation of this laser.

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